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A Review of Soil Erosion Models with Special Reference to the needs of Humid Tropical Mountainous Environments

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Abstract
Humid tropical mountainous environments (HTMEs) are generally considered sensitive ecological regions because anthropogenic disturbance often accelerate hillslope processes such as runoff, erosion, and sediment flux. Reducing accelerated erosion is necessary for the maintenance of the integrity, stability and sustainability of HTMEs. Soil erosion models (SOMs) are potential tools for predicting soil erosion, sediment flux, and the design and assessment of effectiveness of conservation management practices in HTMEs. Within this context, this study provides a critical review of the available SOMs with a focus on their applicability in HTMEs. The review indicates that because most SOMs have been developed for "flat agricultural lands" in temperate regions, to be useful in conservation planning in HTMEs models should be calibrated for local conditions. For humid tropical mountainous regions, lumped parameter models (LPMs) linked to Geographical Information Systems (GIS) are more practicable for conservation planning than sophisticated distributed parameter models (DPMs). This is due to the less stringent data requirements and ease to which land managers can implement LPMs, an essential consideration within the physical and socioeconomic context of HTMEs.

*Keywords:*Soil erosion models; Humid tropics, Mountainous environments; Conservation planning

1. Introduction

Accelerated soil erosion is a serious environmental problem in many agricultural regions of the world (Pimetel 1993, Kaihura et al. 1999, Chaplot et al. 2012, Lal 1990). The problem is particularly acute within humid tropical mountain environments (HTMEs) (El-Swaify 1997, Millward and Mersey 1999, Smith et al. 2000). Recognition of the high soil erosion rates within this region has only occurred during the past few decades. The powerful conceptual framework provided by Langbein and Schumm (1958) regarding the relationship between precipitation, vegetation, and soil erosion suggested that erosion rates declined in humid settings because of the protective influence of lush vegetation. However, work by other scholars since the 1970s has generally shown that erosion rates are greatest in the humid tropics because the influence of vegetation on erosion rates diminishes as annual precipitation exceeds ~2,000 mm,

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and this has generally been confirmed by comprehensive reviews of soil erosion and sediment yield (e.g.Walling and Webb 1983).
Since mountainous regions represent the upper catchments of major river basins there is a diverse suite of possible downstream impacts associated with accelerated erosion (Stoddart 1969), such as increased flood risk, loss of stream habitat, and reservoir siltation (Lal 1990). These settings are characterized by steep, complex slopes, and abundant intense rainfall events frequently in excess of soil infiltration capacity. For this reason, soil loss tolerance, the maximum allowable amount of soil loss beyond which soil productivity becomes unsustainable (Wischmeier and Smith 1978) in HTMEs is comparatively lower than for tropical or temperate lowland regions. In addition to these biophysical limitations, the resilience, stability, and sustainability of the fragile ecosystem of HTMEs are threatened by increasing population pressure, improper land use and deforestation (Sharma, Rai and Sharma 2001, Harden 2001, Nyssen et al. 2008). Because of the difficulties and costs associated with combating soil erosion and its associated geomorphic hazards especially in HTMEs, a preventive land use and management strategy capable of evaluating the impacts of current and future land use is required. Soil erosion models (SOMs) that simulate and evaluate the effects of land management strategies provide a sound framework for identifying the impacts of land use on erosion, and contribute to the development of appropriate intervention plans. Unfortunately, there is a dearth of SOMs calibrated for these regions (Table1). The numerous SOMs developed over the latter half of the twentieth century were designed with widely ranging philosophical and logistical considerations, with little thought as to the economic environment in which they would be utilized. A number of general reviews of the strengths and weakness existing SOMs have been published (see for example (Fu et al. 2010, Aksoy and Kavvas 2005, Merritt et al. 2003) but none have addressed the unique needs of HTMEs. This study offers a detailed review of some of the most commonly used SOMs with special reference to the needs of HTMEs.

