Effects of Scale on Interpretation and Management of Sediment and Water Quality (Proceedings of a Boulder Symposium, July 1995). IAHS Publ. no. 226, 1995.

Spatial variability of cover affecting erosion and sediment yield in overland flow

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Abstract A simple overland flow sediment yield model is applied to an irregular slope to evaluate the influence of varying slope shape, length, and steepness, as well as percent canopy and surface ground cover on sediment yield (mean sediment concentration) along the hillslope. Assuming a uniform distribution of cover along a hillslope profile can result in significant distortions in apparent, or simulated, erosion and sediment deposition rates and thus sediment yield. Therefore, the concept of non-uniformity of cover must be incorporated in simulation models to more accurately describe hillslope erosion and sediment yield processes.

INTRODUCTION

Direct links exist between the form and structure of hillslopes, vegetation composition and patterns, soil and soil surface characteristics, and the interactive processes shaping them. Modern erosion prediction technology (Lane *et al.*, 1992) often represents a hillslope as a single plane, a cascade of plane segments, or a combination of planar and convex or concave segments. Estimated erosion is generally based on spatially-averaged estimates of canopy cover and surface ground cover along the hillslope profile in the direction of flow.

The objectives of this study are (a) to characterize the spatial variability (in the down slope direction) of vegetation canopy cover, surface ground cover (rock, gravel, basal area, litter) referred to as ground cover hereafter, and topography for a small basin on the Walnut Gulch Experimental Watershed in southeastern Arizona, USA; (b) to incorporate this spatial variability into a simple overland flow sediment yield model for rill and inter-rill erosion; (c) to use the sediment yield model to determine the influence of this spatial variability on hillslope erosion processes; and (e) to interpret the erosion model simulation results in the context of stability and disequilibrium of hillslopes.

DESCRIPTION OF THE MODEL

A simple, yet physically-based, sediment yield model is used to evaluate qualitatively the influence of spatial variability in hillslope properties on sediment yield. Though lacking the superior predictive capability of more complex models, the single-event model used has the advantages of an analytic solution, simplified input, and a limited number of parameters. Overland flow on a plane is described by the kinematic wave equations:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = R \tag{1}$$

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

where h is the local depth of flow (m), t is time (s), q is discharge per unit width ($m^2 s^{-1}$), x is distance in the direction of flow (m), R is rainfall excess rate ($m s^{-1}$), and $k = Cs^{1/2}$, where C is the Chezy coefficient ($m^{1/2} s^{-1}$) and s is slope. For this particular formulation, rainfall excess rate is constant and uniform:

$$R(t) = \begin{cases} R & 0 \leq t < T \\ 0 & \text{Otherwise} \end{cases} \tag{3}$$

where T is the duration of rainfall excess and the other variables are described above. The continuity equation for sediment is:

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

where c is sediment concentration ($kg\ m^{-3}$), e_i is the inter-rill erosion rate ($kg\ s^{-1}\ m^{-2}$), and e_r is rill erosion or deposition rate ($kg\ s^{-1}\ m^{-2}$).

The inter-rill erosion rate is assumed to be:

$$e_i = k_i R \tag{5}$$

where k_i is the inter-rill coefficient ($kg\ m^{-3}$). The rill erosion/deposition equation is:

$$e_r = k_r[Tc - cq] = k_r[(b/k)q - cq] \tag{6}$$

where k_r is the rill coefficient (m^{-1}), Tc is the transport capacity ($kg\ s^{-1}\ m^{-1}$) and is equal to $(b/k)q$, b is a transport capacity coefficient ($kg\ s^{-1}\ m^{-2.5}$), k is the hydraulic resistance coefficient, c is sediment concentration ($kg\ m^{-3}$), and q is discharge per unit width ($m^2 s^{-1}$). Equations (1) through (4) (with equations (5) and (6) substituted for the right hand side of equation (4)) are called the coupled kinematic wave and erosion equations for overland flow. The form of equations (5) and (6) was suggested by Foster & Meyer (1972). An analytic solution of the coupled kinematic wave and erosion equations for overland flow during the rising hydrograph only was derived by Hjelmfelt *et al.* (1975). An analytic solution for the entire runoff hydrograph was derived by Lane *et al.* (1988).

