

THE ROLE OF PROCESS-BASED MODELS AND SCALING IN GEOMORPHIC DESIGNS¹

Leonard J. Lane² and Mark S. Wigmosta

Abstract. A model of soil erosion and sediment transport on hillslopes is used to illustrate the role of process understanding in determining dominant processes as a function of spatial scale. Erosion and sediment yield from hillslopes are primarily determined by surface runoff, topography, vegetative canopy cover, ground surface cover, soil erodibility, and sediment properties. In areas where winter processes (snow, snowmelt, soil frost, etc.) are important, erosion and sediment yield also determined by these factors. The Hillslope Erosion Model (HEM) incorporates these factors in simulating erosion and sediment yield. The world's largest rainfall simulator database for arid and semiarid areas and data from small hillslope-scale watersheds are used to calibrate and validate the spatially distributed, process-based HEM. Spatially distributed estimates of sediment transport and yield along hillslopes from the HEM are used with an understanding of dominant processes as a function of spatial scale as the scientific basis to determine stability of slopes at plot to hillslope scales. Interrill processes of raindrop splash and thin sheetflow transport are diffusive. Concentrated flow (rill erosion) processes are advective. Spatial loci of transition from diffusive to advective processes are inherently zones of landscape instability and channel formation. The HEM is used to define these areas of instability on hillslopes. Stability criteria for hillslopes are in turn used as criteria for geomorphic designs. Field data taken on a mine rehabilitation site in Queensland, Australia and at the Yakima Training Center in Washington State were used to extend the erosion model to disturbed site rehabilitation problems. These example applications from natural and designed slopes are used to illustrate model predictions and their applications in scaling and geomorphic designs.

Additional Key Words: Hillslope Erosion, Soil Erosion Models, Sediment Yield Models, Landscape Stability

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Introduction

Land reclamation at the landscape scale includes several key objectives. First, the remediated or reclaimed site should be designed such that its hydrologic characteristics (i.e. soil moisture, surface and subsurface runoff, soil erosion, sediment transport, sediment yield) should tend to evolve toward stability defined by onsite regulatory requirements, offsite water quality constraints, and the need for minimal additional remediation procedures. This hydrologic stability implies positive feedback between topography, soils, vegetative canopy cover, surface ground cover and hydrologic response. Simply put, this means that a properly designed site will tend to evolve toward a condition (i.e. stable topography with soil erosion decreasing through time, increased site cover, increasing evapotranspiration to reduce soil moisture influencing runoff and mass wasting) of increasing stability through time. Second, site properties should be robust in the sense that departures from stability should be “self-healing” to the extent possible. Third, site behavior should be predictable within the constraints of scientific understanding of the controlling processes and monitoring data limitations. And fourth, the site designs should be amenable to adaptive management depending upon departures from optimal performance as determined by predictive modeling, monitoring, and observations of successful vs. unsuccessful design elements.

Objectives of This Paper

To determine, and provide examples of the proper use of process-based simulation models and scaling techniques in determining geomorphic and hydrologic design features which will meet the site reclamation objectives outlined above.

Scope and Limitations

Hydrologic modeling drives the soil erosion and sediment yield calculations. However, the emphasis herein is on the erosion processes and their relation to scaling techniques and landscape stability. Specifically, we examine the relative importance of diffusional and advective sediment transport processes as a function of spatial scale and hillslope characteristics to provide a quantitative indicator of the areas of instability (and thus likely channel initialization) at the hillslope scale. We use the HEM as our primary analysis tool.

The Hillslope Erosion Model (HEM)

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 (see Lane et al. 1988 for the theoretical basis and Lane et al. 2001, upon which much of the following is based). 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 computes erosion and sediment yield as a function of position (x) on the hillslope 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 (such as WEPP, Laflen et al. 1991b), 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.

