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HYDROLOGICAL APPROACH TO SOIL AND WATER CONSERVATION

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INTRODUCTION

The main world environmental problem is the degradation of the soil and water resources, mostly associated to the growing agricultural, urban and industrial developments. This degradation is affecting, directly or indirectly, all the vital processes on the world earth surface, depending on the conservation of soil and water in adequate places, amounts and qualities.

Soils play a very important role in the hydrological cycle. They are one of the main reservoirs of fresh water, and transform discontinuous and erratic rainfall sources of water into a continuous supply of water to the roots of plants and continuous discharges of water to groundwater, streams and rivers. Continuing shrinkage of quality water supplies for different uses (human consumption, irrigation, etc) points out the importance of water conservation besides soil conservation (Hurni et al, 1996). An integrated approach in the conservation of soil and water is further justified by the close relationship between soil and water quantity and quality (El-Swaify, 1996)

The soil moisture regime, determined by the changes in soil water content with time, is the main single factor conditioning plant growth and crop production. This will also depend on the possibilities of use by plants of the water stored in the soil, which is determined by the possibilities of access of roots to the soil depth where water remains available for plant use during the different plant growing periods. That will be mainly conditioned by soil properties affecting the capacity and possibilities of infiltration, retention and drainage of rainwater, and the limitations to root growth under the particular rainfall characteristics. These conditions may be modified through soil and plant management practices, including tillage, irrigation, drainage, date of sowing, etc.

The other main functions of soil, as regulator of the water cycle and environmental filter are also vitally affected by the soil moisture regime. Hydrological processes determine the transport of water soluble materials and pollutants occurring naturally or human derived. Naturally occurring constituents within the soil are mobilized and transported as a result of the infiltration and flow of rainfall and irrigation water. Pollutants are partially retained, released and transformed in the soil before reaching ground waters. Therefore, the quality of water resources may be greatly influenced by soil hydrological processes..

Soil properties, and specially physical properties, present a high variability, both vertically and horizontally, and they are submitted to continuous changes under natural conditions, and particularly with the man intervention. When those changes affect negatively the soil conditions for plant growth or crop production, or for other previewed uses or functions, or when it becomes necessary to apply more inputs to sustain those uses or production, we refer to them as soil degradation processes.

The processes of soil degradation start with the degradation of the soil structure, specially of the functional attributes of soil pores to transmit and retain water, and to facilitate root growth (Lal et al, 1989). The deterioration of those attributes is manifested through inter-related problems of surface sealing and crusting, soil compaction, impeded root growth, poor drainage, frequent drought, excessive runoff, and accelerated water erosion. Water, that is often the main limiting factor of plant growth, is also the main factor directly or indirectly responsible for soil and land degradation processes.

The main factor attempting against the sustainability of agricultural production is soil and land degradation. Also of growing importance are the offsite effects of land degradation on increased risks of catastrophic flooding, sedimentations, landslides, etc, and on global climate changes. Although land degradation is affected by soil and climate characteristics, it is mainly due to inappropriate use and management of the natural resources soil and water, generally imposed by social and economic pressures. The processes of soil degradation caused by soil-climate-management interactions, generally result on unfavourable and some times drastic changes in the soil hydrological processes.

The problems of soil and water degradation, and derived effects are increasing through the world. This is partially due to a lack of appropriate identification and evaluation of the degradation processes and of the relations cause-effects of soil degradation for each specific situation, and the generalized use of empirical approaches to select soil and water conservation practices. The main soil and water degradation processes include soil water erosion (surface and mass movements), soil sealing and crusting, soil compaction, soil and water salinization and sodification, and soil and water pollution. In addition to the negative effects on plant growth and on productivity and crop production risks, soil and land degradation processes may contribute, directly or indirectly to the degradation of hydrographic catchments, affecting negatively the production of hydroelectric power, and the quantity and quality of water supply for the population and for irrigation or other uses in the lower lands of the watershed. Catastrophic flooding, sedimentations and landslides are also rooted on accelerated land degradation.

The processes of soil and water degradation are closely linked through unfavourable alterations in the hydrological processes determining the soil water balance and the soil water regime. They are also conditioned by the climatic conditions and by the use and management of the soil and water resources. Although the close interaction between the conservation of the soil and water resources is increasingly being accepted, still in most of the cases they are evaluated separately, and consequently the prediction and prevention of the effects derived from their degradation are inadequate in many situations. This will become more important under the previewed effects of global climatic changes, which would mainly affect hydrological processes in the land surface, mostly related to the field water balance (Varallyay, 1990).

Global climate change prediction, although still rather uncertain, will increase rainfall in some regions, while others might become drier, in a rather uneven spatial and time distribution. This may contribute to accelerate some land degradation processes leading to larger runoff and erosion, and to increased risks of flooding, landslides, mass movements and mud-flows in tropical regions, and to higher risks of crop production in subtropical and temperate regions. But in any case, land use changes, including deforestations, and other human activities leading to soil degradation processes may affect more the soil hydrological processes and their effects on land degradation, than the previewed global climatic changes, or may increase the influence of these changes. A good example of this influence of human activities on the effects of events supposedly associated to global climatic changes, are the increased incidence in the last decade of catastrophic flooding, sedimentations, landslides, etc in tropical and subtropical regions of the world, where population pressures and social and economic factors have led to large deforestations and drastic changes in land use and cropping practices. By the contrary, adequate land use and soil and crop management practices may make soils more resistant against the effects of climate changes and derived extreme events.

INTERACTION OF SOIL HYDROLOGICAL AND DEGRADATION PROCESSES

The top layer of the soil is the one supporting most of the plant growth, and also the part with higher direct interactions with climate and vegetation, and more influenced by human activities. Climate is probably the main variable that influences, directly or indirectly the topsoil, and particularly the surface layer. Other surface processes are caused by the properties of the soil itself.

Unprotected soil surface is exposed to the direct impact of raindrops, causing disruption of soil aggregates and sealing and crusting effects. Sealing effects make reference to sharp decreases in water infiltration rates under wet conditions, while crusting effects refer to seals that have dried and hardened, offering resistance to seeding emergency. Surface seals are thin soil layers with lower - sometimes by several orders of magnitude - saturated hydraulic conductivity than the underlying soil.. The most important effect is the reduction in infiltration rates which may result in runoff and erosion, and inefficient use of rainwater in sloping lands, and plant injury due to water logging and reduced exchange of gases in flat lands. Although the hydraulic properties of the plow layer and deeper soil horizons are often used as a basis for deducing infiltration, in lands with scarce cover, infiltration and runoff are determined more by the changing soil surface conditions, than by internal soil physical properties. The amount of surface soil removed by runoff water depends to a large extent on the resistance of soil aggregates to be disrupted by the energy of raindrop impact.

When sealing effects decrease infiltration and cause runoff, it is necessary to distinguish the rainfall data from the amount of water that really enters the soil and contribute to the available soil moisture and internal drainage. This is very important both in agronomy and hydrology. The analysis of the genesis of soil surface seals is also basic for the understanding of soil surface erosion processes. Runoff induced by seal formation not only poses a problem with respect to soil erosion, but it is also water lost for storage of plant available water in the root zone, which my cause periods of water deficit for the plant, depending on the soil rooting depth and rainfall regime. In order to optimise the use of rainfall water and to control surface soil erosion, land and soil management practices have to be effective in reducing runoff and erosion, by imparting structural stability to the soil, improving water storage characteristics and reducing sealing. Protecting the soil surface with residues or cover crop against the impact of rainfall, and maintaining high levels of soil organic matter (SOM) in the surface soil, are the most effective methods of avoiding surface sealing. A possible negative consequence of better infiltration , is the possibility of increased losses of water through the soil profile as internal drainage, and the possibilities of larger transfer of pollutants from the soil to the groundwater.