2. Overview of the process of soil erosion

Rainfall induced erosion is a two-phase hydro-geomorphic process that involves the detachment of individual soil particles from the soil surface, and its down slope transportation (see Ellison 1947, Morgan 2005, Hudson 1995). Within a humid environment the rate of erosion is limited by detachment (D), or transport capacity (T) (Fig.1). In general, when the detachment rate exceeds the transport capacity a third phase of deposition occurs. The process of sediment detachment (D) and transport (T), which begins with the impact of raindrop, is dependent on the hydrological processes, and a host of other interacting environmental factors (Fig. 1). Rainfallerosivity, the aggressiveness or potential of rain to cause erosion is a function of several properties, and varies with climate. Effective rainfall erosivity depends on a host of interacting variables (Fig. 1). Erodibility defined as the resistance of the soil to detachments by raindrop impact and surface runoff (Bryan et al. 1989) is a function of several soil properties and other interacting environmental factors (Fig. 1).

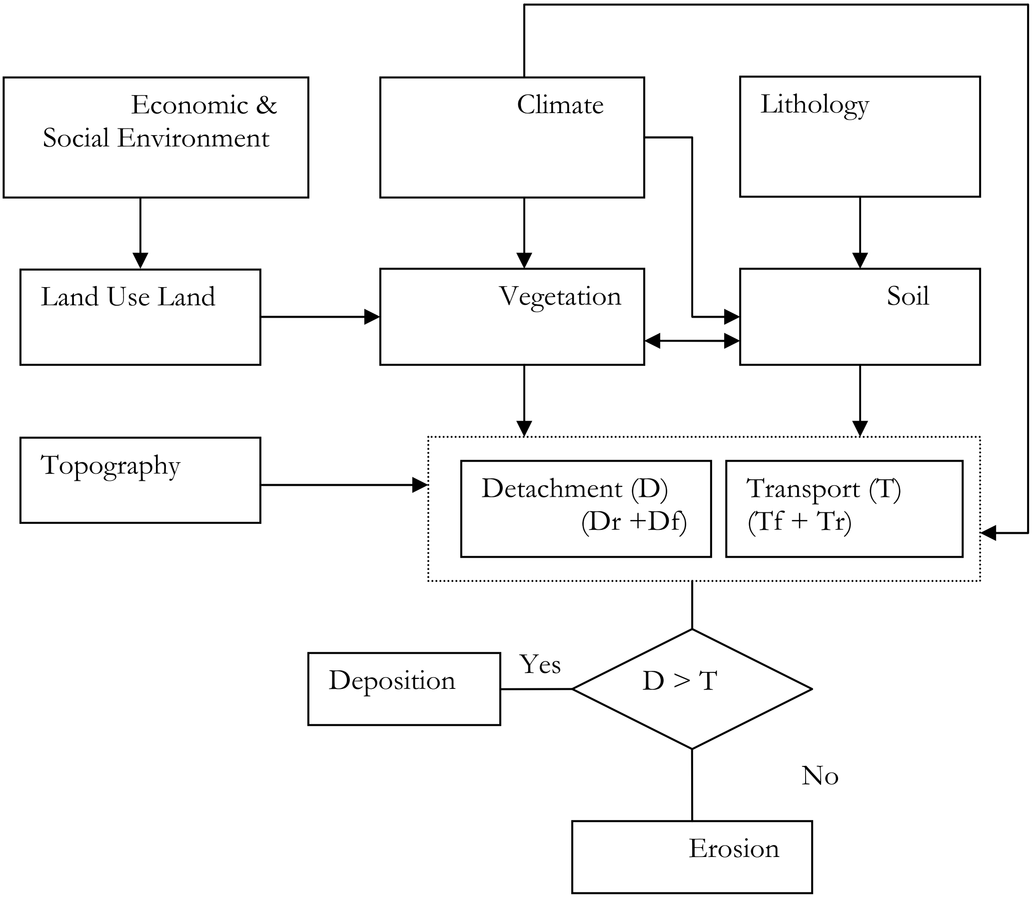

***Figure 1**. Soil erosion process and controlling factors: (Dr =soil detachment due to raindrop impact, Df = soil detachment due to surface runoff or overland flow, Tr = soil material transport due to raindrop impact; Tf = soil material transport due to surface runoff or overland flow).*

Finding a universally acceptable erodibility index has eluded modelers because of the large variation of soilsand physical settings, which introduce significant temporal and spatial variability (Bryan et al. 1989).