The hydraulics of overland flow on a plane are approximated by the kinematic wave equations:

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

and

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

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 $\text{m}^{1/2}/\text{s}$, 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:

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

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

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

where c is total sediment concentration in kg/m^3 , E_i is interrill erosion rate per unit area in $\text{kg}/\text{s}/\text{m}^2$, and E_r is net rill erosion or deposition rate per unit area in $\text{kg}/\text{s}/\text{m}^2$. 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:

$$E_i = K_i r, \quad (5)$$

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

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

where K_r is the rill erosion coefficient in $1/\text{m}$, T_c is the sediment transport capacity in $\text{kg}/\text{s}/\text{m}$ and is assumed equal to $(B/K)q$, and B is a transport-capacity coefficient in $\text{kg}/\text{s}/\text{m}^{2.5}$. 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. (Nonetheless, these assumptions still capture

dominant erosion and transport processes while allowing derivation of analytic solutions to the coupled equations)

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). 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:

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

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.

The Hillslope Erosion Model as a Generalization of Equation 7

The above sediment-yield equation (Eq. 7) for a single plane was extended to irregular slopes (Lane et al. 1995). This extension was accomplished mathematically 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 ground surface 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 (Fig. 1) and *USLE* fallow plot data from throughout the eastern United States. Personnel at the USDA Agricultural Research Service (ARS) 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.

The calibration results using the database described above, corresponding relationships from the literature, and expert judgment 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 computer program is called the simulation model

for sediment yield on hillslopes, or hereafter, the Hillslope Erosion Model. The model, its structure, calibration, validation, and applications are presented in detail by Lane et al. (2001).

The Hillslope Erosion Model and appropriate documentation are also 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. As suggested by Lane et al. (2001), this web site, or Internet-based, method of technology dissemination and transfer should enhance and accelerate use of erosion prediction technology.

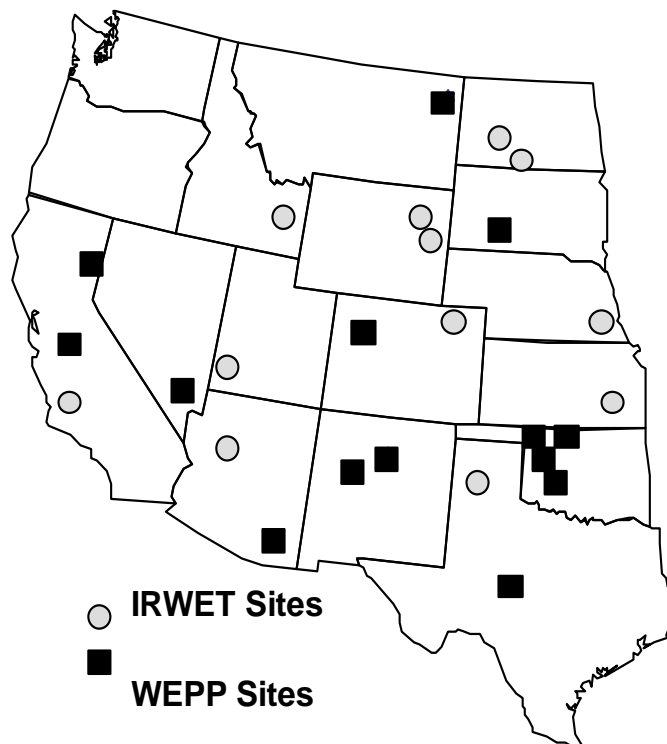


Figure 1. Location map of rainfall simulator sites used in the WEPP and IRWET field experiments.

Interpretation of Erosion Processes and Hillslope Features Using the HEM

There is a large and comprehensive body of literature on hillslope morphology, modeling, and landscape evolution. However, a few key references were most influential in developing the results herein. Tarboten, et al. (1992) plotted the logarithm of drainage area vs. the logarithm of slope steepness (as others have done) and stated "...the break in slope-area scaling represents the transition point between hillslope and channelized regimes." Their generalized findings were that for very small areas slope tended to increase with drainage area up to a maximum and decline with increasing area thereafter. Based upon analyses by Smith and Bretherton (1972),

the relationship between slope and area was interpreted as follows. For small areas where the slope is increasing, diffusive sediment transport processes dominate and “smooth” hillslopes develop. At the peak or maximum, instability occurs which leads to rilling and channel growth and the concurrent decrease in slope with increasing area. Moreover, for areas less than the critical area, A_c , corresponding to the peak on the slope-area curve, slopes are convex and for areas larger than this, advective or concentrated channel sediment transport processes dominate and slopes are concave. As Tarboten et al. (1992) state “Where there are multiple sediment transport processes present, the break point is the point where domination by stable diffusive processes yields to domination by unstable channel-forming processes.” A schematic of this relationship is illustrated in Fig. 2.