Root growth is frequently restricted by excessive soil compaction. Compaction implies a decrease in volume, or increase in density, as a soil response to external forces. The result is a reduction in pore volume, and changes in pore size distribution, affecting air capacity and gaseous exchange, water retention, hydraulic conductivity, soil strength, and mechanical impedance to root growth. Compacted layers limiting root growth and water percolation may be natural or man induced. Excessive soil compaction by man activities is many times associated to the use of heavy machinery for tillage and other mechanical activities, and to more intensive land use. Shallow compacted layers generally become limiting barriers for root development and for deep percolation and drainage of excess infiltrated rainfall (Pla, 1990). This may affect directly plant growth and crop production, and indirectly increase the risks of soil erosion, water logging, and water runoff losses. In some situations compacted layers close to the soil surface may be loosened by tillage to enhance root duration of the effective rainfall period, and consequently to the availability of soil water, which determines the possibility of successful establishment and sustainability of the cropping systems. The adverse effects of drought can be effectively minimized by selecting plants, crops and cropping systems with duration that match the secure moisture available period. Adequacy of moisture determines - when temperature is not limiting - the length of the growing period (LGP). There have been proposed different approaches to define the length of the growing period (Monteith and Virmani, 1991; FAO 1981, 1984). The ones based on water balance models appear the ones more adequate to predict the reliability of the water supply for a plant during its growth, but most of them do not yet adequately consider surface sealing effects on water intake, water logging and runoff, and the effects of limiting shallow soil layers, natural or man induced, on root penetration, water retention at field capacity, and internal drainage.

Figures 1-4 show how the LGP (assuming no temperature and internal drainage limitations) in sloping lands would be influenced by the climatic conditions (rainfall and potential evapotranspiration), the distribution between infiltration and runoff (% of rainfall lost by runoff), and the soil storage capacity (available water capacity, determined by the effective rooting depth and water retention properties of the soil), for climates going from semiarid to humid. It may be seen that as the sealing effect increases (increasing % runoff), the influence of the rooting depth (AWC) on the LGP decreases, being completely masked

