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A Soil Water Balance Model for Monitoring Soil Erosion Processes and Effects on Steep Lands in the Tropics

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A soil water balance model for monitoring soil erosion processes and effects on steep lands in the tropics

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Abstract

Water erosion is the major threat to soil and water conservation in the steep lands of the tropics. Besides surface erosion on gentle to moderate slopes, mass movements are common on steep slopes. In addition to the negative effects on productivity and crop production risks, in many tropical regions, offsite effects of sedimentation, floodings and landslides are also rooted in accelerated soil erosion. The prediction of water erosion by direct measurements in erosion plots, or by using empirical models has not generally given satisfactory results in the tropics, specially when mass movements are the potential erosion processes. Modeling the surface soil hydrological processes, under the prevailing conditions of climate, use, management and cropping in two selected sites of Venezuela, resulted in fairly accurate simulations of both the soil surface and landslide erosion processes and their main effects. The model SOMORE, used for such simulation, is based on easily available climate and soil input parameters, and produces as the main output the soil moisture regime in a daily basis, including the average soil moisture at root depth, and the water losses by surface and subsurface runoff, and by internal drainage. The output of the model is used as the basis for the selection, with a probabilistic approach, of the best alternatives of use and management of soil and water resources for each combination of soils, climate and topography.

Keywords: Erosion processes; Steep lands; Surface erosion; Landslide erosion; Water balance; Mass movements; Process-based models; Tropics; Hydrological processes; Soil management; Water management; Simulation; Soil water erosion

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1. Introduction

The main factor acting against the sustainability of agricultural production is land degradation. Also important are the offsite effects of land degradation on increased risks of catastrophic floodings, sedimentations, landslides, etc., and on global climate changes. Land degradation is affected by soil and climate characteristics, but it is mainly due to inappropiate use and management of soil and water. Water, that is often the main limiting factor of crop production, is also the main factor directly or indirectly responsible for soil and land degradation processes (Pla, 1992a).

Among the different land degradation processes, soil water erosion is the major threat to the conservation of soil and water resources. The susceptibility of soils in the tropics to surface water erosion is on the average not much higher than in other climatic regions of the World, but the erosive power of rainfall is generally much higher (El-Swaify and Fownes, 1992). Erosion is exacerbated by deforestations, by the introduction of seasonal crops leaving the soil unprotected, by intensification of agriculture, by overgrazing, and by improper maintenance of plantations. Water erosion processes have been accelerated in most of the tropical regions in recent decades, due to population pressure and limited resources, which have also led to increased and more continuous use of steeper lands for agriculture.

1.1. Soil water erosion processes

Besides surface erosion in gentle to moderate slopes, mass movements and landslide erosion are common in more steep slopes (Pla, 1992b; Pla, 1993). Severe surface erosion is linked with intense precipitation events, high detachability of surface soil material and reduced infiltration. This reduction is induced by poor and weak surface soil structure, and by poor cover of vegetation or plant residues in critical periods. Under these conditions, generally created by inadequate soil and crop management practices, the surface soil particles are detached by raindrop impact or by running water, and are transported downslope by runoff water, which flows more or less uniformly distributed on the soil surface, or concentrated in rills and gullies of different dimensions.

Mass or landslide erosion generally affects soils with exceptional resistance to surface erosion due to the excellent structural and hydraulic properties of the surface soil (Pla, 1992b). Sometimes mass erosion occurs on the steep walls of gullies initially formed by surface erosion processes. Mass movements are generally initiated during and after concentrated and continuous precipitation events, and are associated with prolonged wet periods as a result of persistent antecedent rainfall, in soils with infiltration rates higher than internal drainage, which causes periodic saturation of the overlying soil. This erosion process is induced by the marked change in weight and consistence, decreasing cohesion among particles and microagregates, of the surface soil overlying a layer retarding drainage. This retarding layer may be a natural pedogenic pan, a lithic contact, or a compacted layer produced by inadequate tillage practices. The loss of cohesion and the fluid consistence after wetting close to saturation is more common in the surface layer of some soils like Ultisols and Andosols with very stable microagregates. The water in the saturated surface soil is under a hydraulic gradient (depending on water