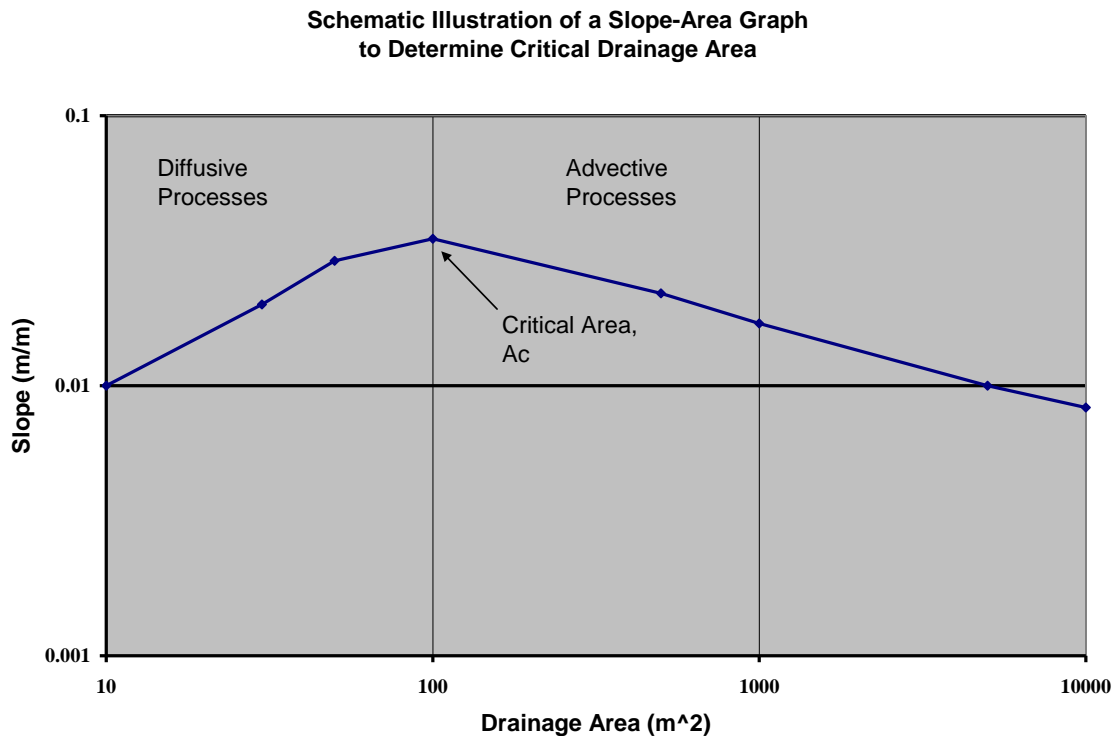


Figure 2. Schematic illustration of the relationship between drainage area and slope steepness at the hillslope scale.

The most comprehensive source dealing with soil erosion processes affecting hillslope and watershed morphology as discussed above is the book by Rodriguez-Iturbe and Rinaldo (1997) wherein the fractal, scale, and process-morphology relationships from hillslopes to major drainage basins are dealt with in detail. Finally, Lane et al. (1988) derived diffusive and advective relationships for sediment transport in the HEM.

