Chapter 8

A Simulation Model for Erosion and Sediment Yield at the Hillslope Scale

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1. INTRODUCTION

1.1. Background

As a physical feature of the landscape, hillslopes connect high points with low points. A *hillslope* can be defined as the zone of the landscape from the crest of a ridge along the slope in the direction of flow to a defined drainage, water body, or other feature that interrupts the overland flow profile at the toe of the slope. The evolution and visible forms of hillslopes are in large part determined by the effects of water driven erosion. In the absence of activities such as land forming, grading, cultivation, etc., hillslopes are relatively stable and their forms evolve slowly.

Early understanding of the factors affecting erosion on hillslopes was based on qualitative studies designed to address erosion problems associated with cultivated agriculture and included many measurements from experimental plots. The study of erosion plots led to the development of empirically based erosion equations. The dominant characteristics that describe an individual hillslope, such as shape, surface cover, vegetation, length, and slope are also factors that affect infiltration, runoff, and erosion. Land use, such as military training activities, can directly change those factors that have been determined to affect hillslope erosion.

The term *rangelands* is a broad classification that includes pasture lands, scrub lands, and other non-crop and non-forest lands. Rangelands are found

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in every state and cover 55 percent of the land surface of the United States (e.g., see Branson et al., 1981). From western deserts and grasslands to meadows and woodlands, rangelands comprise over 360 million hectares or some 80 percent of the land in the western states. Soil erosion on rangelands has been widely recognized as a problem since the early 1900's. The susceptibility of rangelands to erosion is exacerbated by land uses that disturb vegetative cover, alter runoff courses, and change the characteristics of the soil. Rangeland soils are typically fragile, thin, and relatively nutrient poor in comparison with cropland soils (e.g., see Lane et al., 1997). However, experiences gained from the long history of erosion research dedicated to resolving soil erosion problems on cultivated soils offer a starting point for adaptation to rangeland conditions.

1.2. Purpose, Scope, and Limitations

The purposes of this chapter are to:

- provide a brief historical perspective and overview of erosion modeling,
- briefly review hillslope erosion processes on rangelands,
- describe a particular model called the *Hillslope Erosion Model*, its calibration, and validation using data from rainfall simulator studies and from very small watersheds, and
- discuss applications of the *Hillslope Erosion Model* at a large number of sites on the Ft. Carson Military Reservation and the Pinon Canyon Maneuver Site in Colorado.

The focus here is on hillslope scale erosion and the emphasis is on surface processes and overland flow that contribute to hillslope erosion and evolution. Processes related to seeps, subsurface flow, snowmelt, and freeze-thaw cycles are not considered.

2. REVIEW OF EROSION AND SEDIMENT YIELD MODELING AT THE HILLSLOPE SCALE

2.1. Historical Perspective

Research on water-induced soil erosion dates to the early part of the 20th century and soil erosion was identified as a serious problem in the United States as early as the 1920's (Chapline, 1929). Chapline's early research demonstrated that overgrazing by cattle reduces the soil's water holding capacity resulting in accelerated soil erosion and decreased soil fertility.

During the 1920's, H.H. Bennett, a soil surveyor with U. S. Department of Agriculture (USDA) Bureau of Soils, considered soil erosion to be a national menace to farmers and to society in general (USDA, 1928). Bennett's influence on early soil conservation efforts was significant and led to a congressional appropriation of funds for soil erosion research to the USDA in 1929 (Meyer and Moldenhauer, 1985). Erosion research stations were established in areas with serious erosion problems, initiating a major soil and water conservation program in the United States.

The use of equations and models to predict soil erosion by water dates back to the mid-1930's. Cook (1936) identified three major variables useful for understanding soil erosion: the susceptibility of soil to erosion (soil erodibility), the potential erosivity of rainfall and runoff including the influence of degree and length of slope, and the protection offered by vegetative cover. Zingg (1940) developed an equation for sheet and rill erosion as a function of slope length and steepness using data from other researchers and his own experiments, and is often credited as the developer of the first erosion prediction equation. Smith (1941) evaluated the effects of mechanical conservation practices for four combinations of crop rotation and soil treatments, and added crop and supporting practice factors to Zingg's equation. A graphical method was developed for selecting conservation practices on soils in the Midwest. Soon after, Smith and Whitt (1948) proposed the "rational" equation to estimate soil loss, modifying Zingg's equation further to incorporate climate, cropping, and management factors. This equation, along with a large body of experimental plot data, formed the basis for the *Universal Soil Loss Equation, USLE* (Wischmeier and Smith, 1965, 1978).

Historically, the principle application of erosion prediction technology was for on-farm conservation planning to assess a variety of farming practices. Soil loss was estimated for specific field conditions on a farm for each of the practices. If the amount of erosion under a particular practice exceeded the soil loss tolerance, the amount of erosion was considered excessive. A farmer could then choose between those practices for which the computed soil loss was less than the soil loss tolerance value based on his overall preference (Foster, 1991).

By the late 1960's the research effort in the United States was focused on the principles and processes governing soil erosion by water and expressing them in mathematical models to improve erosion prediction and control (Meyer and Moldenhauer, 1985). Concurrently, the environmental movement and the energy crisis of the 1970's resulted in worldwide concern for natural resources. This provided the impetus for initiating a research effort to develop a better understanding of the offsite effects of soil erosion.

2.2. Water Erosion Modeling on Non-Croplands

Many wind and water soil erosion models for application on croplands and non-croplands have been developed over the last half-century, both nationally and internationally. Although soil erosion and sedimentation are problems generally associated with cropland agriculture, rangeland resources are also commonly degraded as a result of soil erosion. Rangeland represents an important land type, possessing significant values for domestic livestock, wildlife habitat, recreation, watershed resources, and soil and water conservation. Rangelands cover almost half the earth's land surface (Williams et al., 1968), many of them in arid and semiarid zones (Branson et al., 1981), and contain drought resistant grasses, shrubs and forbs. Such regions occur around the world including East Africa, the Middle East, Asia, Australia, and the western United States.

Branson et al. (1981) list the following main characteristics of rangeland:

- the potential natural vegetation is predominantly grasses, grass–like plants, forbs and shrubs,
- natural herbivory was an important influence in its pre-civilization state, and
- it is more suitable for management by ecological principles than by agronomic principles.

The health of rangeland areas in the United States is currently a major focus of research (NRC, 1994). Evaluation of soil stability is one criterion that can be used in assessing rangeland health, as many rangeland ecosystems are particularly vulnerable to erosion problems that arise from drought, overgrazing, and other stresses. Erosion prediction tools play an important role in the recognition of high-risk areas, and are widely used for soil conservation planning and design to rank alternate management practices with regard to their likely impact on erosion. Such tools are critical for erosion control and soil conservation because there are frequently many alternative management practices from which to choose, the practices tend to be costly, and the results of these practices often do not exert a measurable influence on soil erosion until many years after they have been implemented (Lane et al., 1992).

Soil erosion models range from simple to very complex, and are generally developed either for research purposes or for practical application by land management agencies (Doe et al., 1999). Computer simulation models use mathematical representations to simplify the physical systems, based on the observation and measurement of natural functions and processes, and can be classified as either empirical model or theoretical (physics- based) models. Data collected from field and/or laboratory experiments are used to develop the relationships represented in empirical models. These relationships may or may not necessarily represent actual physical processes, so care must be taken to ensure that variables are truly correlated and that the relationships are not applied outside the range of the data set from which they were developed.

Process-based mathematical models provide an approach that enables a better understanding of fundamental erosion and deposition processes leading to improved erosion assessment and control technology. However, attempts to model these systems are constrained by the complexity of the component processes and state variables that may change rapidly in time and space, and so a simplified representation must be used to model the complex erosion and deposition processes (Lopes, 1987). According to Foster (1982), some of the main advantages of process based models for estimating space and time-dependent erosion/deposition rates and sediment yields are that they:

- can be extrapolated more accurately to different land use conditions,
- represent the erosion/deposition processes more accurately,
- can be applied to more complex conditions including spatially varying surface characteristics and soil properties, and
- are more accurate for estimating erosion/deposition and sediment yield on a single storm event basis.

Process-based models often require extensive data for parameterization, particularly on rangelands where significant spatial and temporal variations in soil and vegetation characteristics affect infiltration, surface runoff, and soil erosion. Therefore, to generate accurate predictions from process-based models that have the ability to predict the effects of spatially variable inputs, it is important to parameterize these models accurately, taking the spatial variability of certain model parameters into account.