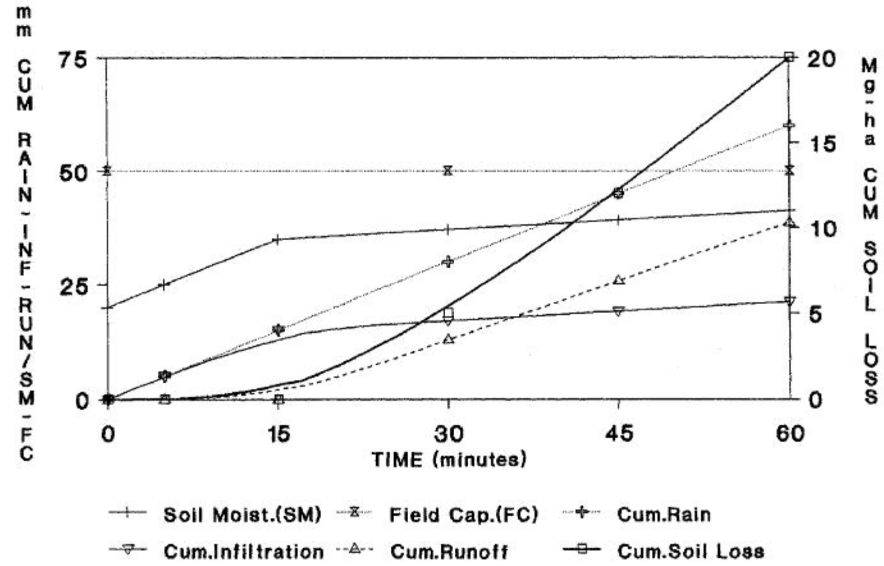


Fig. 1. Hydrology of a surface erosion process in a bare, tilled, sandy-loam Alfisol, originally dry and with a slope of 6%, under a simulated storm of 60 mm in one hour. There are shown the changes during the simulated storm of the cumulative rainfall (RAIN), infiltration (INF), and surface runoff (RUN), and of soil moisture (SM) in mm, as related to field capacity (FC); and of cumulative soil losses (SOIL LOSS) in Mg/ha during the simulated storm.

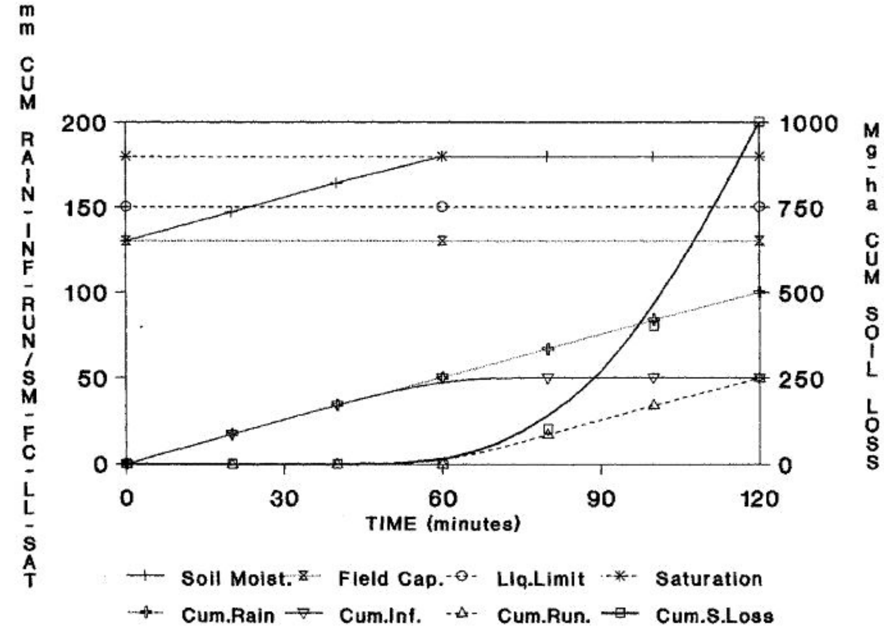
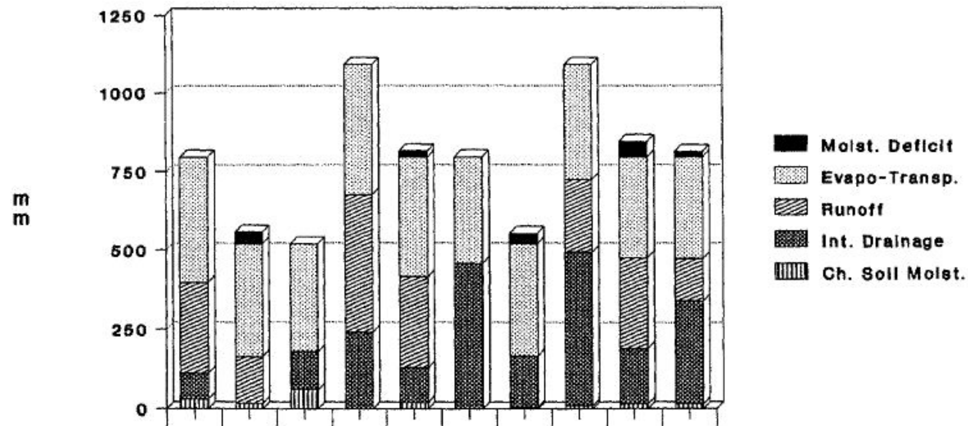


Fig. 2. Hydrology of a landslide erosion process in a bare, clay–loam Ultisol, originally at field capacity (FC), in a 50% slope, under a simulated storm of 100 mm in two hours. There are shown the changes in cumulative rainfall (RAIN), infiltration (INF), and surface runoff (RUN); and of soil moisture (SM) in mm as related to field capacity (FC), liquid limit (LL) and saturation (SAT); and of cumulative soil losses (SOIL LOSS) in Mg/ha during the simulated storm.