The quantity of sediment transported (T) depends on the volume of runoff and the velocity of flow, both of which are in turn influenced by the degree and length of slope (Hudson 1995). The modeling task is complicated by the considerable temporal and spatial variability of the erosion controls, which is particularly common in HTMEs (Fig. 1). This includes complex slope configuration, varied lithology and soils, intense rainfall, and high antecedent moisture of humid environments. This concern is further compounded by the lack of adequate baseline data pertaining to soils, topography, or monitoring stations for precipitation in many countries within HTMEs.

3. Soil erosion models (SOMs)

Long-term interest in soil erosion and sediment transport processes by geomorphologists, hydrologists, agronomists, environmental engineers and other earth science disciplines has led to the development of a number of SOMs for a variety of purposes, including simulation of the effects of watershed variables on erosion rates and processes, conservation planning in agricultural lands, site-specific assessments and project evaluation (Foster 1990, Albaladejo and Stocking 1989). Classification of existing SOMs into a mutually exclusive typology is a difficult task, but can be based on combinations of characteristics, such as spatial scale, process, duration, hydrological processes, and model output. On the basis of spatial scale, a distinction can be made between slope and catchment based models (Fig. 2). Models can also be distinguished temporally, ranging from single-event to decadal scale models. A common theme is the spatial representation of the physical process. In this regard there are two broad distinctions, lumped and distributed parameter models (Witinok 1988).

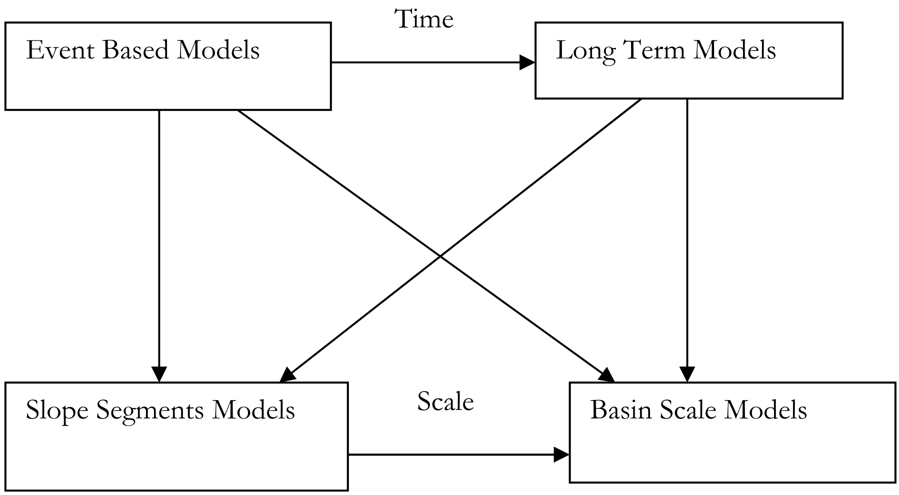

Figure 2. *Conceptual model of the relationship between various SOMs in relation to time and space*

3.1 Lumped Parameter Models (LPMs)

LPMs use averaging techniques to lump the influences of non-uniform spatial processes of a given area, such as a basin-averaged precipitation for runoff computation. The initial focus of most LPMs such as RUSLE and SLEMA (see Table 1 for the full meaning of model acronyms) was to estimate long term average annual soil erosion at the field scale. In the late 1960's and 1970's the on- and off-site impacts of agricultural management practices and soil erosion on water quality and soil productivity became a major concern (Renschler and Harbor 2002). This stimulated the development of a number of LPMs that included routines for evaluating the effect of different agricultural practices on nutrient loss, ground water pollution, and crop productivity. Although these later models were to some extent based on process description, they retained essentially an empirical base. Examples include the ANGPS, CREAMS, GLEAMS and the EPIC models (Table. 1).

The USLE model (Wischmeier and Smith 1978), now RUSLE (Renard et al. 1991), is the most widely used LPM (Ahamed, Rao and Murthy 2000). The RUSLE is an empirical equation for predicting long-term average soil erosion from agricultural fields under specific cropping and management practice (Renard et al. 1991). Because the RUSLE is an empirical equation, its application is dependents on field data and the equations are valid within the limit of data from which it was developed. Indeed, a major criticism of the model is that its rainfall erosivity factor is not suited for capturing the erosivity of intense precipitation events, which are common in the humid tropics (Jeje, Ogunkoya and Adediji 1997, Lal 1990, Odemerho 1990, Stocking and Elwell 1976).