2.3. Examples of Rangeland, Hillslope Scale Water Erosion Models

The *USLE* and the revised *USLE* (*RUSLE,* Renard et al., 1991) are two of the most well known empirical erosion models applied to rangelands. The *USLE* was developed as a method to predict long-term average annual soil loss from interrill and rill field areas, and was designed as a convenient working tool for land managers, planners, technicians and conservationists. It continues to be the most widely applied soil erosion technology around the world. The equation is simple to understand and use, and its application has resulted in incalculable benefit to soil conservation and land management

(Lane et al., 1992). Despite its popularity and the many strengths of the *USLE*, the equation also suffers from a number of constraints and limitations. For instance, the model estimates soil loss from sheet and rill erosion only on areas where erosion, and not deposition, occurs. It does not account for ephemeral gully erosion and does not provide any information about sediment characteristics. While the *USLE* is useful for predicting average long-term soil loss, it is not useful for short-term predictions. Furthermore, it should not be applied to conditions that are different from those under which it was developed; namely, cropland with medium textured soils. As an empirical equation, the *USLE* does not explicitly represent fundamental erosion processes and their interactions (Renard et al., 1991), and does not separate factors that influence soil erosion such as plant growth, decomposition, infiltration, runoff, soil detachment, or sediment transport (Weltz et al., 1998).

The *CREAMS* model (Knisel, 1980) is an example of a distributed hillslope model. It was developed as a new approach to estimating soil erosion with particular emphasis on assessing the impact of agricultural practices on off-site water quality, including pollutants in surface runoff and in soil water within the root zone. A major benefit of the *CREAMS* model for application to rangelands is its ability to accurately estimate erosion and sediment yield for individual storms, which is important because a small number of storms can dominate the amount of annual erosion. The model also tends to be more accurate where transport capacity limits sediment yield because transport capacity is considered separately from detachment (Foster and Lane, 1981). The major disadvantage of using *CREAMS* on rangelands is that many parameter values have not been measured or validated for many rangeland conditions.

The *Water Erosion Prediction Project* (*WEPP*) model (e.g. Laflen et al., 1991b; and Chapter 7 of this volume) provides an example of a distributed, process-based model that is based on numerical solutions. Although the complexity of models such as *WEPP* makes them more robust and accurate than other erosion prediction tools, it also makes them very expensive and time consuming to develop, test and apply. However, the advantages of models such as *WEPP* over empirical soil erosion models are many. For example, *WEPP* can estimate the spatial and temporal distributions of soil loss and sediment yield at any point on a hillslope or within a watershed, erosion and hydrologic parameters are calculated directly from soil and vegetation characteristics, and the model can be applied beyond the range of conditions for which it was validated (Stone et al., 1990). From a management perspective, *WEPP* can provide better information about where to locate conservation practices to achieve specific goals such as the reduction of soil loss or sediment deposition at the bottom of a slope (Laflen et al., 1991b).

The subject of this chapter, the *Hillslope Erosion Model*, is a distributed, process-based soil erosion and sediment yield model that is based on analytical solutions. As will be described later in this chapter, the *Hillslope Erosion Model* is used to simulate erosion and sediment yield as a function of position on the hillslope and to simulate the influence of spatial variability in hillslope properties on sediment yield and mean sediment concentration.

More detail about these and many other soil erosion models can be found in Doe et al. (1999) and Morgan and Quinton (this volume). Additional details on simulation models for erosion on rangelands can be found in Lane et al. (1997).

2.4. Hillslope Erosion Processes

Raindrops impacting on the soil surface induce tremendous hydraulic forces that tend to crater the soil surface, and in the presence of a thin sheet of water on the surface, rebound in what is called a jet. This jet thrusts water and soil particles upward producing a rainsplash and intense localized erosion. Under sufficiently intense and sustained rainfall, overland flow (also called sheet flow at this scale) begins and the detached soil particles (and aggregate particles of soil) are transported downslope. The soil particles and soil aggregates being transported are then called sediment particles. In the agricultural context, this is called interrill erosion or sheet erosion. Any cover material shielding the soil surface from raindrop impact tends to reduce the cratering, rebound jet, and thus the detachment and splash of soil particles. In general, cover on or near the ground surface is much more effective in reducing rainsplash erosion than is vegetative cover above the soil surface. Surface cover also forms hydraulic roughness that reduces the velocity of sheet flow and its ability to transport detached soil particles.

Water does not travel far before it begins to concentrate in soil depressions and flow paths. The depth of flow, velocity of the flow, shear stress on the soil surface, and the flow's ability to transport sediment are, in general, greatly enhanced by flow concentration. Sediment delivered to the concentrated flow paths by splash or sheet flow transport is then much more rapidly transported in the concentrated flow. In addition, the flowing water exerts shearing forces on the soil surface upon which it is flowing. These forces may literally tear or rip aggregates and soil particles from the soil and bring them up into the flow where they may be transported downslope. As the slope steepness increases or decreases in the direction of flow, some areas are subject to net detachment of soil particles. In other areas soil particles settle out of the flow and are deposited. Detachment and deposition occur in all areas but it is often possible to identify areas of net detachment or net deposition. In the case that both net detachment and net deposition are zero, there is an equilibrium condition where the capacity of the flow to transport sediment is exactly matched by the amount of sediment contained in the flowing water.

In the agricultural context, the processes of soil detachment, sediment transport, and sediment deposition in concentrated flow are called rill erosion. Vegetative cover above the soil surface has some limited impact on rill erosion. In contrast, cover in contact with the surface that isn't swept away by the flow significantly reduces flow velocity and shear stresses acting directly on the soil and increases hydraulic roughness. Thus, the detachment and transport of soil particles decreases and the rate of sediment deposition may increase. A central challenge for erosion and sedimentation researchers has been to measure, understand and model these complex processes called interrill and rill erosion in overland flow.

At the hillslope scale, where channelization occurs at the microtopographic level and larger channels are usually absent, overland flow processes dominate. Land use and disturbances affecting these processes are also important and significantly influence sediment yield from hillslopes.

Processes involving vegetative canopy cover, surface ground cover, and topography play a major role (along with rainfall amount and intensity) in controlling infiltration and runoff as well as sediment detachment, transport, and deposition in overland flow on rangelands (e.g., Lane et al., 1995b). The impact energy of raindrops at the soil surface is reduced due to interception by vegetative canopy cover. Most rangeland vegetation is of sufficiently small size that raindrop re-formation and fall results in much less energy transferred to the soil surface than is transferred through unobstructed rainfall. The inherent soil erodibility controls the rate of soil detachment at the soil surface, but ground cover (rock, gravel, litter, and plant basal area) shields the soil surface from direct raindrop impact and significantly enhances infiltration (Lane et al., 1987). Surface ground cover also significantly influences the hydraulics of overland flow (Weltz et al., 1992), reduces flow detachment capacity, and reduces sediment transport capacity of the flow. Finally, small sediment particles and litter combine with basal vegetation and microtopography to produce debris dams that result in water ponding and sediment deposition.

Thus, soil erodibility, rainfall amount and intensity, vegetative canopy cover, surface ground cover, and topography (and their collective spatial variability) largely determine sediment yield at the hillslope scale. They act to control soil detachment and runoff and in so doing impact the supply of sediment available for transport and yield and the amount of runoff available to transport it.

To improve the scientific understanding of hillslope erosion processes and resulting landforms, physically based models were developed that are based on mathematical equations that observe the laws of conservation of mass, energy, and momentum. The *Hillslope Erosion Model* describes the mechanics of the erosion processes that take place on hillslopes. These include particle detachment, transport, and deposition.

3. DEVELOPMENT OF THE *HILLSLOPE EROSION MODEL*

3.1. Overland Flow and Erosion Equations

The *Hillslope Erosion Model*, a simple, robust model, was developed to estimate erosion and sediment yield at the hillslope scale. This model is a time-averaged solution of the coupled kinematic wave equations for overland flow and the sediment continuity equation. Thus, the solution emphasizes spatially distributed soil erosion and sediment yield processes averaged over a specified time period. The model was developed specifically for hillslopes and was tested, evaluated and parameterized primarily for rangeland applications. The model was used to simulate erosion and sediment yield as a function of position (x) on the hillslope and to simulate the influence of spatial variability in topography, vegetative canopy cover and surface ground cover on sediment yield and mean sediment concentration. While the simple model may be less powerful than more complex models, the single-event model has an analytic solution, simplified input, relatively few parameters, and internal relationships to relate slope steepness, soil erodibility, vegetative canopy cover, and surface ground cover to the model parameters.

Lane et al. (1995b) described the model and its application in rangeland areas in detail, and the following material is an abbreviated version of that description. The hydraulics of overland flow on a plane are approximated by the kinematic wave equations:

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

and

$$q = Kh^{m}, \tag{2}$$

where h is the average local flow depth in meters (m), t is time in seconds (s), q is discharge per unit width in m^2/s, x is distance in the direction of flow in m, r is rainfall excess rate in m/s, the depth-discharge coefficient is $K = CS^{1/2}$, C is the Chezy hydraulic resistance coefficient for turbulent flow in $m^{1/2}$/s, and S is the dimensionless slope (slope steepness) of the land surface. The exponent m in Equation (2) is 1.5 when the Chezy hydraulic resistance formula is used.

A simplifying assumption required for an analytic solution is that rainfall excess rate is constant and uniform:

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

where $r(t)$ is rainfall excess rate, t is time, and D is the duration of rainfall excess in the same units as in Equation (1). The analytic solution eliminates all the problems of numerical solutions at the expense of simplifying the complex rainfall excess pattern to a simple step function.