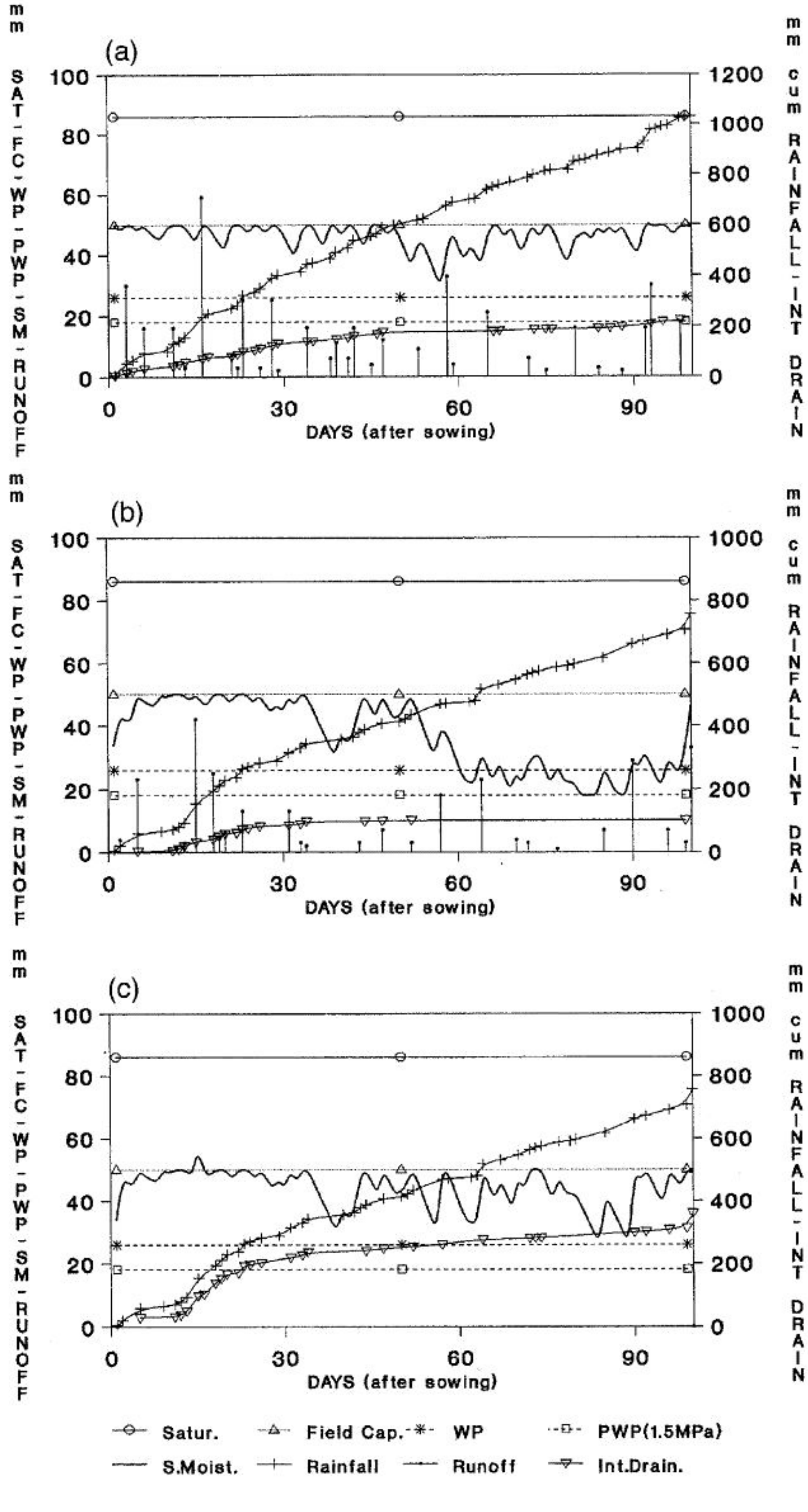
	40cm B A	40cm B L	40cm C L	20cm B H	20cm B A	20cm C A	20cm C L	10cm C H	10cm B A	10cm C A
Moist. Deficit	0	38	0	0	19	0	34	0	49	17
Evapo-Transp.	399	365	340	416	381	340	352	367	321	323
Runoff	285	147	0	436	285	0	0	233	285	133
Int. Drainage	82	0	118	240	109	454	162	482	174	324
Ch. Soil Moist.	30	17	61	0	21	2	5	10	16	16

Fig. 3. Water balance in the rooting zone during the growing period of sorghum, in a sandy-loam Alfisol, bare (B) or covered with plant residues (C), under high (H), average (A) and low (L) annual rainfall, and effective rooting depths of 10, 20 and 40 cm. There are shown, for each combination, the total volume in mm of the moisture deficit (Moist. Deficit), evapotranspiration (Evapo-Transp.), surface runoff (Runoff), internal drainage (Int. Drainage) and change in soil moisture (Ch. Soil Moist.).

supply and slope), and imparts lubrication to the underlying surface facilitating the sliding of the surcharged overlying soil material (Pla, 1992b). Change in weight and consistence of the surface soil cannot in themselves cause a landslide, but they do affect the susceptibility of a sloping land to triggering by some other factor, like earthquakes, removal of downslope (road cuts, etc) or lateral support (gullies, cracks, etc.) (Crozier, 1986). In natural forested areas the possibilities of landslides are generally much less than in clean cropped areas, and less than in pastures. Forests may have different stabilizing influences, but the main one is the mechanical reinforcement by tree roots, attaching potentially unstable surface soil to stable substrata, and providing a matted network which offers lateral attachment near the surface.