The need to localize the factors and improve its parameterization led to the formulation of SLEMSA (Ewell and Stocking 1982) for use in tropical and subtropical regions. Both RUSLE and SLEMA and similar LPMs are incapable of measuring sediment deposition, the implication being that sediment detached by rainfall and runoff is implicitly assumed to be transported from the field or catchment, a condition highly improbable in mountainous environments having complex topography. In addition, nutrient and runoff is not estimated by the models. CREAMS, GLEAMS, and EPIC models were developed to address this later shortcoming. While CREAMS evaluates the relative effects of agricultural practices on pollutants in surface runoff and in soil water (Knisel 1980), GLEAMS, an extension of CREAMS, models the movement of nutrients within the root zone (Leonard et al. 1995). EPIC measures quantitatively the impact of erosion on crop productivity (Williams et al. 1983). However, these models have limited routing capabilities for application at the watershed scale. In addition, soil, cultural, and conservation management practices are assumed to be spatially homogeneous, a condition very unlikely within HTMEs where inter cropping and rotating crops on steep slopes utilizing swidden technology are often the dominant signature on the landscape.

3.2 Distributed Parameter Models (DPMs)

In contrast to LPMs, DPMs take into consideration the natural variation in parameter values and erosion controls. The goal is to represent the spatial and temporal variations of the physical process. Examples of these models include WEPP, EUROSEM, MEDALUS, LISEM, and KINEROS (Table. 1). Others in this category include models with the capacity to simulate nutrient and agricultural chemicals loadings in runoff, e.g. GAMES, ANSWERS, and AGNPS. Unlike LPMs, relatively few attempts have been made to evaluate DPMs outside the environment in which they were developed, e.g. EUROSEM in Mexico, Costa Rica and Nicaragua (Veihe et al. 2001) and LISEM in South Africa (De Roo and Jetten 1999). Unfortunately few reports are available for HTMEs to confirm their usefulness.

WEPP, EROSEM and other DPMs have several advantages over the RUSLE and the other existing erosion prediction technology. They have the capabilities of predicting the spatial and temporal distribution of net soil loss and deposition for an entire hillslope for any length of time. They have a wider range of applicability due to inbuilt process-based sub-models for describing the physical processes affecting erosion, and WEPP in particular generates its own weather and climatic data using a stochastic weather generator (Tiwari et al. 2000). It is hoped that the WEPP model will finally replace the RUSLE as a tool for soil conservation planning in the United State.

Table1. Acronym, description, and comments on some soil erosion models discussed in the paper

Model acronym/ Full name	References	Comments
1. **USLE/RUSLE** Universal/Revised Universal Soil Loss Equation	(Wischmeier and Smith 1978) (Renard et al. 1991)	LPM, measures annual soil loss (kg/ha/yr) resulting from rill and inter rill erosion on slopes in agricultural fields. Does not measure deposition or nutrient loss. Has been extensively applied in humid tropics including HTMEs with modification of the climatic component. Has been successfully linked to GIS. Developed in US.
2. **SLEMSA** Soil Loss Estimator Model for Southern Africa	(Stocking and Elwell 1973)	LPM, measures long term annual soil loss (kg/ha/yr) resulting from rill and inter rill erosion on slope and agricultural fields in the tropics. Does not measure deposition. Developed in Southern Africa.
3.**CREAMS** Chemical Runoff and Erosion from Agricultural Management System	(Knisel 1980)	LPM, continuous simulation model, essentially empirical base. Appropriate at field scale. Additional capacity for assessment of nutrient runoff from agricultural fields. Developed in US
4. **GLEAMS** Groundwater Loading Effects of Agricultural Management System	(Leonard et al. 1995) (Knisel and Turtola 2000)	LPM, continuous simulation model with essentially empirical base. Appropriate at field scale. Additional capacity for assessment of nutrient runoff from agricultural field. Shortcomings and advantages similar to CREAMS. Developed in US
5. **EPIC** Erosion Productivity Impact Calculator	(Williams et al. 1983)	LPM, empirical model with the additional capability to compute the impact of soil erosion on productivity. Suffers from the same limitations and strengths of CREAMS and GLEAMS. Developed in US
6. **KYERMO** Kentucky Erosion Model	(Hirschi and Barfield 1988)	DPM, process based soil erosion model for agricultural field scale. Not very popular in its application compared to other models. Developed in US
7. **WEPP** Water Erosion Prediction Project	(Nearing et al. 1989) (Flanagan et al. 2007)	DPM, process-based continues simulation model. Operates at the field scale and small watersheds. Can assess erosion on an event basis. Has the capability to predict erosion and deposition on hillslopes and watersheds. Can be linked to GIS. Developed in US