The sediment continuity equation for overland flow is:

$$\frac{\partial(ch)}{\partial t}+\frac{\partial(cq)}{\partial x}=E_i+E_r, \tag{4}$$

where c is total sediment concentration in kg/m^3, E_i is interrill erosion rate per unit area in $kg/s/m^2$, and E_r is net rill erosion or deposition rate per unit area in $kg/s/m^2$. Since rills can be significant sources of erosion or the locations of significant deposition, E_r in Equation (4) accounts for both processes.

A simplifying assumption for the interrill erosion rate is:

$$E_i=K_i r, \tag{5}$$

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

$$E_r=K_r(T_c- cq)=K_r[(B/K)q- cq], \tag{6}$$

where K_r is the rill erosion coefficient in 1/m, T_c is the sediment transport capacity in kg/s/m and is assumed equal to $(B/K)q$, and B is a transport-capacity coefficient in $kg/s/m^{2.5}$. Equations (1) – (4) are called the coupled kinematic-wave and erosion equations for overland flow. Equations (5) - (6) were suggested by Foster and Meyer (1972) and represent significant simplifications of the erosion and sediment transport processes. Nonetheless, these assumptions do allow derivation of analytic solutions to the coupled equations.

3.2. Analytic Solutions and an Integrated Sediment Yield Equation

The first major step in development of analytic solutions 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). Next, 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).

The next major step was to solve the coupled equations and then integrate them through time 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) and produced a sediment-yield equation for individual runoff events as:

$$Q_s(x)=QC_b=Q\{B/K+(K_i-B/K)[1-\exp(-K_r x)]/K_r x\}, \qquad (7)$$

where Q_s is total sediment yield per unit width of the plane in kg/m, Q is the total storm runoff volume per unit width in m^3/m, C_b is mean sediment concentration over the entire hydrograph in kg/m^3, x is distance in the direction of flow in m, and the other variables are as described above.

3.3. The *Hillslope Erosion Model*

Equation (7) for sediment-yield equation for a single plane was extended to irregular slopes (Lane et al., 1995a). This extension was accomplished by transforming the coupled partial differential equations to a single ordinary differential equation (integration through time). As an ordinary differential equation, the solution on a segment of the plane could easily be solved for sequential segments of the entire plane. Finally, the extension was accomplished practically by approximating irregular hillslope profiles by a cascade of plane segments. With the extension of the model (Equation 7) to irregular slopes, inputs for the entire hillslope model are runoff volume per unit area and a dimensionless, relative soil-erodibility parameter. Input data for each of the individual segments are slope length and steepness, percent vegetative canopy cover, and percent surface ground cover.

From the input data, parameter estimation procedures were derived, by calibrating the model using rainfall simulator data, to compute the depth-discharge coefficient, K, the interrill erosion coefficient, E_i, the rill erosion coefficient, E_r, and the sediment-transport coefficient, B. The calibration was done using rainfall-simulator data from 10.7 m by 3.0 m rangeland plots across the western United States and *USLE* fallow plot data from throughout the eastern United States. These calibration results, corresponding relationships from the literature, and expert judgement were used to relate soil properties, slope length and steepness, vegetative canopy cover, and ground surface cover with the model parameters (coefficients) described above. These relationships were incorporated as a subroutine within the computer program to simulate sediment yield. The entire program is called the simulation model for sediment yield on hillslopes, or hereafter, the *Hillslope Erosion Model*.

In summary, overland flow equations and interrill and rill erosion equations are combined and solved to produce the *Hillslope Erosion Model*. The solution is time-averaged over a runoff event but spatially variable along the hillslope profile. Given input information on the hillslope profile (the number of segments required to represent the topography, cumulative length, slope steepness, canopy cover and surface ground cover for each segment; runoff volume, and a relative erodibility for the entire profile), the *Hillslope Erosion Model* produces estimates of sediment yield, interrill detachment, rill detachment or deposition, and mean sediment concentration for each segment on the hillslope profile.

The *Hillslope Erosion Model* and documentation are available on the worldwide web site: http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel. In comparison with traditional methods of technology transfer, this makes the model widely available, easily accessible, and easy to use. It also has the advantages of having the model and its technical documentation together and of having only one model version to update when improvements and corrections are made. This web site, or Internet-based, method of technology dissemination and transfer should enhance and accelerate use of erosion prediction technology.

4. CALIBRATION AND VALIDATION OF THE *HILLSLOPE EROSION MODEL*

4.1. Specified Parameters and Relationships

The parameters K_i, K_r, B, and K in Equations (1) - (7) are specified within the *Hillslope Erosion Model* as functions of slope steepness and length, vegetative canopy cover, surface ground cover, and relative (or dimensionless) erodibility (Figure 1). Values of relative erodibility are generally determined by optimization or from erodibility-soil textural class relationships as will be described in a subsequent section of this chapter.

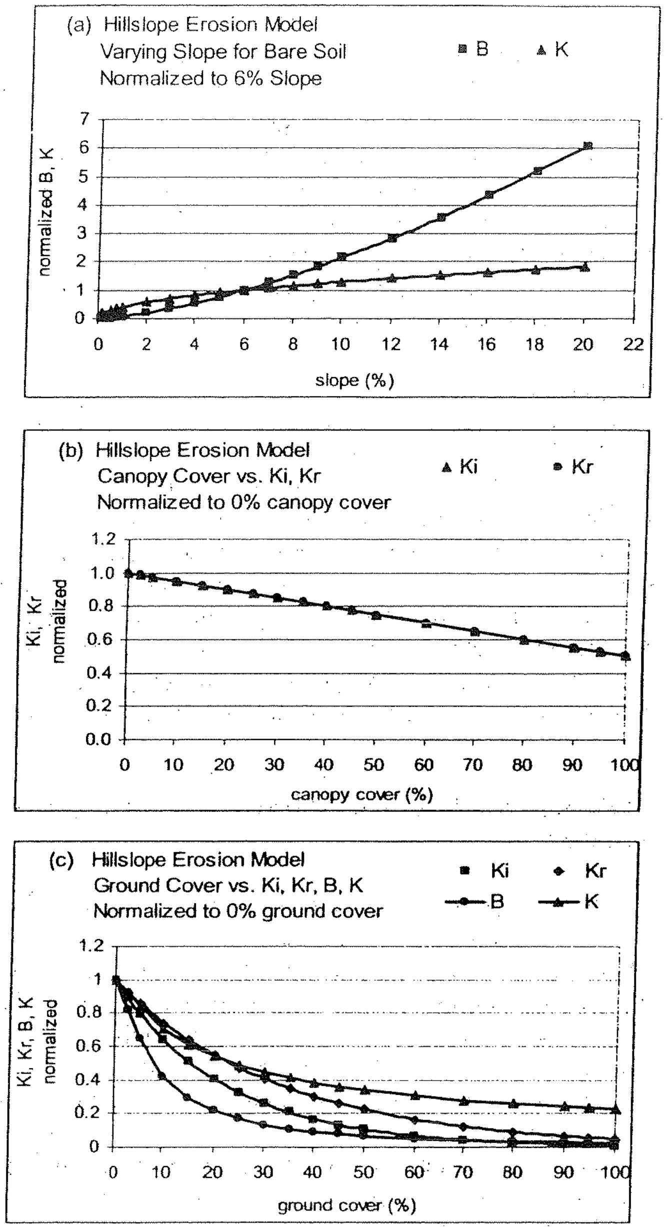

Figure 1. Relationships between model parameters and hillslope characteristics for the *Hillslope Erosion Model*: (a) Varying slope for bare soil, normalized to 6 percent slope, (b) Canopy cover vs. Ki and Kr, normalized to 0 percent canopy cover, (c) Ground cover vs. *Ki, Kr, B* and *K*, normalized to 0 percent ground cover.

Based on extensive review of the literature and analysis of laboratory erosion plot data, and small watershed data (e.g., Wischmeier and Smith, 1978; Shirley and Lane, 1978; Neibling and Foster, 1980; Knisel, 1980; Lane et al., 1985a; Foster, 1982; Weltz et al., 1992; Lane, 1986; Haan et al., 1994; Renard et al., 1997), estimating relationships have been determined for K_i, K_r, B, and K. These relationships are shown in Figure 1. Figure 1a illustrates how the sediment transport coefficient, B, and the hydraulic resistance coefficient, K, vary with slope steepness around a base value of 6 percent. Figure 1b showshow K_i and K_r vary with vegetative canopy cover. Finally, Figure 1c illustrates the variation of K_i, K_r, B, and K with surface ground cover.

Notice that the greatest variation of the model parameters is with surface ground cover and the second greatest variation is for B with increasing slope steepness. The relative least variation is with K and slope steepness and with K_i, K_r and vegetative canopy cover. Simulation model output is generally sensitive to variations in parameter values so that the general relationships for model parameters shown in Figure 1 would also hold true for variations in sediment yield estimates from the *Hillslope Erosion Model*. Parameter values for B, K_i, and K_r also vary nearly linearly with relative erodibility, as does simulated sediment yield. Therefore, before we discuss testing and evaluation of the *Hillslope Erosion Model* and of the parameter estimation relationships shown in Figure 1, we need to examine methods for estimating relative erodibility.