The potential hydrological processes in the surface soil leading to processes of surface and landslide erosion under simulated storms of 60 mm in one hour, and of 100

Fig. 4. Soil moisture regime in the rooting zone, during the growing period of sorghum, in a sandy-loam Alfisol with 6% slope gradient, bare, with an effective rooting depth of 20 cm, and under exceptionally high annual rainfall (return period (RP): 10 years) (a); bare, with effective rooting depth of 20 cm and under average annual rainfall (return period (RP): 2 years) (b); and covered by plant residues, with an effective rooting depth of 20 cm and an average annual rainfall (RP: 2 years) (c). There are shown the changes with time, in mm, of the soil moisture content at root depth as related to saturation (Satur.), field capacity (Field Cap.), wilting point at 0.15 Mpa (WP) and permanent wiltting point at 1.5 Mpa (PWP); cumulative rainfall, cumulative internal drainage (cum. INT. DRAIN), and daily surface runoff.


(a)
(b)
(c)
mm SAT - FC - WP - PWP - SM - RUNOFF
mm cum RAINFALL - INT DRAIN
DAYS (after sowing)
0
30
60
90
100
80
60
40
20
0
1200
1000
800
600
400
200
Satur.
Field Cap.
WP
PWP(1.5MPa)
S.Moist.
Rainfall
Runoff
Int.Drain.

mm in two hours, respectively, are shown in Figs. 1 and 2 (Pla, 1993). The return periods (RP) for the occurrence of such storms are 2 years (surface erosion), and 10 years (landslide erosion). The soil with surface erosion (Fig. 1) is a sandy-loam Alfisol with moderate slope (4–10%) (the same of Figs. 3 and 4), which under bare, dry and