9. **EROSION 2D/3D** 2-D Rainfall Erosion Model	(Schmidt et al. 1999)	DPM, process based model for simulation at the field sale and watershed. Can be easily linked to GIS. Developed in Europe.
10. **MADALUS** Mediterranean Desertification and Land Use	(Kirkby et al. 1988)	DPM, process based for simulation of erosion, plant growth and other process. Have not been applied extensively in other climatic and eco-region. Requires several impute variables. Developed in Europe.
11**. GAMES** Guelph Model for Evaluating the Effects of Agricultural Management Systems on Soil Erosion and Sedimentation	(Rudra et al. 1986)	DPM, simulates erosion and deposition at the field and watershed scales. Developed in Canada.
12. **EUROSEM** European Soil Erosion Model	(Morgan et al. 1998)	DPM, process based, simulates erosion on event basis. Requires intensive data. Can be linked to GIS. Developed in Europe.
13. **LISEM** Limburg Soil Erosion Model	(De Roo 1996, De Roo et al. 1996)	DPM, process based SOM for simulation erosion and deposition at field sale. Requires large amount of data. Developed in Europe.
14. **ANSWERS** The Areal Nonpoint Source Watershed Environment Response Simulation	(Beasley et al. 1980)	DPM, process based soil erosion model that simulates erosion and nutrients from agricultural watersheds. Can be run on an event or continuous basis. Has the capability to be linked to a GIS. Developed in the USA.
15. **SWAT** Soil and Water Assessment Tool	Gassman, et al. 2007)	DPM, basin-scale, continuous-time model, predicts the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. Linked to GIS. Developed in US

Source: Various

4. Geographic Information Systems (GIS) and soil erosion models

Ultimately, the future of any SOM will depend on its successful marriage with GIS. SOMs have been applied at field scale level as a cost-effective tool for soil conservation planning and management. However, until recently, their application at the watershed scale has been limited by the difficulty of managing and manipulating large amount of data and model parameters at such a spatial scale. The development of powerful spatial hydrological within GIS and the linking of various LPMs and DPMs with GIS has enabled modelers to overcome these limitations and extend model capabilities to the watershed scale (Tim and Jolly 1994). The capability to generate topographic parameters from Digital Elevation Models (DEMs) has facilitated three dimensional erosion modeling in areas with complex topography (Desmet and Govers 1995). The coupling of GIS and SOMs has the added benefit of standardizing modelling procedure in terms users choice of model parameters, reduction in resource and the time involved in modeling processes and visualizing modeling output (Green and Cruise

1995). Accordingly, several existing models, e.g. RUSLE, WEP, EUROSEM and ANSWERS, have been successfully linked to GIS while new GIS based models such as LISEM, SWAT have been developed.

5. Evaluation of SOMs in view of humid tropical mountainous environments

Obviously any given SOM is bound to have strengths and limitations because model developers adopt different philosophical approaches and often develop models for specific environmental conditions and processes (Grunwald and Frede 1999). The available SOMs have been developed mainly for agricultural lands in temperate regions of North America and Europe where biophysical environmental variables (e.g. climate, soil, topography) and socio-cultural farming practices (e.g. cropping pattern and management practices) are significantly different from those that typify the humid tropics in general and humid tropical mountainous region in particular. In mid-latitude regions erosion modeling has traditionally been conducted on agricultural fields that exhibit short slope lengths with moderate, relatively homogenous slope angles. Indeed, "data on the effect of slope length and steepness under natural precipitation are rare for slopes exceeding 16%" because such lands are seldom cultivated in temperate regions (El-Swaify 1997) and studies of slopes greater than 50% are rare (Mccool et al. 1987, Nearing 1997). Yet, slope is arguably the most important factor in the erosion process (Zingg 1940, Desmet and Govers 1995) especially in HTMEs. This is a major problem with the use of LPMs (e.g. RUSLE). Recent research on the effects of slope steepness on the erosion process has shown that slope equations employed in LPMs such as RUSLE are not globally applicable (Mccool et al. 1987). A persistent problem has been defining the beginning and termination points of slopes segments. This is a critical issue in areas with complex topography, which are prevalent in HTMEs. Although modelers have been able to overcome this problem by linking LPMs and DPMs with GIS coupled with multiple-flow algorithms based on DEMs manipulation (Desmet and Govers 1996a, Desmet and Govers 1996b), such application are normally suitable for soil erosion simulation at the watershed scale.