4.2. Optimizing the Relative (Dimensionless) Erodibility Parameter

As discussed above, all model parameters except relative soil erodibility have been related to measurable characteristics of hillslope profiles. Relative erodibility must be determined from analyses of measured runoff-sediment yield data. The procedure followed and explained below, was to estimate all model parameters except relative erodibility from measurable characteristics of experimental plots and then to determine relative erodibility by optimization, (i.e., by fitting the model to measured sediment yield data from experimental plot studies).

Personnel at the USDA Agricultural Research Service (ARS) at the Southwest Watershed Research Center (SWRC) in Tucson, Arizona, conducted rainfall simulator studies in 1987 and 1988 to collect data for rangeland *WEPP* (Laflen et al., 1991a) model development, enhancement, validation and parameterization. Subsequent to this data collection effort, the National Range Study Team (NRST) - Interagency Rangeland Water Erosion Team (IRWET; see Franks et al., 1998) collected additional data during 1990. A variety of contrasting rangeland plant communities with different soil series, located across the Western and Great Plains regions of the United States, were evaluated. Geographical distribution of the rainfall simulator sites is shown in Figure 2.

The experimental designs for both sets of field studies were similar. Simulated rainfall was applied to undisturbed, paired plots using a rotating boom rainfall simulator developed by Swanson (1965) and described by Simanton et al. (1991). The plots measured 3.05 x 10.7 m, with the longer side running parallel to the slope. They were grouped within a 50 by 50 m area with homogeneous soil and vegetation type. Three treatments, natural, clipped and bare, were imposed on two large plots at each site. The IRWET study evaluated six plots per site. All plots evaluated for the IRWET study were in natural (undisturbed) condition.

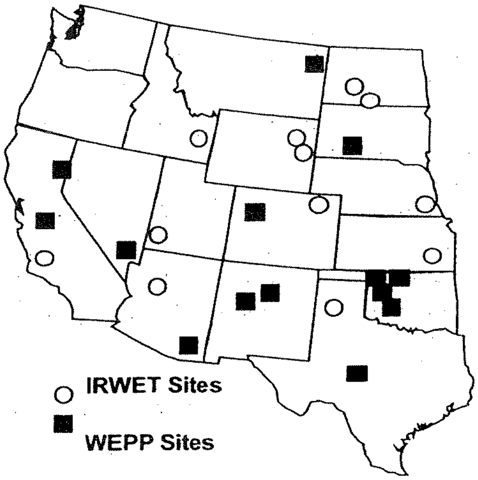

Figure 2. Location map of rainfall simulator sites in the *WEPP* and IRWET field experiments.

Rainfall was applied on two plots at a time. Three rainfall simulations were made on each plot with dry, wet and very wet antecedent moisture conditions. During the dry run, water was applied at a rate of approximately 65 mm/hr for approximately one hour. The wet run was made 24 hours later at the same intensity for approximately 30 minutes. The very wet run was applied approximately 30 minutes after the wet run with varying rainfall intensity (65 and 130 mm/hr). In addition, overland flow was applied on the bare plots for variable periods.

Total rainfall amount and distribution were measured with six non-recording rain gages positioned around each plot. Rainfall intensity was measured with a recording raingage located between the paired plots. Runoff passed through a pre-calibrated supercritical flume at the downslope end of each plot, and flow depths were measured with a pressure transducer bubble gage. Hydrographs and sedigraphs were produced using depth/discharge rating tables and sediment sample concentrations. These graphs were later integrated to determine runoff volumes and total sediment yields.

Vegetation data were collected with the objective of quantifying vegetative canopy and ground surface cover. Ground cover was defined as the percentage of the soil surface protected by litter, plant, rock and cryptogamic material. Canopy cover was the percentage of soil surface area protected from raindrop impact by standing plant material looking straight down into the canopy. Canopy cover was recorded by lifeform and ground cover was recorded by class (soil, rock, litter, basal cover, and cryptogams).

In addition to data collected during the *WEPP* and IRWET field experiments, rainfall simulator data collected from the Walnut Gulch Experimental Watershed in Southeast Arizona and the Nevada Test Site in southern Nevada were included in the analyses to optimize erodibility (Lane, 1986). Experimental design and data collection procedures were as previously described for the *WEPP* experiments. Finally, to include a broader range of soil textural classes in the relative erodibility database, data from 11 *USLE* validation plots were included in the analyses. These plots were 22.1 m in length and varied in width from 1.8 to 6.3 m. These *USLE* plots were in continuous fallow condition, tilled up and down the slope, and produced data on sediment yield from natural, as opposed to simulated, rainstorms. The data used in calibrating the *Hillslope Erosion Model* and in determining relative erodibility for soil textural classes are summarized in Table 1.

Table 1. Summary of calibration data used to estimate relative soil erodibility with the Hillslope Erosion Model.

	# Plot Sites	# Runs	Comments
WEPP	21	347	Natural, clipped and bare plots
IRWET	26	434	Natural plots only
WG & NTS	5	360	Natural, clipped and bare plots
USLE plots	11	1140	Natural storm data
TOTAL	63	2281	

Soil erodibility, as used herein, varies with degree of disturbance to the soil surface. In the *USLE* context, freshly tilled soil is evaluated for baseline erodibility and the soil loss from fully consolidated soil (such as undisturbed rangelands) is reduced to as little as 45 percent of that lost from tilled soil (Wischmeier and Smith, 1978, Table 10, p. 32). In the *CREAMS* Model, critical shear stress for long term, undisturbed soil can be as much as 12 times higher than for freshly tilled soils (Knisel, 1980, Table II-29, p. 249). Therefore, erodibility values determined from the *USLE* plot data were multiplied by 0.45 before being combined with erodibility values determined from undisturbed rangeland soils. The rainfall simulator used in the *WEPP* and IRWET field studies produces rainfall with about 80 percent of the energy of natural rainfall (Swanson, 1965; Simanton et al., 1991). Therefore, erodibility values determined from the *WEPP* and IRWET field experiments were multiplied by 1.0/0.80 = 1.25. With these adjustments, the erodibility values discussed below were standardized, to the extent possible, to undisturbed soil conditions subject to natural rainfall.

The *Hillslope Erosion Model* calibration results summarized in Table 2 suggest the following interpretations. First, calibration was accomplished by fixing all model parameters except the relative soil erodibility, which was optimized by fitting the model to the measured, or observed, sediment yield data from the experimental plots. For the observed data, notice that the standard deviations ranged from about equal to the means to twice their value. The fitted means match the observed means quite closely but the fitted standard deviations were generally less than the corresponding observed values from near zero to about 20 percent. Linear regression between the observed data (x) and the fitted data (y) resulted in R^2 values of 0.62 to 0.89.

Table 2. Summary of calibration results for the *Hillslope Erosion Model*. Values of sediment yield data in t/ha and sample size, N, refers to the number of rainfall simulator runs used in the calibration.

		Observed Data		Calibrated Data		Regression y = a + bx		
Data Set	N	Mean	Std Dev	Mean	Std Dev	a	b	R^2
WEPP	347	1.98	4.28	2.01	4.03	0.252	0.89	0.89
IRWET	434	0.172	0.231	0.163	0.188	0.055	0.64	0.62
WG & NTS	360	1.39	2.18	1.39	1.99	0.237	0.83	0.83
USLE Plots	1140	6.86	6.36	7.46	6.67	0.018	0.63	0.66

Table 3. Representative values and ranges for relative soil erodibility by soil textural class from the calibration study.

Soil Texture	Relative Erodibility Value	Range
Sand	-	-
Loamy sand	2.03	1.31 - 2.75
Sandy loam	2.31	0.33 - 4.29
Loam	1.84	0.03 - 3.65
Silt loam	1.74	1.18 - 2.30
Silt	2.26	-
Sandy clay loam	0.56	0.23 - 0.89
Clay loam	1.38	-
Silty clay loam	1.86	-
Sandy clay	-	-
Silty clay	3.34	0.92 - 5.76
Clay	1.41	0.23 - 2.59

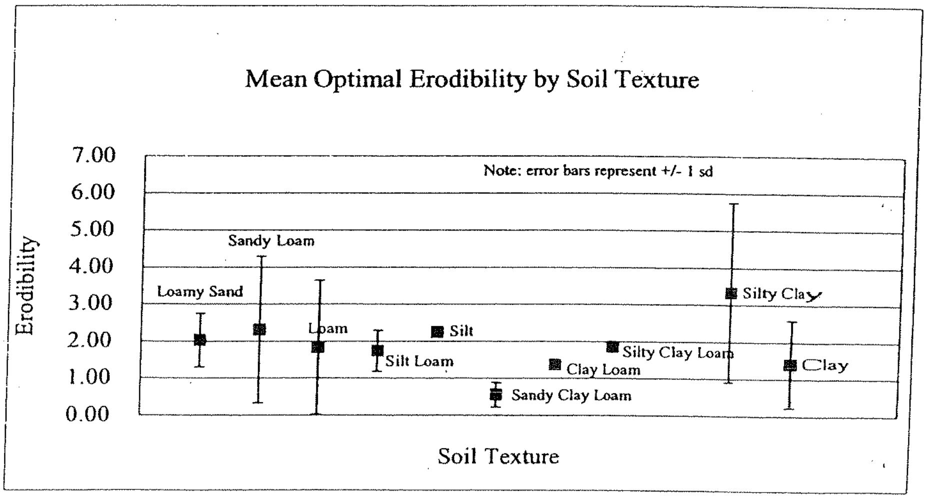

Figure 3. Soil relative erodibility plotted as a function of texture.