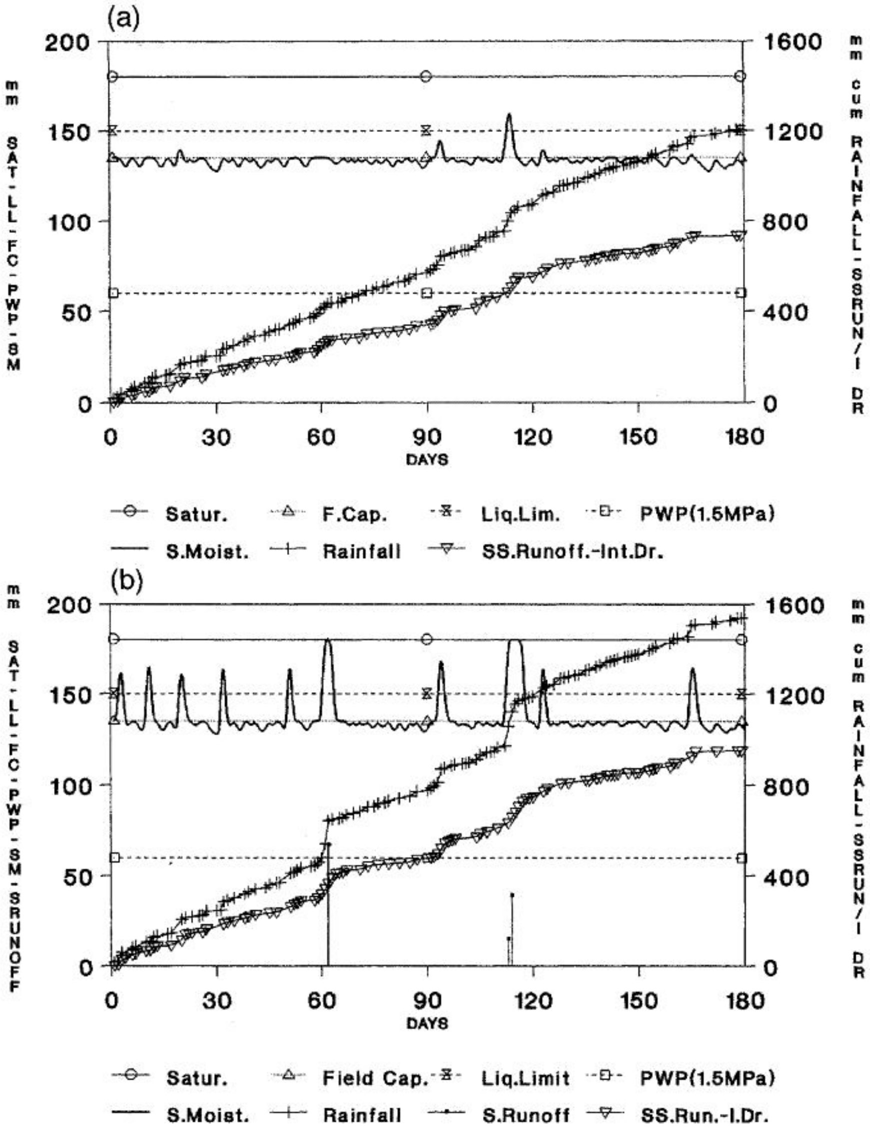


Fig. 5. Soil moisture regime in the surface 30 cm of a clay–loam Ultisol with 30–100% slope gradient, covered with overgrazed pasture, during the rainy season of a year with average total rainfall (return period (RP): 2 years) (a), and of a year with exceptionally high total rainfall (RP: 10 years) (b). There are shown the changes with time in mm of the soil moisture at 0–30 cm depth as related to saturation (SAT), liquid limit (LL), field capacity (FC) and permanent wilting point (PWP); of cumulative rainfall (cum. RAINFALL); of cumulative subsurface runoff + internal drainage (SSRUN-IDR); and of daily surface runoff (S. RUNOFF).

recently tilled conditions, receiving the direct impact of raindrops, suffers a fast surface sealing effect, with a drastic reduction in infiltration rate, resulting in concentrated runoff after 15 min. This low infiltration rate does not allow to reach field capacity in the surface soil (20 cm root depth) after the simulated storm of 60 mm. Soil erosion losses follow the same trend of surface runoff, reaching values in the order of 20 t/ha at the end of the storm. The soil with landslide erosion (Fig. 2) is a clay–loam Ultisol (the same of Fig. 5), with very steep slopes (30–100%), and a clay layer limiting internal drainage at 30 cm depth. The potential infiltration rates, higher than the average rainfall intensity during the simulated storm (50 mm/h), are much higher than the saturated hydraulic conductivity of the underlying (30 cm depth) soil. Under those conditions, and starting with a soil at field capacity, fluid consistence (liquid limit) and saturation of the surface 30 cm of soil are reached after 20 and 60 min respectively. After saturation, infiltration is reduced with possibilities of surface or subsurface runoff. Erosion soil losses, in the order of 1000 t/ha or more, occur as concentrated mass movement when the overlying soil reaches adequate fluid consistence (liquid limit to saturation) and overweight. Therefore, landslide erosion processes or mass movements in general, although occurring less frequently than surface erosion, may lead to much higher and more concentrated soil losses, with more dangerous offsite effects.

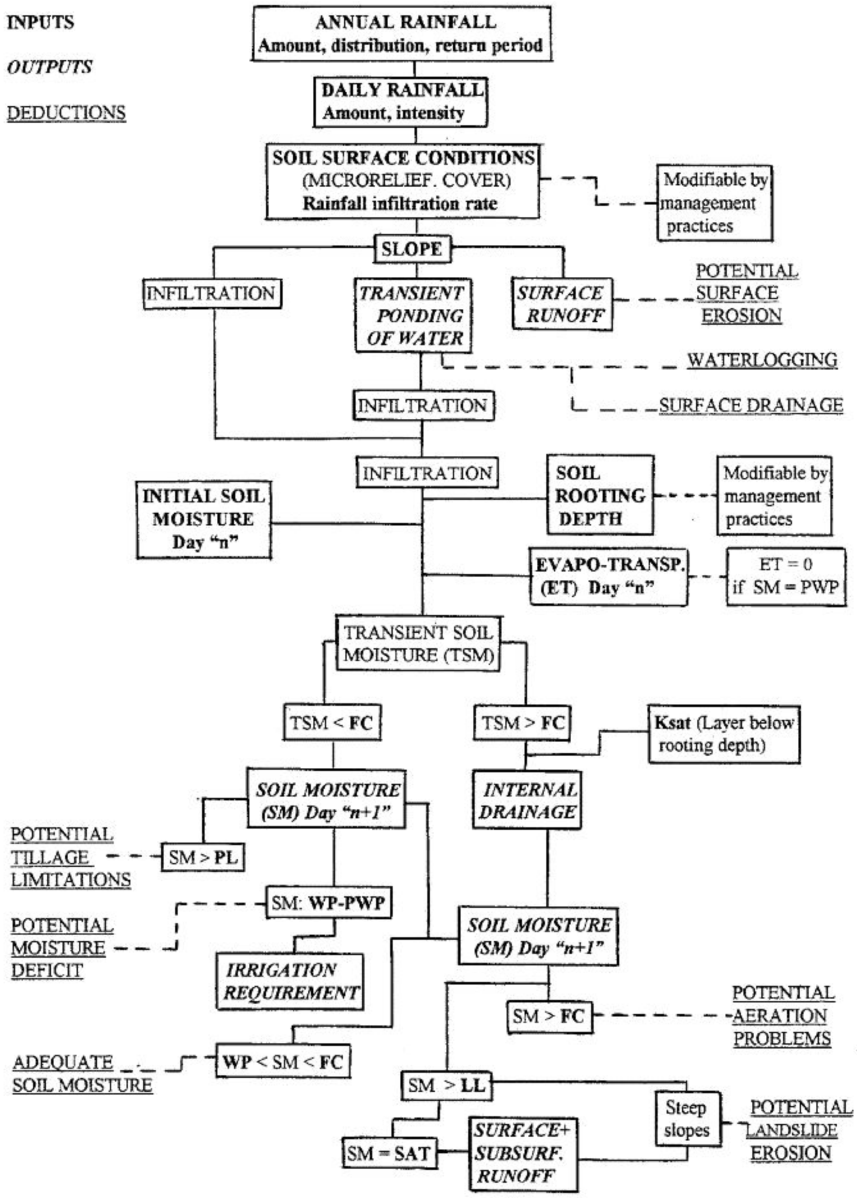
1.2. Evaluation and prediction of soil erosion processes and effects