The assumptions regarding the rainfall characteristics of SOM introduce an additional problem because the rainfall characteristics are significantly different from those of the humid tropics (Morgan 2005). This limitation is more of a problem with LPMs which account for the rainfall erosivity by using a single index computed from temperate rainfall properties (e.g. RUSLE). As shown by (Hudson 1995), erosion in the tropics is almost entirely caused by rainfall at intensities in excess of 25mm/h, a factor that may complicate the application of the RUSLE in the tropics (Ahmad and Breckner 1974). Process based DPMs are comparatively better in this regard as they are based on equations describing the mechanism and processes associated with erosion. Nevertheless, while these mechanisms or physical processes described in the process-based DPMs are universal, the intensity, frequency and magnitude of their operation are different for humid tropical mountains because of the runoff characteristics associated with frequent intense rainfall events. DPMs must be calibrated to local conditions prior to application.

Although the above mentioned problems are significant, data availability is the greatest challenge associated with model adoption in the humid mountainous tropics. DPMs have the capability to model the complex variation in topographic and biophysical variables, particularly when integrated with GIS. However, they require comparably more data inputs than LPMs. Because of their remote location data collection in support of parameters for DPMs is often impractical (ElSwaify 1997). Added to this problem, the extremely variable biophysical environment requires high sampling density to estimate model parameters. Unfortunately, much of this setting is within developing countries where the institutional framework for soil conservation and environmental driven research are often weak or absent. Data collection on a consistent basis from gauged or experimental watersheds is not common because of the lack of financial commitment caused by pressing social needs. The few available data, often the result of an individual scientist, are usually of limited duration and therefore inadequate for model calibration.

Finally, the technical feasibility and social acceptance of a particular erosion model must be considered. To be useful for landscape and conservation planning, models should be suitable to the needs and skill level of the user groups (Renschler and Harbor 2002). Available field conservation personnel should be able to understand and implement the model with little difficulty. More importantly, the small-scale farmers who are in most cases the ultimate land manager should also be capable of implementing the model with little assistance from technical field officers. Unfortunately trained soil technicians are sparse, partly because of a lack of institutional framework for development of human capital. This is where LPMs such as RULSE, SLEMA and CREAMS have greater advantage over more complex DPMs such as WEPP, EUROSEM, especially when linked to GIS. Indeed, the issue of social acceptance has been considered by United States Department of Agriculture (USDA) research scientists who in the 1980s acknowledged the need to develop "a new generation of erosion prediction technology based on modern understanding of the erosion process, but cautioned that such technology should maintain the RULSE style and applicability for support of conservation planning" (Renschler and Harbor 2002). Given the peculiar social and cultural environment of the humid tropics, a conservation technology based on simple LPMs philosophy is technically feasible, socially appropriate, and in the short run, more financially viable for conservation planning compared to complex DPMs.

6. Summary and Implications

The dearth of predictive erosion models for humid tropical mountainous regions means that models developed for temperate mid-latitude regions must be calibrated to meet local environmental conditions. DPMs have the capability to model the complex topographic and biophysical environments of humid tropical mountainous regions when integrated with GIS. However this does not imply that the model outputs produced by DPMs are more reliable (Nearing 1998). Does the amount of money and time devoted to collection of the data justify their application for simple watershed planning in humid tropical mountains? Do communities in these regions possess the institutional framework, personnel, and financial commitment to undertake the long term research necessary for implementation of DPMs? This review of soil erosion models concludes that the use of LPMs is more attractive in the immediate future because of the ease with which data requirements can be met and the greater suitability of these models for the socioeconomic context of these regions. When linked with GIS, LPMs provide great potential for use in simple watershed planning for soil conservation in humid tropical mountainous environments.

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