However, all regression intercepts were positive and the standard deviations were underestimated so that the regression slopes were all less than one. The regression slopes varied from 0.63 to 0.89 suggesting an under-prediction bias of some 0.11 to 0.37. This suggests that the *Hillslope Erosion Model* accurately fitted the mean sediment yield, generally underestimated the standard deviation of sediment yield, under-predicted by about 11 - 37 percent, and explained about 60 - 90 percent of the variance in observed sediment yield. Given that model calibration was limited to relative erodibility, these results are very encouraging.

4.3. Relative Erodibility by Soil Texture Class

Grouping optimal erodibility values from the analyses shown in Table 2 by soil textural class resulted in a soil texture-relative erodibility relationship. For each soil texture class represented by more than four rainfall simulator sites, the standard deviation of relative erodibility was computed and used to provide a measure of uncertainty. Means and ranges of relative soil erodibility are shown in Table 3 and the means and corresponding ±1 standard deviation bars are shown in Figure 3. Notice that standard deviations and error bars are included only when there were more than four experimental sites representing a soil texture class.

4.4. Selected Validation Studies Using Data from the Walnut Gulch Experimental Watershed

Following calibration and optimization of soil erodibility values, the *Hillslope Erosion Model* was used to simulate sediment yield on a semiarid rangeland watershed in southeastern Arizona. These simulations provide a validation of model results. The 149 km^2 Walnut Gulch Experimental Watershed (Walnut Gulch hereafter) is located in southeastern Arizona, USA at approximately 31°45' N latitude and 110° W longitude, and at elevations ranging from 1250 to about 1900 m above MSL (Figure 4). The climate of Walnut Gulch is classified as semiarid or steppe, with about 70 percent of the annual precipitation occurring during the summer months from convective thunderstorms of limited areal extent. Data from Tombstone, Arizona for the period 1941-1970 were used to calculate mean annual precipitation as 324 mm and mean annual temperature as 17.6 °C.

Walnut Gulch is located in the Basin and Range Province and, typical of this physiography, is bounded on the southwest, south, and east by mountain blocks separated by broad alluvium filled basins. A brief description of the geology follows, based on Gilluly (1956), which should be consulted for more detailed and complete geologic descriptions of Walnut Gulch.

The northern 1/2 to 2/3 of the total 149 sq km drainage area consists of Quaternary and Tertiary alluvium outwash, called the Tombstone Pediment, and noted as "alluvium" on Figure 4. Drainage densities (based on analyses for 1:24,000 scale maps) for Subwatersheds 3, 4, 8, 10, and 11 on this pediment range from 2.87 to 3.61 km/sq km with a mean of 3.16.

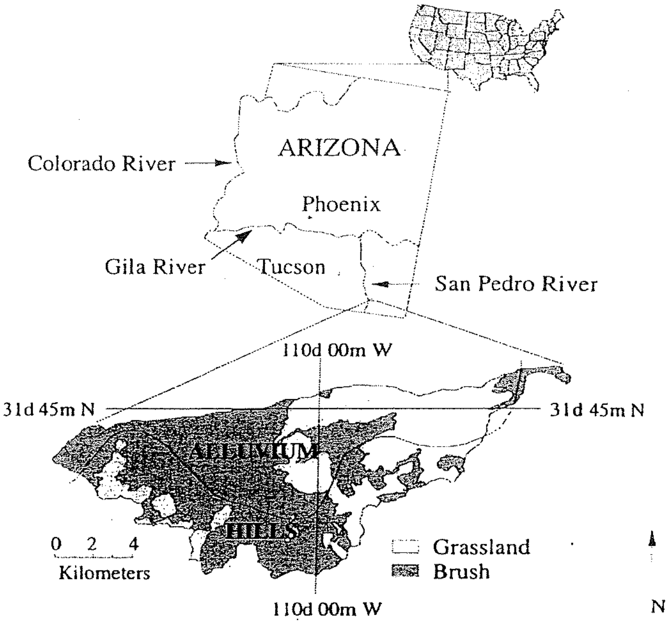

Figure 4. USDA-ARS Walnut Gulch Experimental Watershed location map.

The remaining southern part of the watershed, called the Tombstone Hills, is composed of more complex geologic structures. Areas along the southeast watershed boundary are composed of volcanics of late Tertiary age. Diked ridges, usually exposed on steeper terrain and by stream channels provide geologic controls on channel gradient and headwater extension. Subwatershed 9 includes this material as well as some of the Tombstone Pediment. As a result of the more complex geology and its surface expression, the drainage density of Subwatershed 9 is low at 1.36 km/km^2.

Areas along the southwestern and southern boundaries of the Tombstone Hills are composed of faulted and uplifted sedimentary rocks underlain by, and adjacent to on the west, igneous rocks of Tertiary age. These are areas with complex structure and composition including limestone, quartzite, and granite. Subsurface and surface features controlled by faulting, intrusive rhyolite dikes, and other features exhibit strong influence on channel incision and headwater extension. Subwatersheds 7 and 15 include these features as well as some of the Tombstone Pediment. The drainage densities for Subwatersheds 7 and 15 are 2.56 and 1.69 km/km^2, respectively.

The overall mean drainage density for the entire Walnut Gulch Watershed is 2.45 km/km^2 which is generally lower than drainage densities for subwatersheds on the Tombstone Pediment (average value 3.16) and higher than drainage densities for subwatersheds in the Tombstone Hills areas with more complex geology (average value 1.87). As has been discussed elsewhere (Lane et al., 1997), mean annual runoff and sediment yield are strongly associated with geologic parent material and are higher on subwatersheds with higher drainage densities.

Soils on Walnut Gulch are generally well-drained, calcareous, gravelly to cobbly loams and are closely associated with the geologic features described above. Shrub vegetation, such as creosote bush, acacia, tarbush, and small mesquite trees, dominates (30 to 40 percent canopy cover) the lower two thirds of the watershed. The major grass species (10 to 80 percent canopy cover) on the upper third of the watershed are the gramma grasses, bush muhley, and lovegrass, with some invasion of the shrub species and mesquite (Renard et al., 1993). Land use consists primarily of grazing, recreation, mining, and some urbanization. Within the Tombstone Pediment and the Tombstone Hills areas, mean annual runoff and sediment yield are generally higher on the shrub dominated areas than in corresponding areas dominated by grasses.

Table 4. Summary of validation results for the *Hillslope Erosion Model*. Predictions made using measured hillslope profile and cover data and relative erodibility as mean values from the calibration study. Values of sediment yield data in t/ha and sample size, N, refer to the number of natural runoff events for Watersheds LH-5 and K-2 and the number of rainfall simulator runs for the rainfall simulator plots, respectively.

		Observed Data (t/ha)		Predicted Data (t/ha)		Regression $y = a + bx$		
Data Set	N	Mean	Std Dev	Mean	Std Dev	A	b	R^2
LH -5	40	0.567	1.31	0.570	0.942	0.170	0.70	0.96
LH Plots	18	0.101	0.090	0.118	0.098	0.033	0.85	0.61
K-2	19	0.055	0.061	0.137	0.104	0.071	1.21	0.49
K-2 Plots	6	0.886	0.446	1.01	0.575	0.250	0.85	0.44

Data were collected on several hillslopes and plots within the Walnut Gulch Watershed and used to validate the *Hillslope Erosion Model*. Table 4 presents validation results for model application to hillslopes and rainfall simulator plots at Watershed LH-5 and at Watershed K-2, both located on the Tombstone Pediment. The rainfall simulator plots were 3.05 x 10.7 m natural plots. Rainfall simulator data were taken using the *WEPP* experimental design described earlier. The data in Table 4 represent model validation studies using data not included in the calibration studies. Mean values of the relative soil erodibility, as determined by soil textural class, were used to predict sediment yield in Table 4.

Watershed LH-5 is a 0.182 ha watershed on the Tombstone Pediment dominated by brush comprising a hillslope without well-defined drainage patterns. Soils on Watershed LH-5 are the Lucky Hills-McNeal complex and are sandy loams. Therefore, a default erodibility value of 2.31 was assigned from Table 3. Model predictions were very precise as indicated by the high R^2 value of 0.96 and because the predicted mean was almost exactly equal to the observed mean from 40 natural runoff events. Model predictions for the two Lucky Hills rainfall simulator plots were not quite as precise as indicated by an R^2 value of 0.61 and because the mean sediment yield was over predicted by a factor of 0.118/0.101 = 1.17.