Diffusive and Advective processes in the HEM

With regard to the HEM (i.e. Eqs. 1-7 presented earlier), the quantity $(B/K - Ki)$ can be used to determine if diffusive or advective sediment transport processes in overland flow are dominant. Notice that B/K and Ki are functions of the distance down the hillslope, x , as well as

slope steepness, hydraulic roughness, vegetative canopy cover, and ground surface cover. If $B/K > Ki$, then transport capacity in the rills exceeds sediment supply delivered to them by interrill erosion and thus, sediment yield at a point, x , on the hillslope is limited by sediment detachment rate in the rills and the dominant sediment transport process is advective. If $B/K < Ki$, then transport capacity in the rills is exceeded by the rate of sediment delivered to them by interrill erosion. In this case sediment yield is limited by transport capacity in the rills and diffusive processes dominate. The singular point where $B/K = Ki$ is an equilibrium point where transport capacity in the rills exactly matches the rate of sediment delivered to them from interrill erosion and there is no net detachment or deposition in the rills.

We define a normalized (dimensionless) sediment transport parameter, H , as

$$H = (B/K - Ki)/Ki \quad (8)$$

where the parameters are as described above. The parameter, H is then determined as follows:

$H < 0 \Rightarrow$ diffusive processes dominate and sediment yield is limited by transport capacity in the rills;

$H > 0 \Rightarrow$ advective processes dominate and sediment yield is limited by detachment rate in the rills.

If we assume the drainage area in Fig. 2 is a function of the distance down slope, x , and further that the drainage areas are approximately rectangular, then the hillslope length corresponding to a given area, A , and length width ratio, L/W , is

$$L = [(L/W)*A]^{0.5} \quad (9)$$

where x is less than or equal to L .

Assume we have hillslopes with convex, uniform, or concave slope profiles all with the same length, average slope, and other properties such as soil texture, and cover. Is it possible to use H from Eq. 8 to examine dominant processes along the length of the hillslopes? This question is addressed in the second example in the following section.

Comparison of Observed and HEM Simulated Data

The first data set (not used in the HEM development or calibration) is from Loch (2000) and is used to illustrate the performance of HEM relative to experimental rainfall simulator data on rehabilitated mine land in Queensland, Australia. Plot characteristics (length, slope, surface cover, soil type) and measured rainfall, runoff, sediment yield, and sediment concentration data were given by Loch (2000). The HEM soil erodibility parameter for the bare plots was determined by matching observed and simulated sediment yield for the average of the 2 bare plots. All other parameters in HEM were determined by the default values based upon the plot characteristics.

The measured and HEM simulated plot sediment yield data as a function of surface cover density are shown in Fig. 3. Notice that the HEM predictions match the observed data very closely and reproduce the trend in decreasing sediment yield with increasing cover density over a range of 3 - 100% cover and from 0.02 - 32 T/ha sediment yield. Although one test in Australia is not exhaustive by any means, additional testing data from Australia, India, and New Zealand supporting the results shown herein were given by Cogle et al. (2003). Additional model validation data from experimental plots and small hillslope watersheds on the Walnut Gulch

Experimental Watershed in Arizona (Lane et. al. (2001) supported the robustness of the HEM simulations in a prediction (as opposed to calibration) mode.