The sediment continuity equation can be integrated (Shirley & Lane, 1978) to produce a sediment yield equation for the runoff event as:

$$q_s = q_{vol}(x)\,[(b/k) + (k_i - b/k)\,g(k_r,x)] \tag{7}$$

where q_s is storm sediment yield per unit width of the plane ($kg\ m^{-1}$), q_{vol} is storm runoff volume per unit width ($m^3\ m^{-1}$), x is distance down the plane (m) and g is a function of k_r and x defined as:

$$g(k_r,x) = [1.0 - \exp(-k_r)(x)]/(k_r)(x) \tag{8}$$

This sediment yield equation for a single plane has been extended to irregular slopes to perform the analyses reported herein. Consider a slope composed of n slope segments x_1, x_2, up to x_n where $x_n = L =$ total slope length (m). Hillslope topography can be represented with increasing accuracy by including more segments.

Model inputs for the entire hillslope are runoff volume per unit area and a soil erodibility parameter. Model input parameters for each segment are slope length and steepness, percent vegetative canopy cover and percent ground cover. These input data are used to compute hydraulic roughness, inter-rill erodibility, rill erodibility and a sediment transport coefficient. The model was parameterized via calibration using rainfall simulator data from 10.7 × 3.0 m plots in Arizona and Nevada (Simanton *et al.*, 1986).

STUDY SITES AND PROCEDURES

The climate of the Walnut Gulch Watershed is classified as semiarid or steppe, with about 70% of the annual precipitation occurring during the summer months from convective thunderstorms of limited areal extent (Sellers, 1964). Soils are generally well-drained, calcareous, gravelly to cobbly loams. Land use consists primarily of grazing, recreation, mining and some urbanization (Renard *et al.*, 1993).

A representative hillslope profile was selected on the 1.86 ha Kendall 2 Watershed (K2). Vegetation on this hillslope is dominated by warm season short grasses with an average canopy cover of 40%. The 124.2 m profile is described by 26 segments. Canopy and ground cover along each segment at 10 to 30 cm intervals were determined from line-point measurements (Bonham, 1989). From these data the percentages of canopy cover, ground cover, and bare soil were calculated for each slope segment. Slope segment lengths and slope steepness were determined using an electronic distance measuring device.

Eighteen events with measured runoff and sediment yield from Watershed K2 (Tiscareno-Lopez, 1994, Appendix A) were selected for analysis. Measured volumes of runoff from the small basin, measured topography, canopy cover and ground cover from the representative overland profile, and estimated soil erodibility from rainfall simulator studies on experimental plots near the basin were used as input to the model for calculating sediment yield.

ANALYSES AND RESULTS

Application of the sediment yield model to the Kendall Watershed

Computed sediment yield values for the 18 events were compared with the corresponding measured values. The regression equation between observed sediment yield in kg m^{-1} (x) and the computed values (y) was $y = 25.9 + 0.84x$, with $R^2 = 0.94$. However, this regression relation was dominated by the two largest events. The corresponding regression equation between measured and computed sediment yield without the two largest events ($n = 16$) was $y = 24.4 + 1.01x$, with $R^2 = 0.62$. We feel that the results indicating an R^2 value of about 60% are indicative of the ability of the model to predict sediment yield and thus emphasize the qualitative nature of the model simulations discussed in the following section.

Concept of non-uniformity of cover

Topography, canopy cover and ground cover for the representative profile are shown in Fig. 1. Simulated mean sediment concentration based on spatially uniform average canopy and ground cover and measured (spatially varying) canopy and ground cover are shown in Fig. 2. Notice that simulated mean sediment concentration (total sediment yield divided by total runoff volume) varies in the flow direction and assuming average values for canopy and ground cover significantly distorts the spatial distribution of mean sediment concentration along the hillslope profile.

We hypothesize that departures from a uniform mean sediment concentration in the flow direction represent areas of disequilibrium where either net rill erosion (increasing concentration) or net rill deposition of sediment (decreasing concentration) are occurring. Under this hypothesis, the simulation results suggest that, with spatially varying canopy and ground cover, the hillslope profile is near equilibrium from 0 to about 50 m, is subject to increasing erosion from 50 m to about 90 m, and is nearly in equilibrium for the remaining 32 m of the hillslope. In contrast, a simulation based on spatially uniform canopy and ground cover suggests disequilibrium at all points along the profile. Erosion appears to be occurring from 0 to about 85 m, and then deposition for the remaining 37 m.