Soils on Watershed K-2 are the McAllister-Stronghold complex, a suite of sandy loams with a default erodibility value of 2.31. Predictions for the 1.86 ha K-2 Watershed, a grass dominated watershed on the Tombstone Pediment, were not as precise as those for Lucky Hills. The value of R^2 was 0.49, and the predicted mean was about 0.137/0.055 = 2.5 times the measured mean. The final entry in Table 4 is for 6 rainfall simulator runs on two plots at Watershed K-2. Prediction results for these rainfall simulator data were relatively poor with an R^2 value of 0.44 and the mean sediment yield was over predicted by a factor of 1.01/0.886 = 1.14. Nonetheless, the model explained about 40 to 50 percent of the variance in observed sediment yield at the Watershed K-2 site and about 60 to over 90 percent of the variance in observed sediment yield at the Watershed LH-5 site. Ratios of predicted to observed mean values were 1.01 to 1.17 for LH-5 and 1.14 to 2.5 for K-2 with an overall mean ratio of 1.46. Therefore, the conclusion was drawn that the model validation studies at Walnut Gulch are encouraging, but demonstrate the need for further applications and testing.

5. APPLICATIONS OF *THE HILLSLOPE EROSION MODEL* AT THE FORT CARSON MILITARY RESERVATION AND THE PINON CANYON MANEUVER SITE

Following model calibration and validation studies as described above, the *Hillslope Erosion Model* was applied at two locations in Colorado. This application was part of a larger project to add modern soil erosion prediction technology to a long-standing program for assessing land condition and trends on military training lands. Addition of this technology was necessary to strengthen the emphasis on soil erosion as part of planning and management to ensure sustainable training resources.

5.1. Introduction – The Fort Carson Military Reservation and the Pinon Canyon Maneuver Site

The U.S. Army's Fort Carson Military Reservation (FCMR) and the Pinon Canyon Maneuver Site (PCMS) are used to train, house, and support infantry, cavalry, combat teams, and special forces. There are about 3000 individual tank or helicopter excursions at these sites each year, usually involving heavy mechanized armament such as self-propelled howitzers, Bradley fighting vehicles, and Abrams tanks.

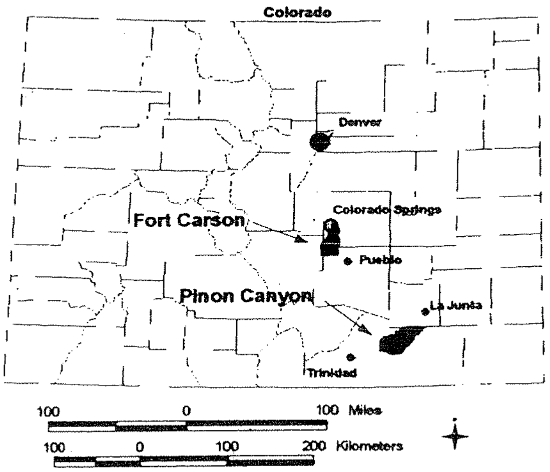

Figure 5. Map of Colorado showing locations of Fort Carson and Pinon Canyon sites, major cities and county lines.

Both Fort Carson and Pinon Canyon are located in the grasslands o Southeastern Colorado (Figure 5). Fort Carson, situated in the foothills o the Rocky Mountains southeast of Colorado Springs, receives about 380 m average annual precipitation, and is predominantly short to mid-grass prairi and shrublands. Soils at Fort Carson are dominated by sandy loams, loams and silt loams. Elevations range from 1560 m to 2121 m. Fort Carson i approximately 55,600 ha in size, and about 90 percent of this area is used fo training activities. The remaining lands are used for administrative an public facilities. Pinon Canyon is located 130 km southeast of Fort Carson. It is mainly short grass prairie, and average annual precipitation is about 340 mm. Soils are generally loam, sandy loam, silty clay loam, and silty loam. Elevations range from 1300 m to more than 1700 m. Pinon Canyon encompasses approximately 98,700 ha, and about 86 percent of the area is used for training. The remaining lands are either off-limits or are in a soil protection area. Administrative facilities are minimal, as most of these functions are performed at Fort Carson.

5.2. The Land Condition-Trend Analysis (LCTA) Program

The *Hillslope Erosion Model* was applied as part of the Land Condition-Trend Analysis (LCTA) program, a component of the Army's Integrated Training Area Management Program (ITAM). ITAM was developed by the US Army Construction Engineering Research Laboratory (CERL) to facilitate improved management of Army training lands (Gordon et al., 1989). The program is intended to provide installation natural resource managers (the Directorate of Environmental Compliance and Management, DECAM), with information that will be useful in the long-term, sustainable management of training lands. This includes information regarding soils, vegetation, topography, land use, and wildlife (Gordon et al., 1989). LCTA is the Army's standard for land inventory and monitoring (Tazik et al., 1992).

In 1989, 203 permanent LCTA field plots were established on Fort Carson, and 206 on Pinon Canyon. The 100 m line-transects have been monitored a total of four times at both sites as of 1999. Plot locations were selected based on land cover/soil combinations (derived from satellite imagery) through a stratified random process in proportion to the percent of land that they cover. For each LCTA plot, collected data include soil samples, slope, aspect, wildlife information, land use, ground cover, canopy cover, and surface disturbance.

5.3. Description of Hillslope Profile Data Collection

Hillslope profile data were collected to provide input to the *Hillslope Erosion Model* for sediment yield prediction, as well as for GIS and other analyses and display. For the hillslope profile data collection, subsets of the Army's LCTA plots were selected at both Fort Carson and Pinon Canyon based on the suitability of the land for military training, soil type, vegetation community and topography. Twenty sites were selected at Fort Carson, and a total of 22 sites were selected at Pinon Canyon. The Pinon Canyon sites included 19 LCTA sites, one control site (not an LCTA plot), and two gully control sites where the gully banks were reformed or bank sloped (see Figure 5 of Miller and Linn, this volume).

Three hillslope profiles were tied to the existing LCTA transects, at the 0, 50, and 100 m points, as shown in Figure 6. Hillslope profiles are transects that follow the apparent flow path down the hillslope. For the Fort Carson/Pinon Canyon surveys, the profiles follow a flow path through the existing LCTA transect, beginning above the LCTA transect at the top of the hill or other obvious topographic break point. They pass through the transect, and end at a gully, road, stream channel, bottom of the hill, or other natural break or surface disturbance that would disrupt the flow of water.

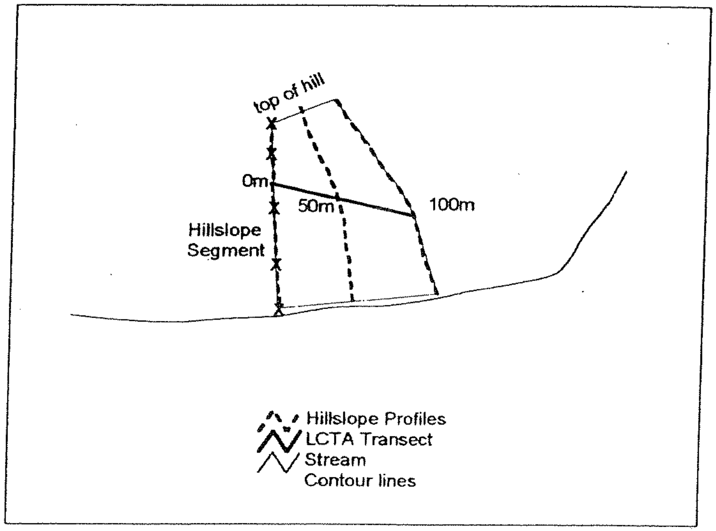

Figure 6. Sample hillslope profile plot design for *Hillslope Erosion Model* data collection at Fort Carson and Pinon Canyon using LCTA transects.

To read the hillslope profile, a 100-m measuring tape is laid out along the flow path starting at the top of the hill. Each notable change in vegetation density, vegetation community, soil type, or slope steepness is marked as a hillslope segment. There are generally at least three segments per profile, and each segment is divided into a minimum of twenty increments for data collection. Data recorded for each segment are length, percent slope steepness, and compass bearing. Data recorded within each increment are vegetative cover and ground cover.

Segment length is read directly off the tape, and slope steepness is determined with a hand held clinometer. Cover is read using a thin sampling rod that is lowered at a 90 degree angle to the ground at each increment along the measuring tape. The first vegetative life form (e.g., tree, shrub, or grass) encountered by the rod as it is lowered perpendicular to the ground, is read and recorded. If a tree or bush overhangs the rod, it is recorded as the vegetative cover for that point. Ground cover is read and recorded as anything lying on the ground surface where the rod first touches the ground. Vegetative cover is classified as grass, shrub, forb, tree, cactus, half-shrub, etc., and ground cover may be soil, litter, rock, gravel, cryptogam or plant basal area.

The data from each hillslope profile were reduced for use in the *Hillslope Erosion Model* and entered as a series of segments. For each segment, the model requires the cumulative length in m, percent slope, and percent vegetative and ground cover. Vegetative cover is calculated as all vegetative cover hits divided by the number of increments in the segment. Ground cover is the number of hits that are not soil (bare ground) divided by the number of increments in the segment.