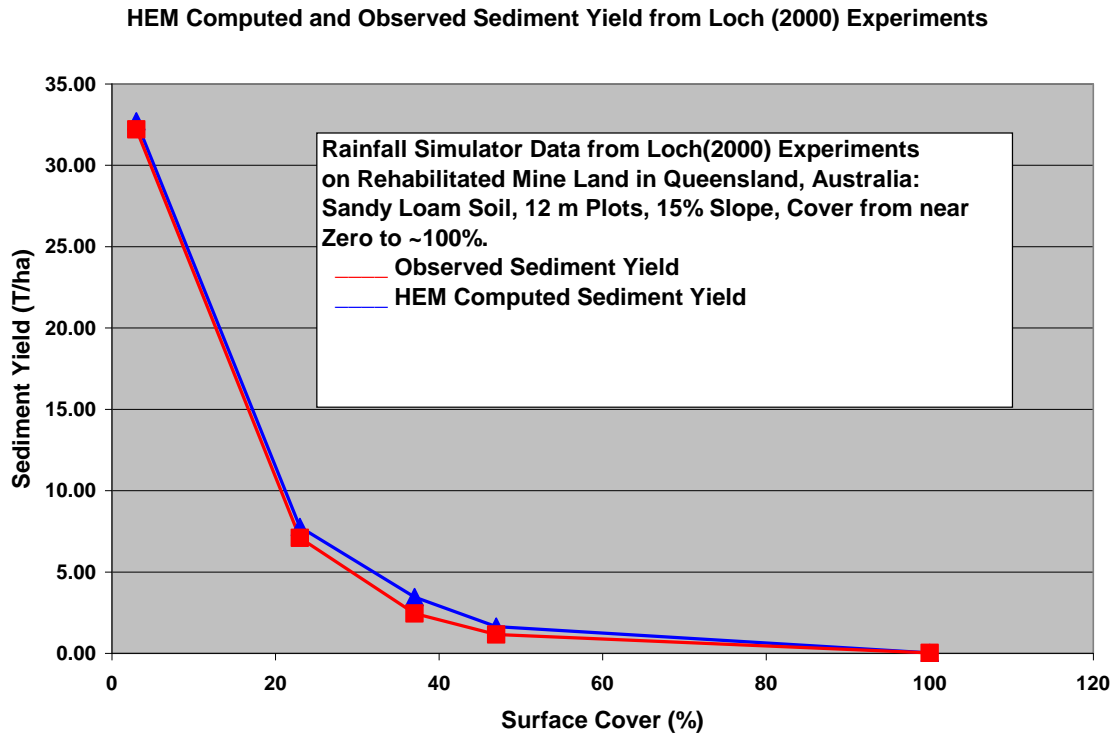


Figure 3. Illustration of observed and simulated sediment yield data from experimental rainfall simulator plots on rehabilitated mine land in Queensland, Australia.

The Yakima Training Center (YTC) is a U.S. Army training facility in south central Washington, USA (see Halvorson et al. 2003 for a brief overview). As part of their training area management, firebreak roads are constructed to help contain wild land fires on the YTC. The question we address in this example is how well the calculated diffusive vs. advective sediment transport areas on a hillslope can be predicted using the HEM relationships as given by Eq. 8 and the discussion related to it. The firebreak roads are about 10 m wide and are constructed with a bulldozer to remove vegetation, and thus fuel load, along ridgelines and around areas prone to fire from training activities.

Calculations for a mild-sloped (1-5 %) firebreak road segment at the YTC are illustrated in Fig. 4 and a photograph of the segment is shown in Fig. 5.