The control of soil erosion processes, and derived effects, will depend on an appropriate land use and management planning. A prerequisite is an adequate identification and evaluation of erosion processes, and of the relations between cause and effect of the different problems. The processes of soil erosion, caused by the interactions of soil, rainfall, slope, vegetation and management, generally result on unfavourable changes in the soil moisture regime, and in the possibilities of root development and activity. Therefore, it is very important to select the right soil properties to predict the processes and effects of soil erosion, based on changes in the soil water balance caused by different crop and soil management systems. Simulation models may be very helpful to integrate and to convert the measured, or estimated, soil, climate, crop and management parameters, into predicted soil water balances (Pla, 1988; Pla, 1992b; Littleboy et al., 1992). They may be very simple, or they can be extremely complex requiring many resources (time, equipment, manpower) and input information which is seldom available, making less complex models often more suitable for practical purposes. Simulation errors, derived from estimation errors in soil properties, and the sampling costs, are generally lower when simple models are used to predict water balance in space (Leenhardt et al., 1994). Additionally, simpler models require fewer input data, and therefore allow larger samples and sampling densities for a given measurement.

In general there has been good progress in the understanding of the mechanisms and processes of detachment and transport in the soil surface erosion, but the knowledge about landslides and mass movements is much less. In tropical regions, direct measurements of soil water erosion is too costly and not practical, because erosion varies greatly in time and space (Pla, 1991). Therefore, the prediction of water erosion is presently generally done using mostly empirical, and much less process based models, combining climate, soil, topography and management. Among the empirical models, the one more widely used is the so-called Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), sometimes with adaptations to tropical conditions. In many cases, erosion plots and empirical models, designed for surface soil erosion studies and prediction, have been used, and are being used, to predict soil erosion processes and soil losses under conditions (soil, slope, climate) where most of the actual and potential erosion occurs, or may occur, as mass movements. Moreover, frequently there are recommended conservation practices effective to control surface erosion but counterproductive to control mass movements. There is not a fixed value of slope gradient above which mass movements are the most predominant erosion processes, but accurate field observations and the use of process-based prediction models, based on equations that represent fundamental hydrological processes, including rainfall, infiltration, drainage and runoff, may be more useful to identify the factors inducing different erosion processes, and to deduce the probabilities of surface or landslide erosion. To be applicable these models have to be based on fundamental or critical information, available or easily measurable, and on the use of probability of risk approaches (Pla, 1994). The objective, more than to predict quantitatively soil losses, which are also very difficult to measure directly, has to be to guide land use and conservation practices to prevent or to control accelerated erosion.

2. General description of the model SOMORE

The model SOMORE (Scheme 1) is based on a description of the more important hydrologic processes in soils, accounting for infiltration of rainfall into the soil as limited by sealing effects and limiting layers (natural or induced by management) close to the soil surface; and for internal drainage or subsurface runoff as affected by rainfall infiltration, effective root depth, and saturated hydraulical conductivity of the limiting soil layer. To make it applicable, some simplifications have been necessary in the formulation of the different hydrological processes, reducing the number of required input parameters from climate, soil and crops. SOMORE requires as basic inputs, before starting simulation, daily rainfall and potential evapotranspiration (measured or estimated), and the soil conditions having influence on infiltration rates, on runoff losses, on internal drainage, on soil moisture retention, and on root development. Such conditions are expressed through parameters based on field and laboratory measurements or estimates, using simple methodologies and equipment (Nacci and Pla, 1993), sufficiently accurate to cover the needs at the least possible cost. They include infiltration rates with or without sealing effect, effective rooting depth, and saturated hydraulic conductivity of the layer limiting root development or internal drainage. For the effective rooting depth the information required includes the water contents at saturation, at liquid limit, at field capacity or drained upper limit, and at permanent wilting point, which may be measured preferably under field conditions, or in the laboratory, or estimated through pedotransfer functions. The main output of the model is the soil moisture regime on a daily basis, including the average soil moisture at root depth, and water losses by runoff and internal drainage. The soil moisture is updated at one day (24 h) interval, depending on inputs of



Ksat: Saturated hydraulic conductivity, **FC**: Field capacity; **WP**: Water retention at 0.15 Mpa; **PWP**: Water retention at 1.5 Mpa; **PL**: Plastic limit; **LL**: Liquid limit; **SAT**: Saturation

Scheme 1. Flow diagram of the simulation model SOMORE (soil water balance in daily time steps).

rainfall and evapotranspiration, and outputs of runoff and internal drainage. Runoff is dependent on the relation between rainfall intensity, infiltration rate and water capacity of the soil overlying the limiting layer, affected or not by the sealing effect and slope gradient.