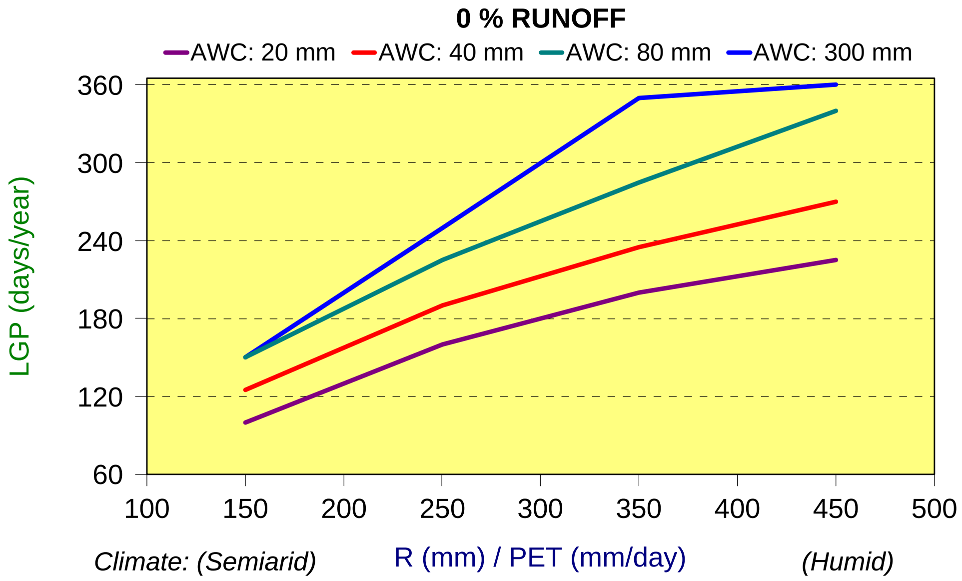


Figure 1

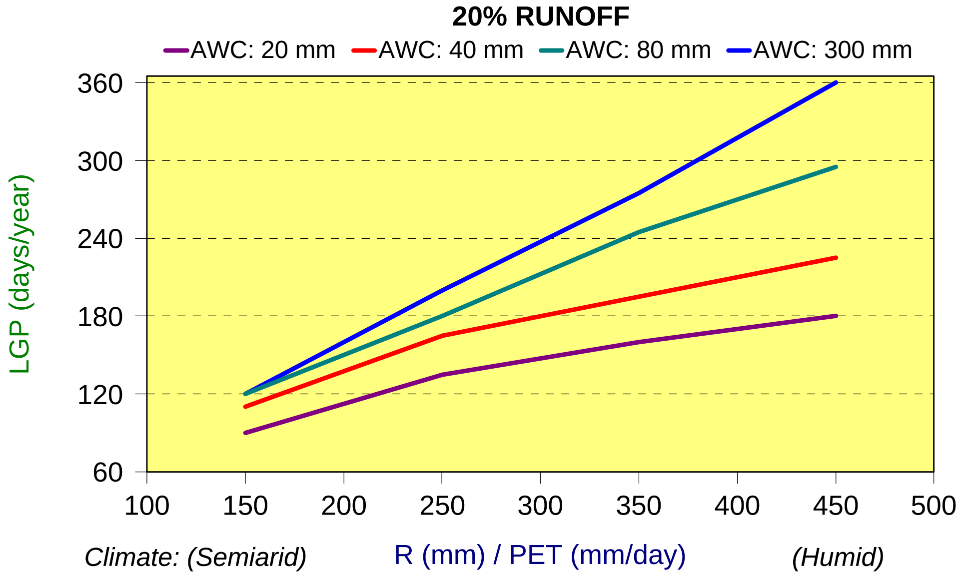


Figure 2

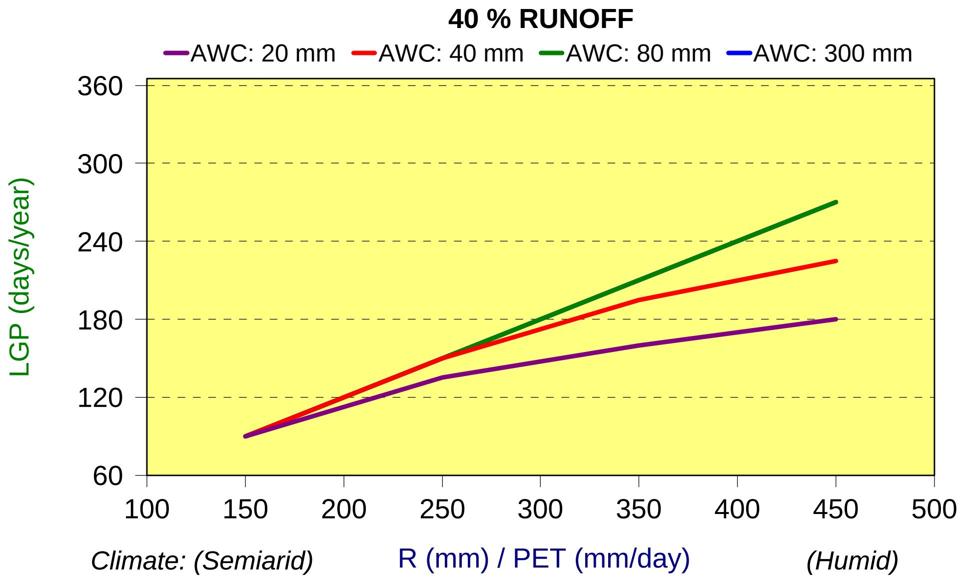


Figure 3

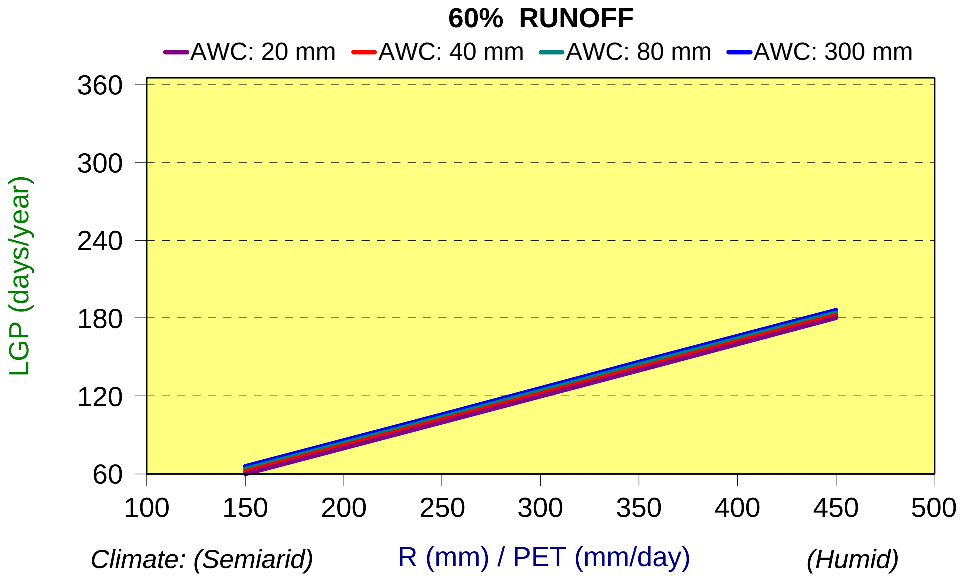


Figure 4

when runoff reaches 60% (Fig. 4). It is clear that the runoff and effective soil water capacity components of the water balance, both highly affected by soil degradation processes, cannot be neglected in the evaluation and prediction of the effects of those processes on water conservation and potential plant growth and crop production.

Among the different land degradation processes, soil water erosion is the major threat to the conservation of soil and water resources. The processes of soil erosion, caused by the interactions of soil, rainfall, slope, vegetation and management, generally result on, or there are caused by unfavourable changes in the soil water balance and in the soil moisture regime, and in the possibilities of root development and activity. Soil erosion processes have direct negative effects on plant growth and crop production, and offsite effects on increased risks of catastrophic floods, sedimentation, landslides, etc. Erosion is exacerbated by deforestations, by introduction of seasonal crops leaving the soil unprotected, by intensification or abandonment of agriculture, by overgrazing, and by improper maintenance of plantations and conservation structures. Besides surface erosion in gentle to moderate slopes, mass movements and landslide erosion are common in more steep slopes (Pla, 1992; 1993). In surface erosion, the soil particles detached by rainfall or running water, are transported by surface flowing water (surface runoff). Mass movements are the gravitational movements of soil material without the aid of running water (El-Swaify and Fownes, 1992; Crozier, 1986). The hydrological processes leading to surface or landslide erosion are different (Pla, 1992, 1997), and therefore, soil conservation practices very appropriate for controlling surface erosion processes may increase erosion danger by mass movements under specific combinations of climate, soil and slope.

Surface erosion is linked with intense precipitation events, high detachability of surface soil material and reduced infiltration. This reduction is induced by poor and week 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 down slope 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 excellent structural and hydraulic properties of the surface soil (Pla, 1992). Sometimes mass erosion occurs on the steep slopes 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 (Pla, 1997). This erosion process is induced by the marked change in weight and consistence, decreasing cohesion among particles and microaggregates, of the surface soil overlying a layer retarding internal 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 microaggregates. The water in the close to saturation surface soil is under a hydraulic gradient (depending on water supply and slope), and imparts lubrication to the underlying surface facilitating the sliding of the surcharged overlying soil material.

In deeper unconsolidated sedimentary or volcanic materials or in deeply weathered rocks, with decreasing permeability with depth, the accumulation of internal drainage water below the surface soil cover may lead with time to potential conditions for larger and deeper mass movements. Change in weight and consistence of the surface soil, or deeper materials, 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 down slope (road cuts, etc) or lateral support (gullies, cracks, etc). In natural forested areas the possibilities of shallow landslides are generally much less than in clean cropped areas, and less than in pastures. Forest 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. 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 (Pla, 1997), with more dangerous offsite effects.

The benefits derived of irrigation of agricultural lands frequently there are not sustainable due to salinization or development of salt affected soils. Soil salinization processes may lead to the partial or complete loss of the soil productive capacity, causing an internal degradation of their chemical and physical properties. Although the area affected by human induced soil salinization is much less than the areas affected by soil erosion processes, this soil degradation process is also very important from the economical, social and environmental points of view, taking into consideration the high costs of irrigation development, the high use of increasingly scarce water resources, and the high relative contribution of irrigated lands to local or world food production. The increasing contribution of drainage waters from irrigated lands to other environmental problems, like water logging in lower lands and contamination by salts, nitrates, and other pollutants coming from organic or inorganic products used in irrigated fields, is another important factor to be considered.

The introduction of irrigation causes drastic changes in the regime and balance of water and solutes in the soil profile. The salinity problems appear as a consequence of salt accumulation in zones and depths where the soil moisture regime is characterized by strong losses of water by evaporation and transpiration and by reduced leaching of the remaining salts. The problems of secondary salinization are a consequence of non adequate water management by irrigation and drainage, under a particular set of conditions, including climate, crops, soils, fertilization, groundwater depth, water quality and irrigation system.

The excess of water required to leach salts from the soil, to reclaim or to prevent salinization, may cause other environmental problems derived of the disposal and further use of that water. The problem is aggravated because those leachates may contain not only natural salts, but also residues of fertilizers and pesticides - which are generally used in large amounts in intensive irrigated agriculture), and other pollutants contained or derived from animal wastes and composted materials used as amendments, and from partially or non treated urban and industrial effluents used for irrigation. They may contaminate surface or groundwater waters to be used for human, industrial or agricultural purposes. In those cases, the practices and systems of drainage and irrigation must pursue a maximum efficiency in the use of irrigation water, reducing the possibility of losses and contamination of other waters, but keeping at the same time the salts at depths not reached by the crop roots.

EVALUATION AND PREDICTION OF SOIL HYDROLOGICAL AND DEGRADATION PROCESSES

Available information, technical manuals, supporting literature, concepts and theoretical approaches to preventing or reclaiming soil degradation are impressive in both amount and diversity, but with very new approaches. Based on that high amount of "information" it is said that on the technical level we already know more than we use, but soil and water degradation problems continue to escalate. This is partially due to the non consideration of a quantitative hydrological approach to the evaluation of soil and water degradation processes, and the use of mainly empirical approaches for such evaluation. An hydrological approach to the evaluation and prediction of the conservation of soil and water against degradation processes would be essential for an adequate development, selection and application of sustainable and effective land use and management practices. The main objective must be to evaluate such hydrological processes, and to select and develop methodologies and techniques to correct or to control them under different conditions of soils, topography and climate. This is required for suppressing or alleviating the negative effects of soil and water degradation on plant growth, on sustainable agricultural production, on the supply of water in adequate quantity and quality for the different potential uses, and on catastrophic events such as flooding, sedimentation, landslides,etc.

Relationships between soil physical characteristics and soil hydrological properties are the beginning point to simulate or to predict dynamic soil degradation processes and their effects. Standard soil profile descriptions in the present soil surveys are more oriented toward taxonomic grouping, with observations and measurements of long lasting features. Most of the important soil physical characteristics - specially from the surface soil - required for the assessment of soil degradation processes are overlooked at that point. Sometimes there are used pedotransfer functions, to translate trough mostly empirical relationships, the basic information collected in soil surveys into soil properties. Although soil hydraulic properties are correlated to simply obtainable data - texture, bulk density, SOM - a detailed study of the mutual relationships in a given region is indispensable and the results are not simply transferable to other regions and soils (Kutilek, Nielsen). In any case it has to be preferred direct measurements and estimations of soil hydraulic properties, preferably in situ.