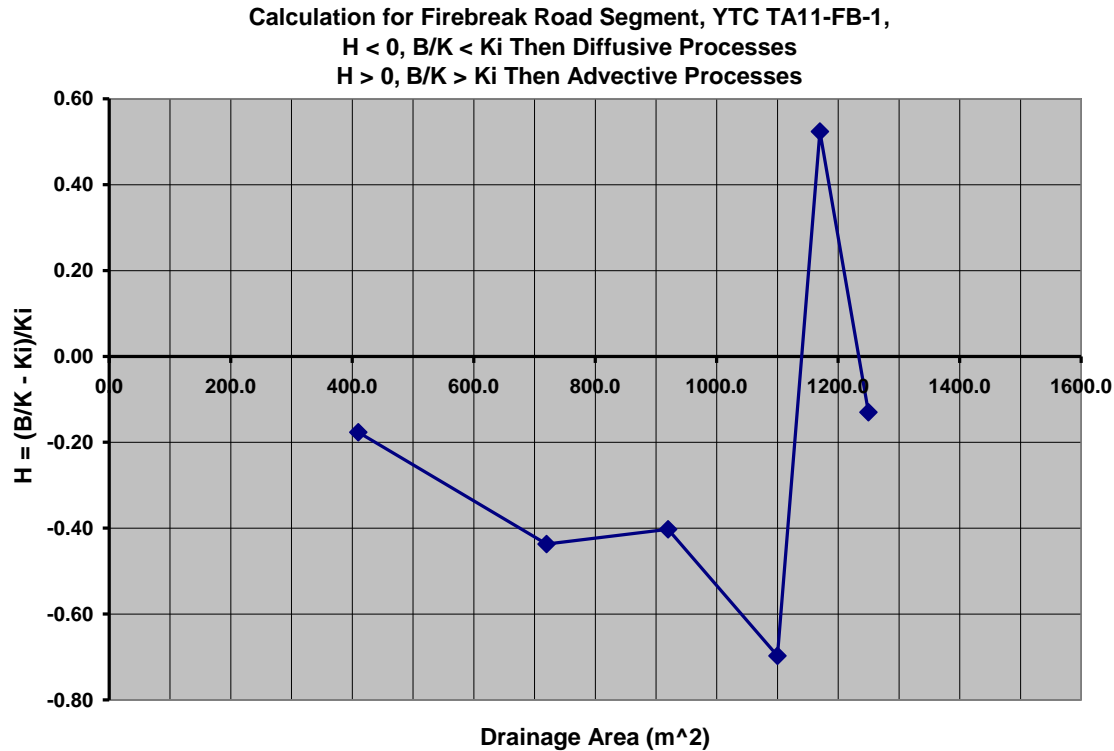


Figure 4. Representative illustration of HEM relationship predictions of the locations of diffusive and advective sediment transport processes on a mild-sloped firebreak road at the YTC.

Notice that Equation 8 predicts that diffusive sediment transport processes are dominant everywhere along the slope profile except for the next to the last segment where advective sediment transport (and thus rilling) is predicted. To examine the reliability of this prediction, a photograph of the firebreak road segment is shown in Figure 5. From the end of the profile where the observer is standing, looking upslope about 8 m, the sediment processes are diffusive and sediment deposition is evident. From 8 to 15 m upslope there is evidence of rilling as suggested by the “*H*” calculations in Fig. 4. While this represents but one example, analyses of “*H*” calculations and photographs on firebreak roads at YTC are generally consistent in identifying areas of deposition and areas of rilling.

Potential Applications in Scaling and Geomorphic Designs

The Hillslope Erosion Model was shown to be applicable from plot to hillslope scales. It was calibrated on small plots (10.7m by 3 m) and validated on small plots (10.7 x 3 m) and small hillslope watersheds up to 1.86 ha in area. These calibration and validation studies span a drainage area scale of about 30 m² to 20,000 m², or some three orders of magnitude. Analyses at this scale are primarily applicable to the center and left portions of figures such as the hypothetical Fig. 2 herein.