The predicted soil moisture regime may be interpreted in relation to problems of drought or aeration in the overlying soil, at different times and growth stages of natural vegetation or crops, and also in relation to erosion hazard by different processes. This interpretation requires a previous knowledge of the growing pattern of the particular crop, and its susceptibility to drought or poor aeration at the different growing periods, affecting vegetative growth and production. To preview the possible influences of different combinations of soil and water management on the soil moisture regime, there is required a previous identification and evaluation of the main critical factors affecting problems of soil erosion and of water supply to crops. The variable annual rainfall data, with a particular return period, are used to simulate the behaviour of a particular condition or management system in different years, and therefore, based on that previewed behaviour it is possible to select or to design, with a probabilistic approach, the best systems of soil and water management to control erosion. It is also possible to predict the soil erosion processes and effects, with different return periods of annual rainfall, for each condition or proposed land use and management. The selection of certain return periods is important, because they largely determine the requirements of management practices and conservation structures in relation to costs and benefits, for different levels and probabilities of risks. A particular season or year is described, or analyzed, in relation to the long-term variability, based on rainfall records from the past.

3. Examples of application

As examples of the application and possible output of the proposed approach, and of the water balance and soil moisture regime simulation model 'SOMORE', there are presented two situations with different soils, slopes, use and management, under tropical semiarid and subhumid climate in Venezuela. In both cases, most of the basic information on soils and climate to feed the computer simulation program was available. In one case (Figs. 3 and 4), the results were validated through data gathered in previous field experiments, carried on for six continuous years, to test the effects of surface soil conditioners on the soil moisture regime and on crop production (Pla, 1980, Pla et al., 1987, Pla, 1988; Pla et al., 1985; Pla et al., 1987), while in the second example (Fig. 5), the validation is only based on accurate field observations and measurements on site, and on historical evidences (Pla, 1993).

The first example (Figs. 3 and 4) refers to a sandy-loam Alfisol (US Soil Taxonomy) from the central rolling plains (4–10% slope) of Venezuela. The climate is tropical moist semiarid, with strong seasonal distribution and high variability of rainfall from one year to another, and in the same year. Cropping is reduced to rainfed grain sorghum (*Sorghum bicolor*), with a length of growing period (LGP) of 90–110 days. The plant residues are generally used as forage for cattle in the dry season. The main constraints for a high and sustained productivity have been identified (Pla et al., 1985; Pla, 1988) as soil moisture deficits and surface soil water erosion. Sealing effect on bare soil appear to be the main cause of concentrated runoff during intense storms, causing water and soil losses. The root growth is limited by the presence of an argillic B horizon at 20–40 cm depth, which gets closer to the soil surface, due to the accelerated erosion of surface soil, when the land is continuously cropped. Shallow (10–15 cm depth) clean tillage, using mostly disk harrow, also contributes to shallow root growth. The soil, in the selected site for the simulation, has a minimum infiltration rate of rainfall water of 80 mm/h when the surface is protected (mulch cover or plant residues) against raindrop impact, which decreases (sealing effect) to 8 mm/h in a recently tilled bare soil. The average saturated hydraulic conductivity of the B horizon is close to 2 mm/h. Average rainfall intensity of the main storms is generally higher than 60 mm/h.

In the calculation of the water balance components (Fig. 3) there were simulated the conditions of bare and mulch covered soil, and of rooting depths at 40, 20 and 10 cm, during the growing period of grain sorghum, in the rainy season of years with annual rainfall close to average (return period (RP): two years), exceptionally high (RP: ten years) and exceptionally low (RP: ten years). Fig. 3 shows the resulting water balances for various simulated combinations of those different climate, soil and management factors. It is clearly observed how the sealing effect (bare soil) would increase runoff (and potential surface erosion) especially as rainfall increases, and would create problems of water deficits, especially in drier years and with more restricted root growth. Shallower root growth and soil cover would increase water losses by internal drainage (percolation below root depth), and would increase the possibilities of subsurface runoff. Although high rainfall, and deep roots, prevent moisture deficits during the growing period of sorghum in bare soil, the high runoff, and therefore the high surface erosion hazard, will make that situation non sustainable, as it happens in reality. Fig. 4a–c shows the predicted influence on the soil moisture regime (SMR) of high (Fig. 4a) and average (Fig. 4b and c) rainfall, under bare (Fig. 4a and b) and covered (Fig. 4c) soil conditions, during the growing cycle of sorghum (1 June–20 September), with an effective rooting depth of 20 cm. The simulated SMR of Fig. 4a shows that in years with high rainfall there would not be water deficits, even in bare soil and shallow (20 cm) rooting depths, but concentrated runoff, specially in the first 1/3 of the growing period (with scarce canopy cover), will probably cause accelerated surface soil erosion, with offsite floodings and sedimentations effects in the lower areas of the landscape. Fig. 4b shows that under conditions of average rainfall, bare soil and shallow rooting depth (20 cm), the runoff and potential surface soil erosion may be more critical in the first 1/3 of the growing period, while water deficits are concentrated in the last 1/3, coinciding with the critical reproductive and grain filling period. Therefore, we may expect a relatively good vegetative growth, but reduced grain production. The effectivity of soil cover in preventing runoff (and potential soil surface erosion) and water deficits, even under average rainfall and with shallow rooting depth (20 cm) is shown in Fig. 4c.