The model requires soil erodibility and runoff volume in addition to the segment data. For these simulations, soil erodibility was based on soil texture, as described in Sections 4.2 and 4.3. Runoff volume may be calculated if it is not otherwise available. For the Fort Carson/Pinon Canyon simulations, the *Infiltration and Runoff Simulator* (*IRS*) Program was used to simulate runoff. That program and its application to this project are described in the following section.

5.4 Estimation of Runoff Using the *IRS* Model

Runoff is a required input value to the *Hillslope Erosion Model* and may be simulated in the absence of observed data. The *Infiltration and Runoff Simulator* (Stone et al., 1992) model was developed as part of the U.S. Department of Agriculture Water Erosion Prediction Project (*WEPP*). This DOS-based program computes infiltration and rainfall excess on a plane and then routes the runoff across the plane to produce an overland flow hydrograph. Rainfall excess is calculated using the Green-Ampt equation given an arbitrary rainfall rate. The runoff hydrograph at the end of a single plane is calculated by solving the kinematic wave equation using the method of characteristics (Stone et al., 1989; Stone et al., 1992).

The data input requirements are: a rainfall time-intensity distribution, the time step for rainfall excess (1-5 min), Green-Ampt parameters, the percentage of canopy and ground cover, average slope of the plane in percent, a depth-discharge equation coefficient and exponent, and the length of the plane in m.

Output data include rainfall rate and depth, infiltration rate and depth, rainfall excess rate and depth, final infiltration rate, infiltration volume, final rainfall excess rate, peak rainfall excess rate, rainfall excess volume, and the runoff hydrograph at the end of the plane. Rates are in mm/hr, and depths and volumes are in mm.

5.5. *IRS* Model Results and Analyses

Runoff on each profile at both the Fort Carson and Pinon Canyon sites was simulated, and the resulting rainfall excess volume (mm) was used as the runoff input value required by the *Hillslope Erosion Model*. The design rainfall was the 1 hour, 10 year frequency storm. Wet (-1/3 bar) and dry (-15 bar) conditions were simulated using *IRS* at both sites to characterize differences in response with antecedent soil moisture. Runoff at both locations was largely dependent upon soil texture class. The highest runoff values were associated with clay textures, the lowest with sandy textures, and silty textures fell in between the two. Differences in response between wet and dry conditions were minimal for all texture classes, although runoff was slightly higher at Pinon Canyon than at Fort Carson for the same soil texture because of less canopy and surface cover at the Pinon Canyon sites. Runoff values from the wet condition simulations were used in the model.

5.6. Estimation of Sediment Yield using the *Hillslope Erosion Model* - Application at Fort Carson and Pinon Canyon

The *Hillslope Erosion Model,* presented in Section 3, was used to simulate erosion and sediment yield at the Fort Carson and Pinon Canyon sites. As described, the model calculates sediment yield as a function of position on the hillslope and simulates the influence of spatial variability in hillslope properties (topography, vegetative canopy cover and surface ground cover). The model was applied using both 1998 Fort Carson and

1999 Pinon Canyon field data to predict erosion at the two sites, and t compare sediment yield from the two sites.

The inputs required for the model were described previously. Mode outputs include interrill and rill detachment and deposition in kg/m^2, mea sediment concentration in percent, runoff volume in m^3/m, and sedimer yield in kg/m and t/ha. The model generates results for each segment alon the hillslope as well as for the entire hillslope profile.

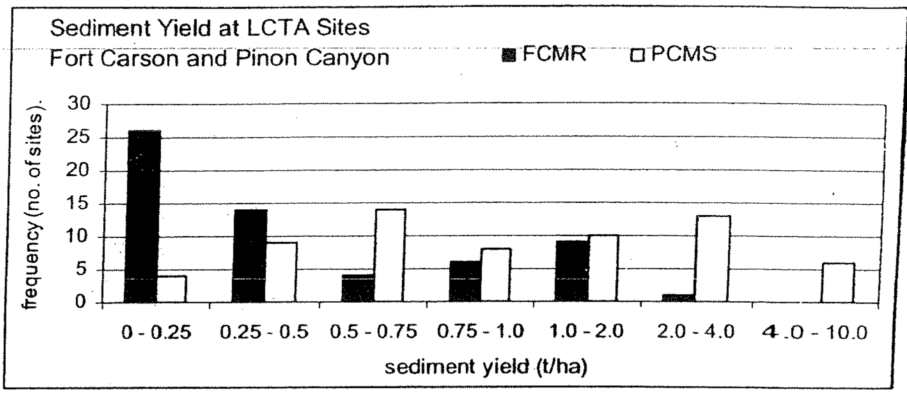

Figure 7. Frequency distribution of sediment yield from *Hillslope Erosion Model* simulations at LCTA sites at Fort Carson (FCMR) and Pinon Canyon (PCMS).

5.7. Model Results and Analyses

The model results were analyzed to determine the influence of the various factors such as soil texture or topography on sediment yield. The frequency distributions of sediment yield predicted by the *Hillslope Erosion Model* at both sites are shown in Figure 7. In general, sediment yield decreased with increasing vegetative and ground cover, and increased with increasing slope. Lower sediment yield values were predicted at Fort Carson than at Pinon Canyon. This can be attributed to differences in soil textures, cover, and slopes at the sites evaluated at the two installations. Sediment yield by soil texture class for Fort Carson and Pinon Canyon, shown in Figure 8, illustrates that sandy textures were associated with the lowest sediment yield, silts and loams the highest, and clays in between.

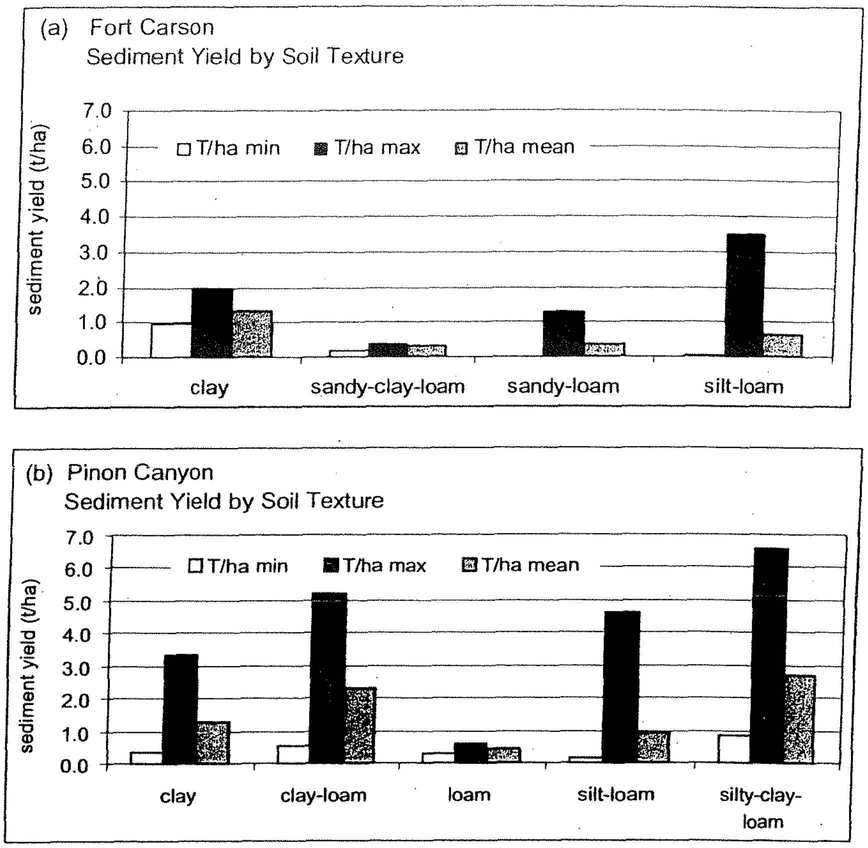

Figure 8. Sediment yield from the *Hillslope Erosion Model* by soil texture at (a) Fort Carson and (b) Pinon Canyon LCTA sites.

5.8. Comparisons with Data from Erosion Control Structures

5.8.1. Fort Carson

Although no direct hillslope sediment yield data were collected at Fort Carson or Pinon Canyon, data are available from small watersheds above small reservoirs at these sites. In 1978, a Technical Report was released entitled: "*Analysis and Assessment of Soil Erosion in Selected Watersheds at Fort Carson.*" The goal of the work described in this report was to assess the impact of training activities on soil erosion. Six watersheds were chosen, and a predictive technique to estimate average annual sediment yield wa developed (Keown and West, 1978). Reservoir sediment yields includ sediment from hillslopes as well as from gully erosion and channel bed an bank erosion. Reservoir sediment yields may be reduced by sedimen deposition in stream channel systems draining into them. Therefore relationships between reservoir sediment yield rates and hillslope erosio rates are qualitative only as they are not directly comparable. However, a hillslope erosion is an important component of watershed sediment yield, th *Hillslope Erosion Model* was applied to 20 hillslopes (60 profiles) at For Carson to estimate sediment yields from hillslopes in an attempt to refin interpretations of watershed sediment yield. Reservoir sediment yields ar expressed as an average annual rate whereas hillslope sediment yield are fo a specific event (the 1-hour, 10-year storm). Results from the reservoi surveys and hillslope simulations are shown in Table 5.