Recently there have been attempts to use soil quality attributes and indices to evaluate the vulnerability of soils to degradation processes, and the potential effects, mainly in sustainability of crop production. Although the original proponents of the soil quality paradigm (Larson and Pierce, 1991) suggested a rigorous approach to soil attributes qualification, soil quality assessments have been using in many cases mostly subjective perception and unquantifiable, even unresearched measurements (Sojka and Upchurch, 1999). The use of soil quality indices, scored from empirical judgements, generally narrow in scope and with a taxonomic bias, do not allow to relate the evaluation to the overall sustainability of alternate land use systems (production, control of environmental impacts, etc). This would be only possible if they were based on clear and objective hydrological principles and quantitative measurements or estimations of hydrological parameters, aimed at problem solving. It is necessary to take into account that in most of the cases management can have more impact on a soil's ability to function, than intrinsic soil properties.

Methodology for an adequate quantitative characterization and prediction of the affected soil hydrological properties is required to evaluate the actual problems and to assess the vulnerability of soils to different degradation processes. Besides measurements under precise conditions in the laboratory, useful for understanding the hydrological processes, these have to be approximately quantified at field scale. If we intend to use the hydraulic functions to predict or to solve field problems, it is preferable to estimate them from field measurements and experiments. In structured soils, sampling and laboratory measurements are some times more difficult and time consuming than field measurements. Most of the results of experiments with repacked core samples cannot be directly transferred to quantify soil water behaviour in the field. But field measuring techniques are often less accurate and more expensive than in the laboratory, because it is often difficult to rigorously establish boundary conditions, which fluctuate in space and time. This accuracy may be increased with a larger number of directly field-measured hydraulic properties. The objective has to be obtain approximations acceptable within the limitations of the used methodologies, which can provide practical guidelines for field situations.

The methods and techniques applicable for predicting soil hydrological behaviour under field conditions should allow simple and direct measurements, based on comprehensive physical relations, and should take into consideration the dynamic aspects of the soil hydrological properties, highly dependent on soil structure (Pla, 1990). They include from simple, straightforward field techniques, usually providing rough estimates of soil hydraulic properties, to rather complicated techniques for more accurate time consuming measurements, requiring sophisticated skills and costly equipment. The simple field techniques must be preferred (Pla, 1990), because of operational considerations, and because they are more able to be adapted to the required sample volume and spatial variation - there are possible more replicate measurements- of soil hydraulic properties under field conditions. Although modern indirect techniques like remote sensing, computerized data processing, GIS and simulation models may help in the required evaluations, they will always require of actualised and accurate direct measurements or estimations of soil hydraulic parameters. Specially needed are better and simpler methods to monitor important hydraulic properties of soils and their dynamics on a field scale, for both diagnostic and prediction purposes, These properties should be also quantified in terms of the dynamic action of root growth (Larson and Pierce, 1994). As an example of these kind of methodology, rainfall simulation could be used very efficiently both at field and laboratory levels, for reliable studies where the main objective is to get comparative approximations of the influence of different conditions of soil, rainfall, and treatments on the dynamics of the soil hydrological properties affecting infiltration and mechanical resistance of the surface soil, and runoff (Pla, 1981; Meyer, 1994). In that way, rainfall simulators may be, and have been, very useful tools for acquiring data that can be analysed to test hypothesis, to quantify parameters for modelling, and in general to provide information of great interest for conservation-effective actions.

It is generally accepted that for evaluation and prediction of land degradation there are required long-term experiments on a catchment's basis. Although this would be desirable, it is not possible if required short-term solutions, as it is usually the case. There are required new approaches based on the evaluation of soil hydrological properties together with historical rainfall records, under different scenarios of changing climate, soil properties, topography and land and crop management (Pla, 1998). Research on soil degradation has to concentrate more on hydrological and soil degradation processes for interpretation of land degradation problems, with the help of computer-based programs that can be applied to different environments (Pla, 1998). This process-based approach makes the extrapolations more soundly based, and may allow to select or to develop a more adequate package of technologies to reduce soil degradation, while being social and economically acceptable. In any case it is desirable to keep the information that must be obtained simple, so that basic objectives can be achieved (IBSRAM, 1995). Pressures to change sustainable traditional systems of use and management of land resources must be considered additional parameters (social economic factors) to the biophysical factors in soil degradation processes.

BASIS FOR MODELING HYDROLOGICAL PROCESSES RELATED TO SOIL DEGRADATION

The increased requirements of more quantitative results in probabilities and risks of soil degradation and its influence on crop production and environmental damage (Pla, 1994), may be partially satisfied with the use of modelling, where the large number of important variables involved in the degradation processes, and their interactions, may be integrated. Modern computer technology permits to store, process and to interpret a large amount of data on soils, climate and crops.

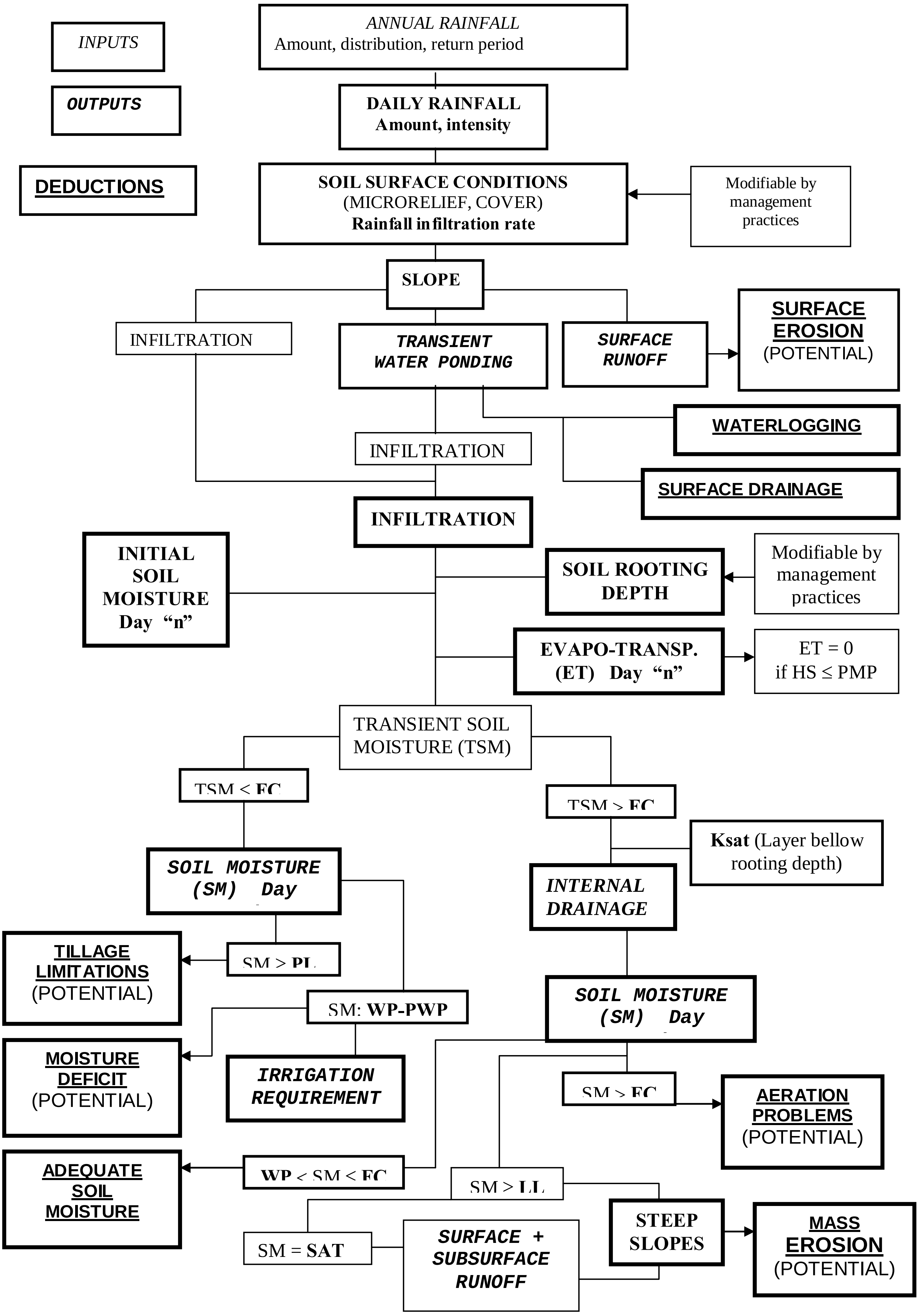
Modelling soil degradation is the process of mathematically describing the relations cause-effects of soil changes leading to soil and water degradation. These models can be used as predictive tools of soil and water degradation for conservation planning, and as tools for understanding degradation processes and their interactions, and for setting research priorities (Nearing et al, 1994). Research must be directed to produce useful models for predicting the impact of changes in use or management practices on water and soil conservation, on sustainable productivity and on off-site effects, as a required step previous to the evaluation, validation and final selection of economically and environmentally appropriate technologies, acceptable by land users.

