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Modelling for planning soil and water conservation: a critical review

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Abstract

Degradation of soil and water resources, which is increasing throughout the World, is affecting directly and indirectly all the vital processes on the Earth's surface. This is partially due to non-appropriate land use planning, where soil and water conservation must be the most important components. Global climate changes may contribute to accelerate some soil and water degradation processes and their effects in some regions of the world. For an adequate planning of soil and water conservation it is required a better understanding and prediction of the interactions between climate characteristics and soil properties, under different scenarios of changing climate and changing land use and management practices and systems, often tied to social economic and political issues. The planning framework for effective soil and water conservation must consider and be aware of the increased complexity of environmental processes and problems derived of soil and water degradation, from local to regional and to global dimensions. These interactions must be integrated over time using simulation modeling. The generated information may be used in planning strategies for land use, and in the selection of soil and water conservation practices, based on probabilities of success, levels of risk, and long term sustainability. Natural disasters like flooding, landslides, etc., linked to extraordinary climatic events need to be considered in modeling soil and water conservation, in order to identify appropriate interventions which could eliminate or reduce the impact of specific kinds of disasters. Models must be based on well established cause-effect relationships for prediction, and flexible enough to be able to include the variety of possible soil-climate-cropping-socio-economic situation, and to be constantly improved as knowledge increases. Empirical regression-based models combining climate, topography, soils, and management as components have been the ones more used in erosion prediction. They are frequently misused, derived from the site specificity of the values assigned to it's factors, and extrapolations beyond the validity limits of its original data base. The consequences have been in many cases arbitrary prescriptions of ineffective soil and water conservation practices frequently leading to failures and even disastrous consequences. Process-based prediction models, based on equations that represent fundamental hydrological and erosion processes may solve the limitations of the empirical soil loss prediction models, like site specificity, limited transferability and others. Many of the so called process-based models developed up to day, still keep critical empirical components like the ones related to the soil hydrological processes, to the use of pedotransfer functions, etc., and/or require input information seldom available or difficult to get in many cases, which limit their practical use. There are presented examples of those limitations and of the potential application of simplified hydrological approaches for evaluating the causes and effects of soil and water degradation as a basis for planning soil and water conservation practices.

Keywords: modeling, hydrology, degradation, conservation, empirical, process-based

Introduction

Land 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. In spite of some technological advances in agricultural production, still millions of people, mainly in developing countries of tropical regions, do not have enough to eat. There are a number of causes, but the main one is the fast reduction in the productive capacity of land and in the quantity and quality of water resources, by increasing rates of soil degradation. Land degradation directly affects food supplies, diminishing crop yields and increasing risks of production (Pla, 1994), and it is related to climate and soil characteristics, but mainly to deforestation and inappropriate use and management of the natural resources soil and water. It leads both to a non sustainable agricultural production and to increased risks of catastrophic flooding, sedimentation, landslides, etc., and effects on global climate changes (Pla, 1992, 2000).

Economic and social problems, connected to population pressure, market changes and prices, and technical needs, may produce drastic and sudden changes in land use and management, which may increase the potential hazard of land degradation and side effects. Global climate changes may contribute to accelerate some land degradation processes and their effects in some regions of the world, but in any case, land use changes, including deforestation and other human activities leading to soil degradation affect more the processes and effects of land degradation than the previewed climate changes, or may increase the negative influence of these changes.

For an adequate planning of soil and water conservation it is required a better understanding and prediction of the interactions between climate characteristics and soil properties, under different scenarios of changing climate and changing land use and management practices and systems, often tied to social, economic and political issues. These interactions may be integrated over time using simulation modeling, in order to reach planning strategies for sustainable land use and soil and water conservation practices. Natural disasters like flooding, landslides, etc., linked to extraordinary climatic events need to be also considered in modeling soil and water conservation, to identify appropriate interventions which could eliminate or reduce the impact of specific kinds of disasters.