Table 5. Fort Carson sediment yield from reservoir/watershed surveys (t/ha/yr) and *Hillslope Erosion Model* simulations (t/ha).

	Sediment Yield		
	minimum	Maximum	average
Watershed Surveys (N=6)	0.22	4.26	1.75
Hillslope Simulations (N=60)	0.015	3.51	0.52

5.8.2. Pinon Canyon Maneuver Site

When the Pinon Canyon site was acquired by the U.S. Army in the early 1980's, the U.S. Geological Survey began a series of hydrologic investigations to establish baseline information. Between 1983 and 1985, 48 stock-watering reservoirs were surveyed for storage capacity. Sediment volumes and sediment yields were determined at twenty-nine of those reservoirs (von Guerard et al., 1987). The results of those investigations were compared with the results of the *Hillslope Erosion Model* simulations (65 hillslope profiles) to compare soil erosion from the hillslopes with sediment yield from the small watersheds above the reservoirs. As at Fort Carson, relationships between reservoir sediment yield rates and hillslope erosion rates are qualitative only as they are not directly comparable. The minimum, maximum and average sediment yield from both the reservoir surveys and hillslope model simulations are presented in Table 6.

Table 6. Pinon Canyon sediment yield from reservoir surveys (t/ha/yr) and *Hillslope Erosion Model* simulations (t/ha).

	Sediment Yield		
	minimum	maximum	average
Reservoir Surveys (N=29)	0.03	5.95	1.37
Hillslope Simulations (N=65)	0.17	6.55	1.68

Measured reservoir sedimentation rates at Ft. Carson (N=6, Table 5) suggest a mean sediment yield rate from small watersheds with incised channel systems of about 2 t/ha/y with a range of values of about 0.2 to over 4 t/ha/y. Application of the *Hillslope Erosion Model* on 60 hillslope profiles at 20 LCTA sites suggest a mean hillslope sediment yield rate of about 0.5 t/ha with a range of about 0.02 to 3.5 t/ha. Since the hillslope profiles were not directly associated with the small watersheds, one cannot make direct comparisons. Rather, the data summarized in Table 5 suggest that the *Hillslope Erosion Model* produced event sediment yield estimates from somewhat less to roughly the same magnitude as mean annual sediment yield measured from 6 small watersheds.

Measured reservoir sedimentation rates at Pinon Canyon (N=29, Table 6) suggest a mean sediment yield rate from small watersheds with incised channel systems as about 1.4 t/ha/y with a range of values of about 0.03 to 6 t/ha/y. Application of the *Hillslope Erosion Model* at 65 hillslope profiles associated with 20 LCTA sites produced event sediment yield estimates with a mean of about 1.7 t/ha with a range of about 0.17 to 6.6 t/ha. The data summarized in Table 6 again suggest that the *Hillslope Erosion Model* produced event sediment yield estimates from somewhat less to roughly the same magnitude as mean annual sediment yield measured from 29 small watersheds.

6. DISCUSSION AND SUMMARY

A hillslope is defined as the zone of the landscape from the crest of a ridge along the slope in the direction of flow to a defined drainage, water body, or other feature that interrupts the overland flow profile at the toe of the slope. Raindrops impacting on the soil surface induce tremendous hydraulic forces that tend to crater the soil surface, and in the presence of a thin sheet of water on the surface, rebound in what is called a jet. This jet thrusts water and soil particles upward producing a splash and intense localized erosion. Under sufficiently intense and sustained rainfall, overland flow begins and the detached soil particles, and aggregate particles of soil, called sediment, are transported down slope. These processes are called interrill erosion in overland flow.

Overland flow soon begins to concentrate in soil depressions and flow paths. The depth of flow, velocity of the flow, shear stress on the soil surface, and the flow's ability to detach and transport sediment are, in general, greatly enhanced by flow concentration. As the slope steepness increases or decreases in the direction of flow, some areas are subject to net detachment of soil particles, while in other areas sediment particles settle out of the flow and are deposited. Detachment and deposition are occurring in all areas but it is often possible to identify areas of net detachment or net deposition. The processes of soil detachment, sediment transport, and sediment deposition in concentrated flow are called rill erosion.

At the hillslope scale, where channelization occurs at the microtopographic level and larger channels are usually absent, overland flow processes dominate. Land use and disturbances affecting these processes are also important and significantly influence sediment yield from hillslopes. A central challenge for erosion and sedimentation researchers has been to measure, understand and model these complex processes called interrill and rill erosion in overland flow.

To improve the scientific understanding of hillslope erosion processes, and resulting landforms, physics-based models were developed based on equations used to describe the laws of conservation of mass, energy, and momentum. These erosion models, at the hillslope scale, describe the mechanics of the erosion processes that take place in overland flow.

A specific model, the *Hillslope Erosion Model* was described and discussed as a simplified, but physically based, model to estimate erosion and sediment yield at the hillslope scale. The *Hillslope Erosion Model* is more physically based than the class of models represented by the *USLE* and its modifications, and less physically based than the class of complex models represented by *WEPP*.

Relationships between topography, vegetative canopy cover, and surface ground cover and parameters in the *Hillslope Erosion Model* were described and discussed. An extensive calibration study involving 63 plot sites and over 2000 runoff-sediment yield events was used to calibrate the *Hillslope Erosion Model*. The model explained about 60 to 90 percent of the variation in observed sediment yield from the experimental plots (Table 2). Optimal values of relative erodibility were then related to soil texture class (Table 3, Figure 3).

Soil erodibility values estimated from soil texture class were then used in a validation study to predict hillslope sediment yield from two small watersheds and four small rainfall simulator plots on the Walnut Gulch

Experimental Watershed (Figure 4, Table 4). The model-predicted sediment yield explained from about 50 percent to over 90 percent of the variance in observed sediment yield from two small watersheds, and from about 40 percent to 60 percent of the variance in observed sediment yield from four rainfall simulator plots.

The *Hillslope Erosion Model* was applied at over 120 hillslope profiles at Ft. Carson and Pinon Canyon to estimate erosion and sediment yields at over 40 LCTA sites. The predicted sediment yields from these hillslopes appear to be reasonable in range and magnitude when compared with measured sediment yields from small watersheds.

Based on the comparison of the *Hillslope Erosion Model* with existing models, its calibration and validation, its application to hillslopes at Fort Carson and Pinon Canyon, and its method of implementation, it is possible to identify some if its strengths and limitations. The model's greatest strengths include its simplicity, its extensive databases used for calibration and validation, its method of internal specification of most of its parameters from measurable characteristics of hillslopes, the availability of default values for relative soil erodibility, and its method of operation directly (without file transfers or downloading) via the Internet. The model's greatest limitations include its simplifications of physical processes, the geographic limitations of its validation studies, its lack of hydrologic components to estimate a water balance and thus provide estimates of runoff, its formulation as an event model rather than a continuous simulation model, and its lack of a component to directly modify the model parameters for changing land use and management.

The *Hillslope Erosion Model* could be significantly improved by additional calibration studies to reduce the variability in its default relative erodibility values. Direct incorporation of spatially varying soil properties inducing a spatially variable relative erodibility might further reduce the uncertainty in model predictions. Additional validation studies over a broader geographical area and for a wider range of soil, climate, and land use and management are needed to decrease the uncertainty of its applications.

7. CONCLUSIONS

A simple *Hillslope Erosion Model* has been developed to estimate spatially distributed interrill and rill erosion on hillslopes including sediment detachment, transport, and deposition processes. Calibration studies on a large set of rainfall simulator data in the western United States demonstrate that the *Hillslope Erosion Model* can be calibrated to accurately compute hillslope erosion and sediment yield on rangelands over broad geographical areas of the USA. Results of the calibration studies include a table of relative soil erodibility, grouped by soil textural class (Table 3), which provide default relative erodibility values for use in the *Hillslope Erosion Model* and thus enable its broad application. Validation studies using data from the Walnut Gulch Experimental Watershed demonstrate that the *Hillslope Erosion Model* and the default soil erodibility values can be used to predict soil erosion in areas similar to Walnut Gulch in Arizona. Application of the *Hillslope Erosion Model* at over 120 hillslope profiles at Ft. Carson and Pinon Canyon, Colorado, suggest that the model produces reasonable sediment yield estimates in generalized comparison with reservoir sedimentation rates monitored at 35 sites.

Finally, the *Hillslope Erosion Model* and documentation are available on the web site: http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel. In comparison with traditional methods of technology transfer, this makes the model widely available, easily accessible, and easy to use. It also has the advantages of having the model and its technical documentation together and of having only one model version to update when improvements and corrections are made. This web site, or Internet-based, method of technology dissemination and transfer should enhance and accelerate use of erosion prediction technology.

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