Direct measurements of runoff and soil loss in the traditional erosion field plots, generally associated to get some of the inputs required by the so called Universal Soil Loss Equation (USLE) (Wishmeier and Smith, 1978), is a slow and costly process, due to the high variability of climate and soils in time and space, which makes it not practical in places where the resources are scarce and there are required short term solutions (Pla, 1991). Therefore, the prediction of water erosion is presently generally done using mostly empirical, and much less process based methods and models. Among these, the USLE, and its derivatives and adaptations, has been by far the most widely used worldwide. These models require local information not available in many cases, which frequently is being substituted by information generated through sub models and regression equations developed under conditions very different to the ones where they are applied. These may lead to great errors in the prediction of soil erosion and selection of conservation practices, with catastrophic results and economical losses in investments and conservation structures.

The presently used empirical models must be replaced with process based event models, which require a better understanding of changing hydrological properties as influenced by soil management, cropping sequences, vegetation, and climate (Foster and Lane, 1987). These models must allow a detailed quantification of hydrological processes for both actual and potential conditions, answering major questions about problems of soil degradation and crop production, related to different alternatives of land management (Pla, 1997a; 1998). While they are developed, the main benefit of these models is the identification of gaps of knowledge and data, and the understanding of the degradation processes. Process-based prediction models, based on equations that represent fundamental hydrological and erosion processes, including rainfall, infiltration, drainage and runoff, may solve the limitations of the empirical soil loss prediction models, like site specifity, limited transferability and others.

Simulation models based on hydrological processes may be very helpful to integrate and to convert the measured or estimated soil, climate, plant and management parameters into predicted soil water balances and soil moisture regimes for each particular combination of them, actual or previewed. These models may be very simple, or they can be extremely complex, requiring many resources (time, equipment, manpower) and input information which is seldom available, or difficult to determine, or non representative, 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 for predicting water balance in space (Leenhardt et al, 1994). Additionally, simpler models require fewer input data, and therefore they allow larger samples and sampling densities for a given field measurement.

The models used in predicting crop performance, and soil degradation processes derived of the impact of land use and management practices in the soil hydrology, must include weather (mainly rainfall) variability in space and time, and soil properties and their spatial variability. The required data about soil properties are those influencing water entry and retention in the soil, limits of water retention capacity of the soil, loss of water by evaporation, and environment for root growth. Methods to approximate the needed soil properties from existing soil taxonomic data have been proposed when there are no possibilities for direct measurement of those soil attributes. But when the used correlations have not been obtained or validated in situ, the possibilities of large errors in the output of the models are very high. The weather data required for modelling are the ones influencing potential water supply to the plants and to runoff and evapotranspiration. These include daily values of rainfall, and monthly values of solar radiation and of maximum and minimum temperatures. When long term weather records or daily rainfall are not available, an alternative procedure, would be to use stochastic time-series modelling, to generate a sequence of weather data similar to historical sequences (Ritchie et al, 1990).


INPUTS
OUTPUTS
DEDUCTIONS
ANNUAL RAINFALL
Amount, distribution, return period
DAILY RAINFALL
Amount, intensity
SOIL SURFACE CONDITIONS
(MICRORELIEF, COVER)
Rainfall infiltration rate
Modifiable by management practices
SLOPE
INFILTRATION
TRANSIENT WATER PONDING
SURFACE RUNOFF
SURFACE EROSION
(POTENTIAL)
WATERLOGGING
INFILTRATION
SURFACE DRAINAGE
INFILTRATION
INITIAL SOIL MOISTURE
Day "n"
SOIL ROOTING DEPTH
Modifiable by management practices
EVAPO-TRANSP. (ET) Day "n"
ET = 0
if HS ≤ PMP
TRANSIENT SOIL MOISTURE (TSM)
TSM < FC
TSM > FC
Ksat (Layer bellow rooting depth)
SOIL MOISTURE (SM) Day
INTERNAL DRAINAGE
TILLAGE LIMITATIONS
(POTENTIAL)
SM > PL
SM: WP-PWP
SOIL MOISTURE (SM) Day
MOISTURE DEFICIT
(POTENTIAL)
IRRIGATION REQUIREMENT
SM > FC
AERATION PROBLEMS
(POTENTIAL)
ADEQUATE SOIL MOISTURE
WP < SM < FC
SM > LL
STEEP SLOPES
MASS EROSION
(POTENTIAL)
SM = SAT
SURFACE + SUBSURFACE RUNOFF

(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 a simplified hydrological model to predict the soil moisture regime and potential soil degradation processes (Pla, 1997a)

The flow diagram of scheme 1, which was the basis for the development of the simulation model SOMORE (Pla 1988; 1992; 1997), simulates the evolution of the soil water balance in the soil profile with a time step of one day, using easily obtainable soil and meteorological data as input. It may be used to predict the soil moisture regime, including water logging, rainfall losses by surface runoff, and surface and internal drainage, under different conditions of soils, topography, climate, vegetation, crops and management. The model accounts for infiltration of rainfall of rainfall into the soil as limited by surface 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 hydraulic conductivity of the limiting soil layer. The predictions may be used to identify the more probable degradation processes, and for the selection of the best alternatives, with more probabilities of success, of soil and water conservation practices for each combination of soils, climate and topography.