Gross distortions in estimated erosion and sediment deposition rates, and thus sediment yield, can result if the assumption of average canopy and ground cover values are used in distributed sediment yield models. This suggests a change in conceptualiza-

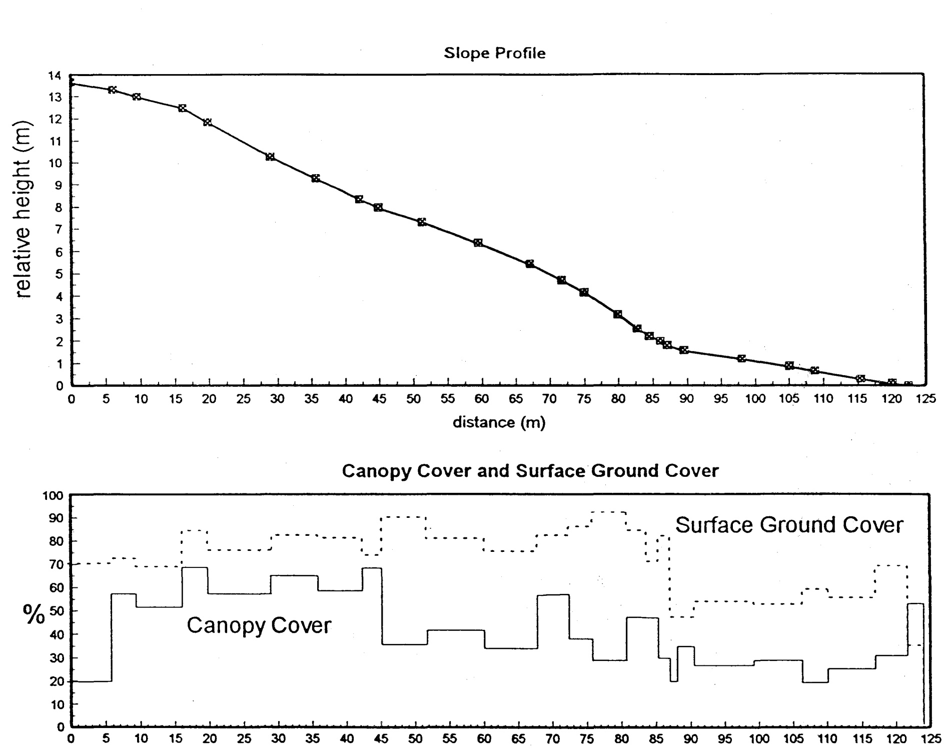

Fig. 1 Representative hillslope profile and measured values of canopy cover and surface ground cover on Watershed K2.

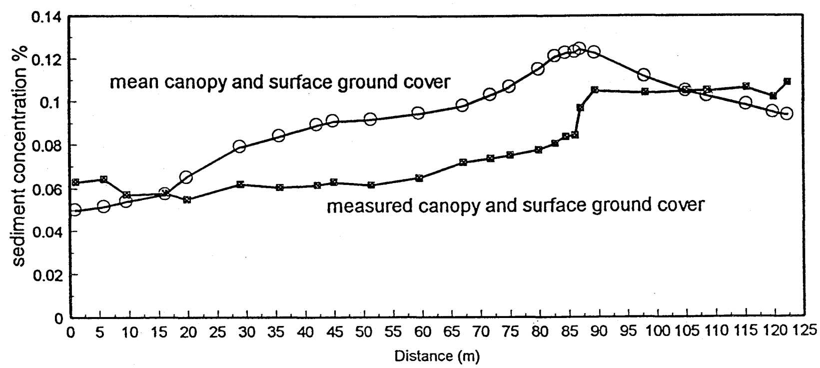

Fig. 2 Simulated mean sediment concentration for the representative hillslope profile on Watershed K2. Simulations with measured values of canopy and ground cover varying along the profile and using average values of canopy and ground cover.

tion of distributed erosion and sediment yield modeling on hillslopes. We recommend a concept of non-uniformity of cover be adopted and question the appropriateness of using overall averages for canopy and ground cover.

DISCUSSION

We have demonstrated that assuming a uniform distribution of cover along a hillslope profile can result in significant distortions in apparent, or simulated, erosion and sediment deposition rates and thus sediment yield. Therefore, the concept of non-uniformity of cover must be incorporated in simulation models to describe more accurately hillslope erosion and sediment yield processes.

Acknowledgement This research was supported by the USDA-ARS, specifically the ARS National Climate Change Research Program and the Southwest Watershed Research Center Erosion and Sedimentation research project. We gratefully acknowledge this support.

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