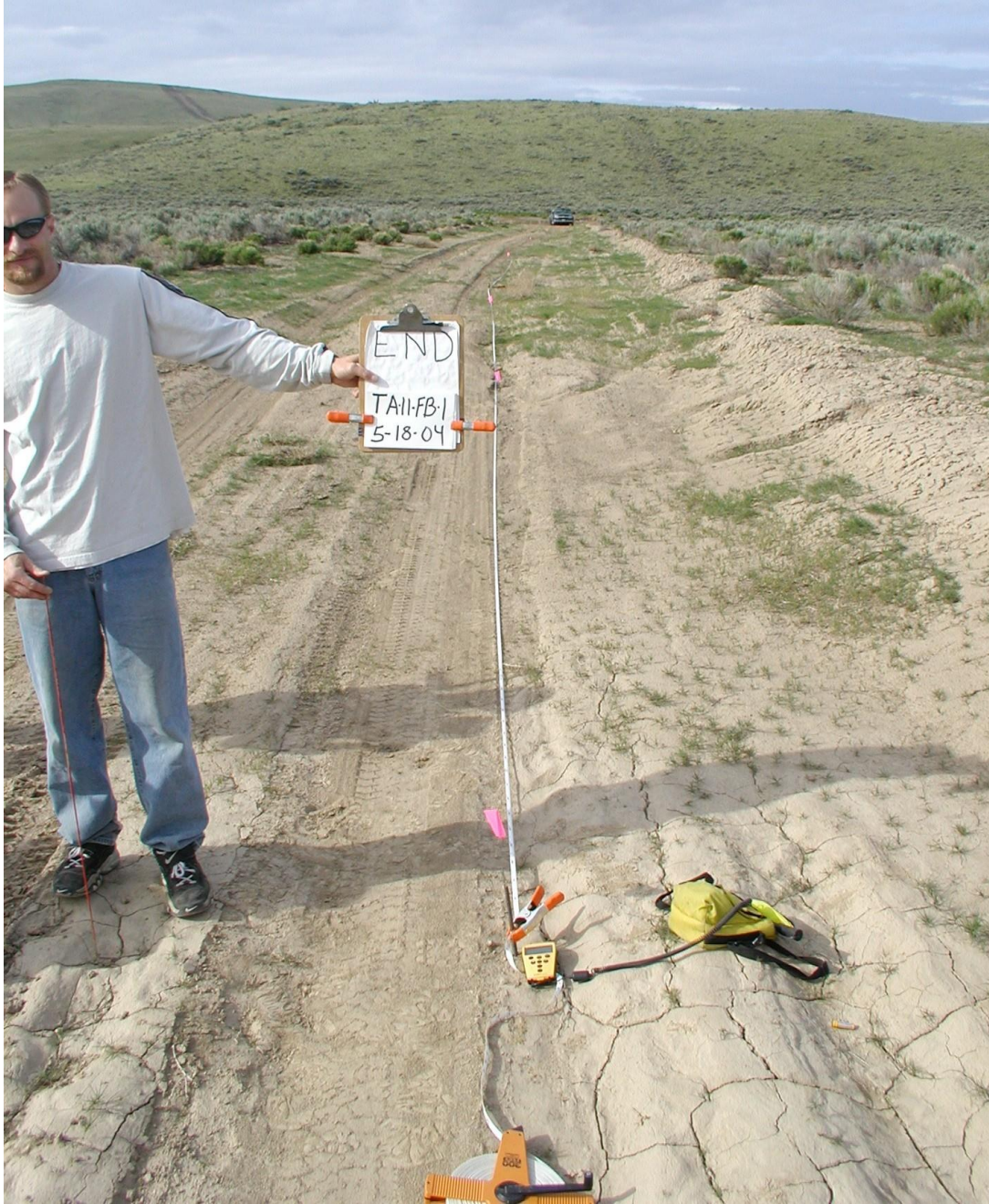


Figure 5. Photograph facing upslope of a mild-sloped firebreak road at the YTC. The pink survey flags mark the segments used to describe the hillslope profile. Notice that there is evidence of rilling between the second and third survey flags (next to last segment) on the profile.

On steep slopes, such as those on the mine spoils at Meandu Mine in southern Queensland, Australia described by Loch (2000), advective processes are dominant. This is true in the HEM at the Meandu Mine, and in nature by numerous observations of mine spoils, road cuts, etc.,

where rilling and channel formation are observable. In such cases where diffusive processes (limited transport capacity in the rills) do not limit soil erosion and sediment yield, then erosion control measures reducing the rate of erosion and sediment yield are necessary. An example of increasing vegetative canopy cover and ground surface cover reducing sediment yield from relatively steep hillslopes (~ 15%) is shown in Figure 3. Notice that the HEM reproduced the magnitudes and trend in sediment yield reduction with increasing vegetative canopy cover and ground surface cover. The HEM thus provides an erosion process-based tool for determining the relationships between slope steepness, slope length, and cover (vegetative canopy cover and ground surface cover) and sediment yield at the plot to hillslope scale.

The H – variable (Eq. 8) derived from the HEM was used to predict which regions of hillslopes are likely to be dominated by diffusive sediment transport processes ($H < 0$) and those likely to be dominated by advective, and thus rilling and channel formation processes, ($H > 0$). These analyses were conducted for several firebreak roads at the YTC. An example of this firebreak road application is illustrated by Figures 4 and 5. In terms of hillslope geomorphic analysis, the HEM provides a means of predicting spatial locations of transitions between diffusive and advective sediment transport processes, and thus, the predicted regions of channel initiation. These in turn can be used to design erosion control mitigation strategies such as placement of turnouts (water breaks) and areas to harden with gravel, cobble, or concrete.

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