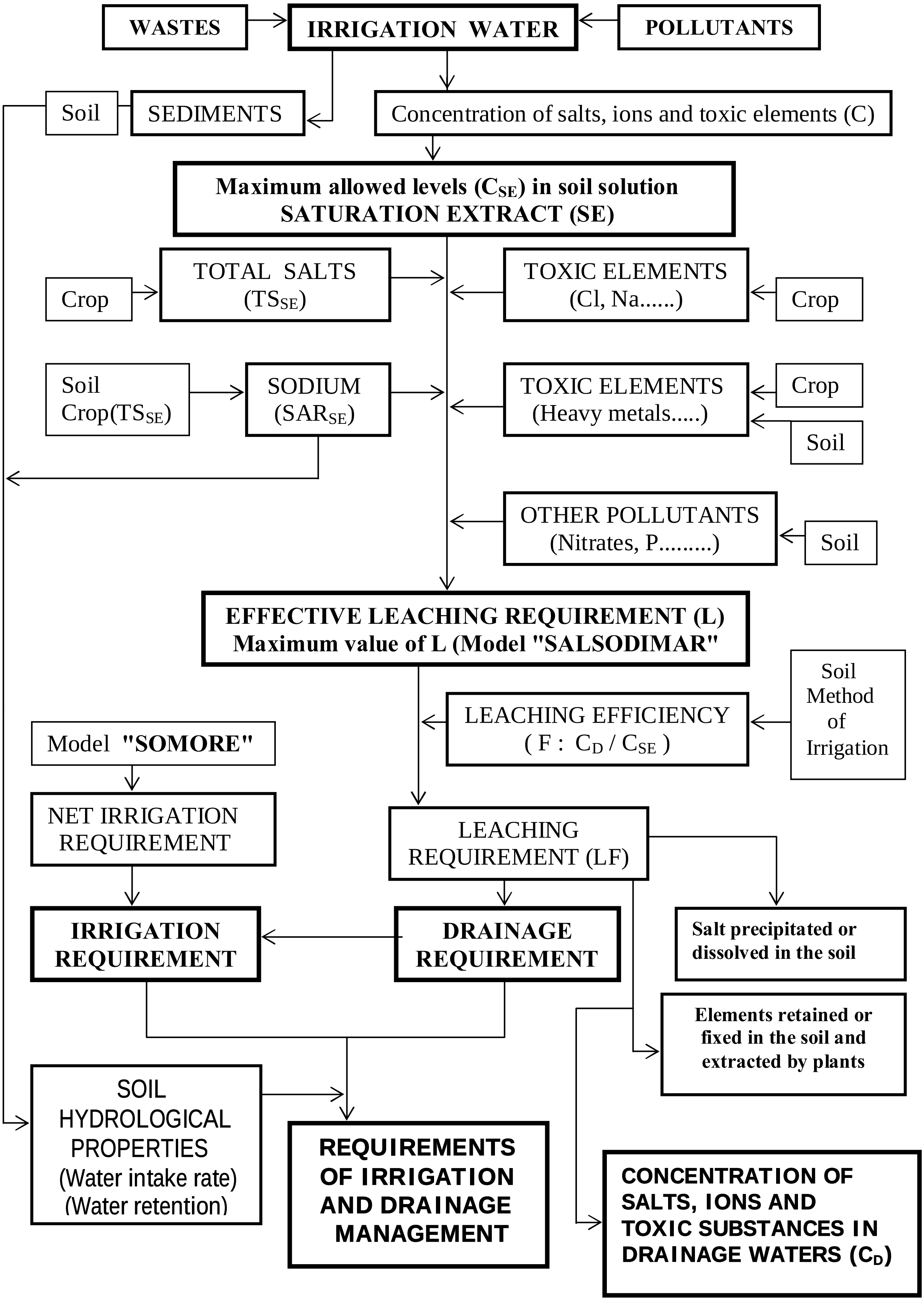
To make the model applicable, some simplifications in the formulation of the different hydrological processes, which have proved not to have significative effects on the required precision of the output, have been necessary in order to reduce the number and kind of input parameters from climate, soil and crops. The model 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 hours) interval, depending on inputs of 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 irrigation requirements, possibilities of tillage operations, and erosion hazard by different processes. 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 degradation 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 design, with a probabilistic approach, the best system of soil and water management to control soil degradation. It is also possible to predict the soil degradation (mainly erosion) processes and effects, and the problems of water supply to crops, with different return periods, 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 of risk and probabilities of failures. A particular season or year is described, or analysed, in relation to the long-term variability, based on rainfall records from the past.

The prediction of concentration of surface and subsurface runoff, and of the conditions of soil moisture, would permit to preview which days or periods of the year would have the greatest flood, erosion and sedimentation hazard, and what would be the most probable erosion process (Pla, 1992; 1993; 1997a; 1998). This is more useful for designing erosion control strategies than the use of empirical models which have proved not to be able to predict the time and probabilities of occurrence of concentrated runoff and erosion, and much less landslides or mass movements in general.

Scheme 2, show an extension of the flow diagram of scheme 1, when the addition of irrigation water, together with wastes and other pollutants to the soil, may cause drastic changes in the regime and balance of water and solutes in the soil profile. It integrates the influences of climate, crops, soils, fertilization, use of pesticides and wastes, groundwater depth and composition, irrigation water quality, and irrigation and drainage management, on the salinization and contamination of soils and grown waters. This flow diagram is the basis of the model SALSODIMAR (Pla, 1996; 1997b), used to predict the processes of salinization and sodification of irrigated soils and drainage waters, as a basis for guiding irrigation and drainage management practices.


WASTES
IRRIGATION WATER
POLLUTANTS
Soil
SEDIMENTS
Concentration of salts, ions and toxic elements (C)
Maximum allowed levels (C_{SE}) in soil solution
SATURATION EXTRACT (SE)
Crop
TOTAL SALTS
(TS_{SE})
TOXIC ELEMENTS
(Cl, Na......)
Crop
Soil
Crop(TS_{SE})
SODIUM
(SAR_{SE})
TOXIC ELEMENTS
(Heavy metals.....)
Crop
Soil
OTHER POLLUTANTS
(Nitrates, P.........)
Soil
EFFECTIVE LEACHING REQUIREMENT (L)
Maximum value of L (Model "SALSODIMAR"
Soil
Method
of
Irrigation
LEACHING EFFICIENCY
(F : C_D / C_{SE})
Model "SOMORE"
NET IRRIGATION
REQUIREMENT
LEACHING
REQUIREMENT (LF)
IRRIGATION
REQUIREMENT
DRAINAGE
REQUIREMENT
Salt precipitated or
dissolved in the soil
Elements retained or
fixed in the soil and
extracted by plants
SOIL
HYDROLOGICAL
PROPERTIES
(Water intake rate)
(Water retention)
REQUIREMENTS
OF IRRIGATION
AND DRAINAGE
MANAGEMENT
CONCENTRATION OF
SALTS, IONS AND
TOXIC SUBSTANCES IN
DRAINAGE WATERS (C_D)

Scheme 2. Flow diagram of a conceptual model of a balance of salts and toxic substances in irrigated soils (SAR: Sodium Adsorption Ratio) (Model "SALSODIMAR": Pla, 1997b; Model "SOMORE": Pla, 1997a)

EXAMPLES OF APLICATION OF HYDROLOGICALLY BASED MODELS

As examples of the potential use of modelling hydrological processes for evaluating and predicting soil and water degradation processes, and for guiding soil and water conservation practices, three situations with different soils, climate, topography, cropping and management conditions are presented. The same approach could be used for any other climatic conditions and combination of soil and management parameters.

The first case, refers to soils, mainly silty-loam Inceptisols, highly calcareous (developed in calcilutites), in undulated-hilly topography (4-20% slope), cultivated with rain fed grapevines for wine production, in a Mediterranean semi-arid climate. Most of the agricultural operations, including harvesting, have become mechanized in the last decades, which has required to change the plantation pattern, and to smooth the slopes and to decrease the irregularities of the original topography. As a consequence of the large earth movements, in most of the cases the soil physical properties affecting infiltration, drainage, and root development have suffered drastic changes. The final effects are increased runoff and soil erosion, and changes in the soil moisture regime at root depth. Figure 5 (undisturbed soil) and figure 6 (disturbed soil) show how the mechanical disturbance of the original soil affects the soil moisture regime and the potential runoff and erosion processes, during the whole year 1999, drier than average (return period (RP): 5 years). The approximate correspondence between the soil moisture simulated (S) regime, and the regime based on actual periodic soil moisture measurements (Nacci et al, 2000), show how well a model based on simple selected reliable hydrological information, may predict actual situations.