As a conclusion, in this case the marked sealing effect on bare soil with moderate slopes, is clearly the main cause of concentrated runoff (30–50% of the rainfall in the rainy season), and of surface soil erosion and moisture deficits. Under those conditions, effective rooting depths below 30–40 cm may be critical for rainfed grain sorghum production, most of the years with average or lower rainfall. Therefore, land management practices would have to be directed to reduce surface runoff, maintaining the soil surface protected (mulch of crop residues or cover crop) mainly during the first 1/3 of the rainy season and of the growing period of sorghum; and if necessary to control runoff with conservation practices like strip cropping, surface soil conditioning, mixed cropping, ridges, terracing, etc. This would have to be complemented with tillage practices (deep plowing, chiseling, ridging) to favour deeper root development. The selection, or test, of the different alternatives would depend on the probabilities of risks of crop production or of soil erosion, and on the effects of the resulting water balance on the hydrology of the watershed, for each combination of factors.

The second case (Fig. 5a and b) is an example of how the simulation of the water balance and SMR, based on climate and the hydrologic properties of the surface soil and underlying layers, may be used for identifying and predicting soil erosion by mass movements. The soil selected for the simulation is a clay–loam Ultisol (US Soil Taxonomy) in the Western Andes of Venezuela, with very steep slopes (30–100%), and under a tropical subhumid climate. In natural conditions it is covered by a dense forest, which is being increasingly substituted by pasture land (generally overgrazed) and shifting agriculture. The main identified problem is accelerated erosion concentrated in large gullies, mainly in the deforested grazed land, creating large sedimentation in a dam used for generation of hydroelectricity in a lower part of the watershed. Soil erosion occurs mainly through landslides, which has made inefficient the control of gullies with the traditional intercepting dams.

The surface soil, with very stable aggregates, do not show any sealing effect, and maintains a minimum infiltration rate of at least 90 mm/h. At about 30 cm depth there is an argillic B horizon, where roots of the original trees are able to grow. After deforestation, and with overgrazing, the grass roots are concentrated in the 10–20 cm surface soil, and the saturated hydraulic conductivity of the B horizon decreases to about 1 mm/h. Under those conditions, the simulated SMR (Fig. 5a) during the rainy season of most of the years (average rainfall) shows that the surface 0–30 cm soil is maintained at moisture close to, and slightly higher than field capacity, most of the time. But in exceptionally rainy years (RP: ten years) (Fig. 5b), the concentration of rainfall (large amount and repeated storms) in some periods increases to, and keeps the soil moisture above liquid limit, reaching saturation in many cases, and causing some surface runoff, but mainly concentrated subsurface runoff. These conditions are the most favourable for landslides and mass movements (Pla, 1993) in those very steep lands. It is clear that in this case the main causes of water erosion and runoff (surface and subsurface) are not the surface sealing effects reducing infiltration, but instead the sharp differences between the high potential infiltration rate and the saturated hydraulic conductivity of a shallow layer, accompanied by high and concentrated rainfall, in soils where the anchorage and beneficial effects on the permeability of the B horizon by deep roots of trees in the original forest have been lost after deforestation (Pla, 1993). The use of dikes or dams alone to control gullies is not effective under these conditions, because they are easily covered by landslides from the steep walls of the gullies. The reclamation and conservation of those lands would require, besides reforestation and overgrazing control, the building of terraces, with drainage ditches, at intervals across the slope to intercept and discharge safely the subsurface (and surface) runoff, together with vegetation barriers of plant species with roots capable of growing into the shallow argillic B horizon. The probabilities, or return periods, for reaching conditions inducing landslides, as well as the previewed volume of subsurface (and surface) runoff, may be used for the design of those drainage terraces.

4. Conclusions

It is clearly shown that the identification and monitoring of different soil erosion processes in steep lands, including surface and landslide erosion, and their effects, may be better done by adequate modeling of the soil hydrological processes. This modeling leads to the simulation of the evolution of the soil water balance in the soil profile under the prevailing conditions of topography, climate, management and cropping. This requires an appropriate selection of input parameters having a critical influence on those processes. Although further testing and validation are required, the soil water balance simulation model SOMORE has the advantage of being based on easily available, or easily measurable, input parameters. Furthermore, the output of the model may be used for guiding the selection of the best alternatives, with more probabilities of success, of use and management of soil and water resources, for each combination of soil, climate and topography, to prevent, or to control water erosion. It is also demonstrated how under climate, soil and slope conditions favourable for landslide or mass erosion processes, the proposed approach and model SOMORE may be applied for prediction of the occurrence and impact of those particular erosion processes, very common in steep lands of the tropics, which have not been considered in previously used soil erosion models. Up to the conditions where it has been tested, this model has produced fairly accurate simulations, but the accuracy of the predictions is mostly dependent on how good and complete are the estimations or direct measurements of the required climate and soil parameters, taking into consideration their spatial and temporal variability.

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