In the second example, the soil is a sandy loam Alfisol , under a tropical semiarid climate, with strong seasonal distribution and high variability of rainfall from one year to the other, and within the same year. The traditional use for pastures have changed to continuous cropping of rain fed sorghum, with a length of growing period of 90 - 100 days. The plant residues are usually used as forage for cattle during the dry season. The main constraints for a high and sustained productivity have been identified as soil moisture deficits and surface soil water erosion (Pla 1988, 1997). 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 horizon at 20-40 cm depth (which gets closer to soil surface after accelerated erosion), and shallow (10-15 cm) clean tillage using mostly disk harrows. Figure 7 shows the daily moisture regime in a bare tilled soil during the growing period of sorghum, under average rainfall (RP: 2 years) and shallow 20 cm root depth. The runoff and potential soil erosion - accompanied of flooding and sedimentation in the lower parts of the landscape - are 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 formation period. From that we may expect a good vegetative growth, but reduced grain production. Figure 8 show how the soil moisture

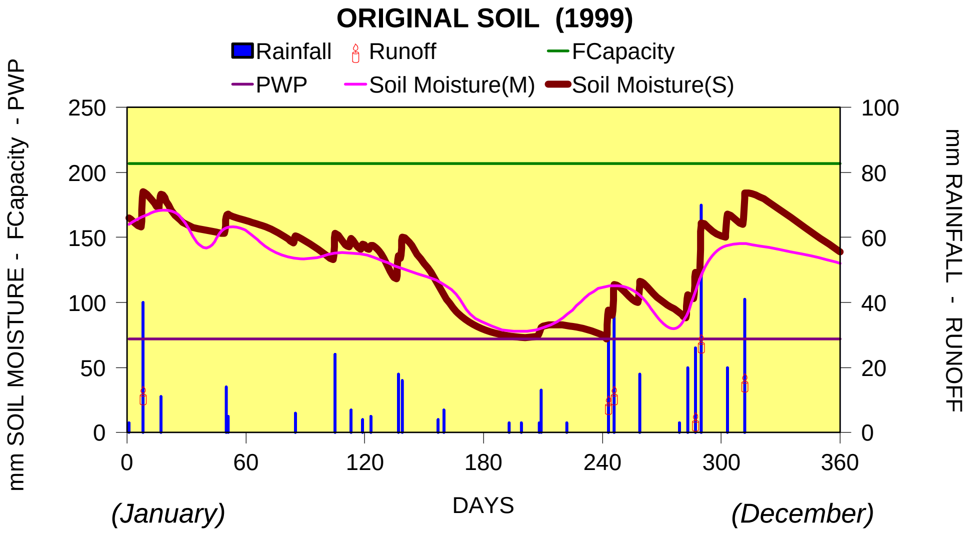


Figure 5

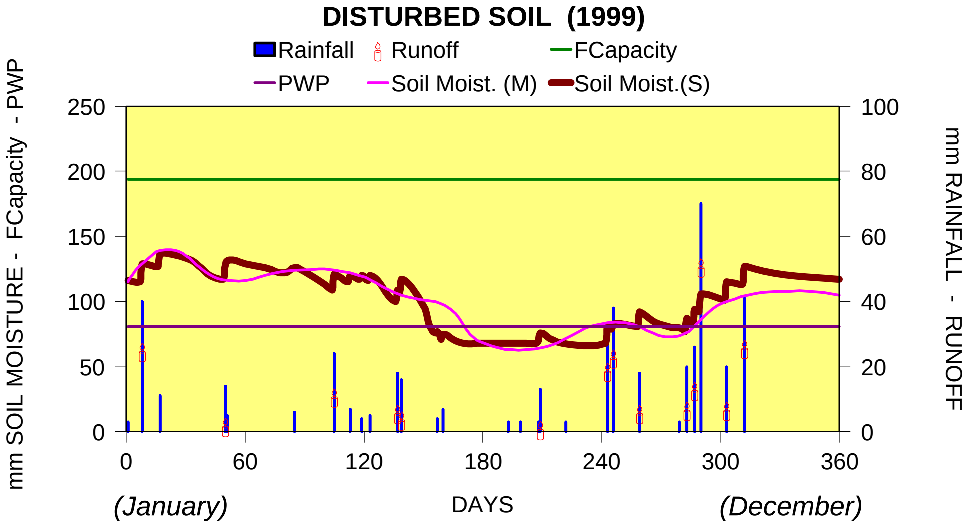


Figure 6

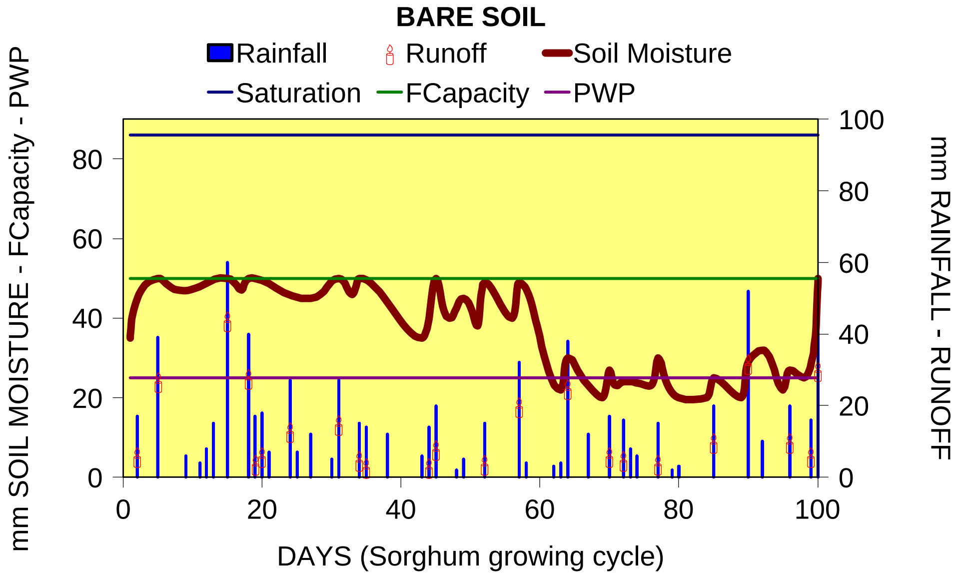


Figure 7

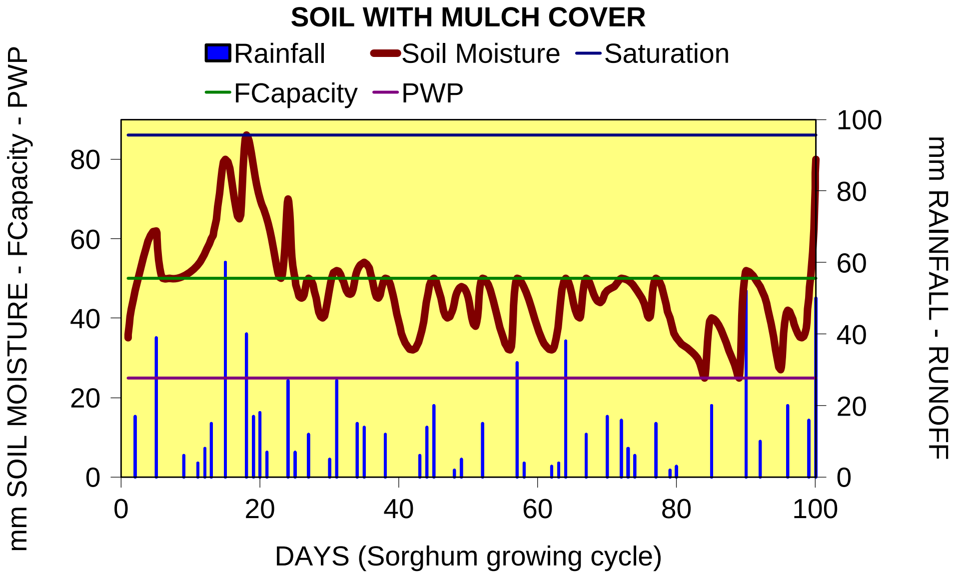


Figure 8

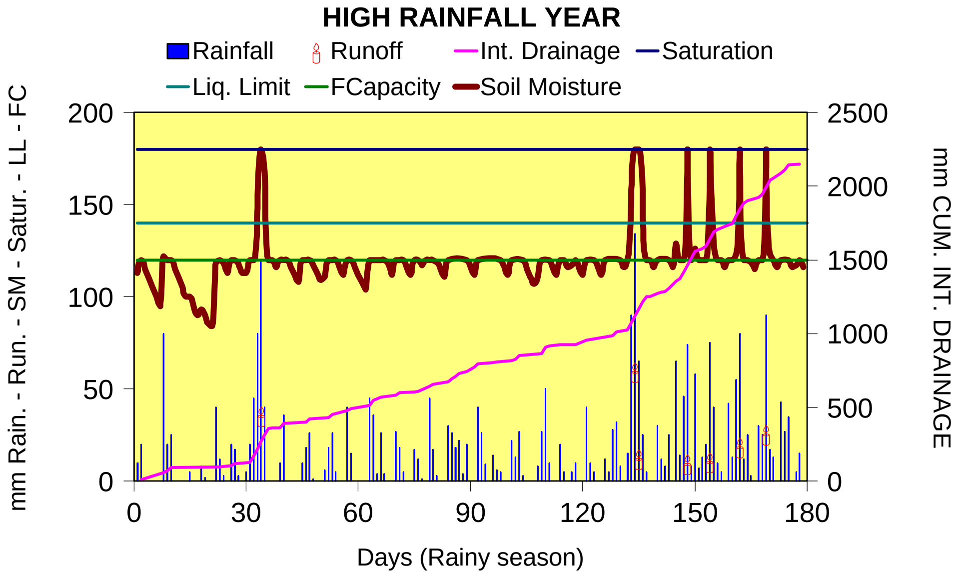


Figure 9

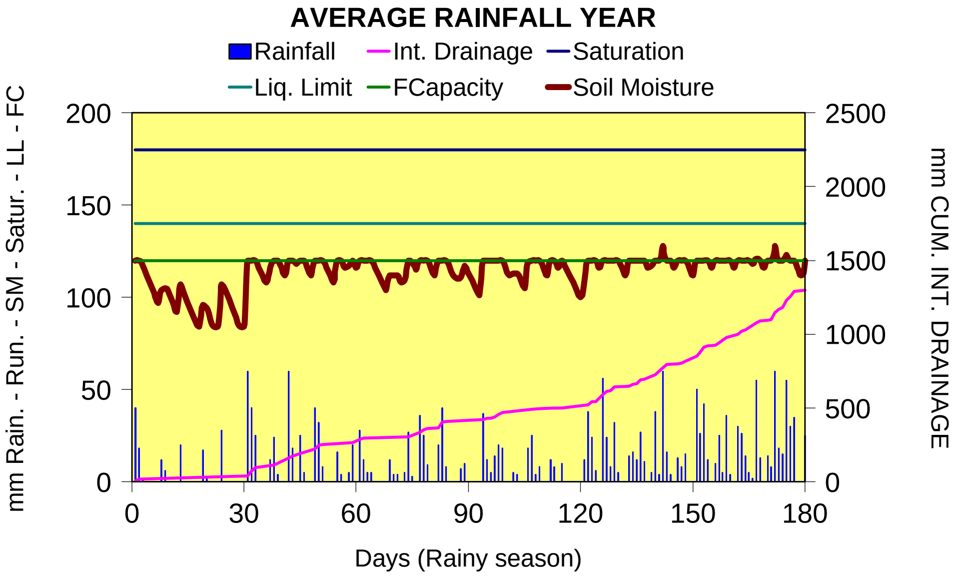


Figure 10

regime is affected by soil cover by sorghum residues, preventing runoff (and erosion) and water deficit, even with the relatively shallow (20 cm) rooting depth and average rainfall. In this case we may conclude that the marked surface soil sealing effect is clearly the main cause of concentrated runoff (30-50 % of the total rainfall in the rainy season), of the erosion and of the moisture deficit in bare soil with moderate slopes. The same procedure could be used to explore the potential soil water balances and moisture regimes for other different combinations of climate, crops, effective soil depth, and management practices .

The third example has to do with an Andosol, developed on young volcanic ash, with very steep slopes (30-50 %), in an area under a tropical humid climate. The land, traditionally used for pastures or permanent crops like coffee, in the last decades has been increasingly used for intense seasonal or annual partially mechanized crops, like potatoes and other vegetables. Under these new management conditions, and due to the tillage operations in mostly humid soil, there have developed a moderate compaction at 15-20 cm depth, with a marked decrease in saturated hydraulic conductivity. The main problem identified in the field is the concentrated and many times catastrophic erosion, mainly trough landslides and mass movements, in years and periods with concentrated and continuous rainfall events (Pla, 1992). The surface soil, with micro aggregates very stable to wetting and raindrop impact, do not show any sealing effect, and maintain a minimum rain water infiltration rates much higher than the underlying soil bellow 20 cm depth. Figure 9, shows that in a year with average rainfall (RP: 2 years), even with the contrasting hydraulic properties between the surface soil and the soil at 20 cm depth, we may not expect conditions (prolonged periods with soil moisture above liquid limit and concentrated subsurface runoff) favourable for landslides or mass movements. The combination of a year with high rainfall (RP: 10 years), and the restriction in internal drainage below 20 cm depth (figure 10), create conditions in two periods (30-40, and 135-170 days) of the rainy season, which may lead to accelerated erosion with landslides and mass movements. In this case it may be concluded that the problem of erosion or runoff has nothing to do with surface sealing effects, but it is mainly caused by the combination of high surface infiltration rates, restricted drainage at relatively shallow depth, loss of the anchorage effect of roots from the permanent natural vegetation or crops, and concentration of rainfall events.

It may be concluded that the estimates of the soil water regime using hydrologically based models, may be very useful:

- To diagnose the main factors responsible for the present and future soil water limitations, and the amount and timing of water stress strongly affecting plant growth and crop yields
- To preview the effects of different soil and water management practices in order to select the most appropriate ones for each case.

This allows to select the long term practices best adapted to the local environment. The model also enables to quantify the weather and soil related variability effects on crops, and to explore ways of matching crops and cropping systems and land management with environment. The aim of soil and water management is not always to increase infiltration, depending on the climate, soil, crop and possibilities of increasing levels of groundwater, groundwater recharge, and use and collection of runoff (water harvesting) for other uses. In those cases the use of these models also may give an insight to these possibilities.

Besides the examples presented here, there may be many other applications based on the interpretation of the simulated water balances and soil moisture regimes, including the best choice of different crops and varieties, and cropping periods or sequences, and the determination of requirements and the best periods for complementary irrigation, tillage operations, fertilization, application of pesticides, etc, for more effectivity and lower possibilities of pollution of surface or underground waters.

ABSTRACT

One of the main environmental problems, derived from the growing agricultural, urban and industrial developments, is the degradation of the soil and water resources. This degradation affects, directly or indirectly, all the vital processes on the world earth surface, which depend on the conservation of soil and water in adequate places, amounts, and qualities. The processes of soil and water degradation are closely linked through unfavourable alterations in the hydrological processes determining the soil water balance and the soil water regime. They are also conditioned by the climatic conditions and by the use and management of the soil and water resources. Therefore, an hydrological approach to the evaluation and prediction of the conservation of soil and water against degradation processes would be essential for an adequate development, selection, and application of sustainable and effective use and management practices. The main objective must be to evaluate such hydrological processes, and to select and develop methodologies and techniques to correct or to control them under different conditions of soils, topography and climate. This is required for suppressing or alleviating the negative effects of soil and water degradation on sustainable agricultural production, on the supply of water in adequate quantity and quality for the different potential uses, and on catastrophic events such as flooding, sedimentation, landslides, etc Although the close interaction between the conservation of the soil and water resources is increasingly being accepted, still in most of the cases they are evaluated separately, and consequently the prediction and prevention of the effects derived from their degradation are inadequate in many situations. This will become more important under the previewed effects of global climatic changes, which would mainly affect hydrological processes in the land surface. New research approaches based on the evaluation of the hydrological processes, under different scenarios on changing climate, soil properties, and soil and crop management, with the use of practical and flexible models and computer based programs, would help to select or develop more adequate packages of technologies to reduce soil and water degradation, and to control their growing negative effects on crop productivity, degradation of ecosystems, and on derived catastrophic events in the whole world. There are presented examples of such potential application of hydrological approaches for evaluating the causes and effects of soil and water degradation, to select the most appropriate use and conservation practices. The requirements of basic adequate information on climate and soils, and the limitations and possibilities to get it are also discussed.

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