Models must be based on well established cause-effect relationships for prediction, and flexible enough to be able to include the variety of possible soil-climate-cropping-socioeconomic situations, and to be constantly improved as more is known about the influence of specific land and climate characteristics on degradation processes. It is desirable to develop models which can show results of interactions among land resources, degradation processes, conservation measures and productivity over future years. The combination of geographic information systems (GIS) and that kind of modeling offers the opportunity of assessing environmental impacts derived of changes in land use and management and of soil and water conservation practices, and presents a logical framework for integrating subsequent monitoring.

Planning Soil and Water Conservation Practices

Soil and water conservation is the most important part of land-use planning, and must be inserted into the whole context of land-use planning for land development. Soil and water conservation programs must be seen as the development and application of land use systems that preserve or enhance soil productivity. The factors responsible for detrimental land use must be identified and removed before the adoption of new land-use systems. For justifying soil conservation projects within land use planning programs, it is necessary to make an economic analysis in terms of costs and benefits. There are required data relating soil degradation to productivity loss, but sometimes the losses and gains are mainly off-site than on-site.

In the economic assessment of land conservation projects it is necessary that the policy makers and land users be aware that land degradation is not only leading to crop yield reductions, but that it may cause serious problems offsite (downstream) including silting up of streams, dams and channels, damage to hydroelectric and irrigation schemes, restrictions to navigation in rivers and harbors, and increased frequency and severity of flooding and landslides.

The development of new and improved technologies for increasing production of crops, wood, cattle, etc. to satisfy requirements of food, fuel, shelter and cash must ensure that the natural resource base water and soil, on which land degradation is based, is not depleted. Sustainable land management focuses in technology that minimizes risk, increases or guarantees production, and ensures the integrity of the resource base. It must match agro technology to the particular agro environment, not only to meet the goal of stabilized and increased yields, but also to protect the land resource base, so that it is conserved for future generations (Virmani and Eswaran, 1991).

Natural disasters like flooding, landslides, etc., linked to extraordinary climatic events, need to be considered in preparing guidelines for evaluating soil and water conservation practices (Brammer, 1991). It is necessary to identify appropriate interventions which could, where feasible, eliminate or reduce the impact of specific kinds of disasters.

The planning framework for the achievement of sustainable land management must consider and be aware of the increased complicity of environmental processes and problems derived of land degradation, from local to regional, to national and to global dimensions. That understanding is essential for developing a realistic approach for effective application of soil and water conservation practices to prevent land degradation, and for the achievement of sustainable land use.

The cost-effectiveness of expenditures on soil and water conservation practices may be greatly increased if a goal balance is previously established, and multiobjective planning is used as a basis for decision making. For this we have to be aware that although the general principles of the control of soil degradation are the same everywhere, there are not ready-made solutions to land degradation which can be applied universally, and each situation requires planning strategies adapted to its own complex local conditions and circumstances.

Climatic and soil information must be integrated with economic and land use data over time in a holistic manner, using modeling and other numeric techniques for assessing sustainable land management and land degradation risks (Baier and Dumansky, 1991). The generated information may be used in planning strategies for land use, and in the selection of land conservation practices based on probabilities of success, levels of risk and long term sustainability (Pla, 1994, 1997). Simulation modeling requires data collection, updating of information and monitoring. Uncritical use of results from any model based on empirical relations or supplied with poor available data, for taking "decisions urgently required", a very common situation, is very dangerous, and may lead to catastrophic consequences.

Planning soil and water conservation needs of reliable data on the characteristics of soil and water resources. To develop modified and improved or new land use and management systems to avoid adverse effects on water supply, food production and quality, and nature conservation, fundamental knowledge about physical, chemical, hydrological and biological processes in soils have to be available. Good soil data base is required for modeling the potential for carbon sequestration, under changing conditions of land use and climate.

Poor, incomplete and/or inaccurate basic data on soils and climate give poor qualitative and quantitative evaluations of land use and management sustainability. In many places, especially in developing countries, the data bases on soils and climate are not enough, or they are not the kind or the quality required for evaluating and modeling potentially useful sustainable land management practices. The analysis itself by models, GIS, etc., does not add any new information, and when it is based on empirical approaches developed for different conditions, to substitute non available local data, it may lead to gross inaccuracies and misinterpretations. In general there is a need for more efficient collection of basic information on land and its use for an appropriate evaluation and modeling of land use planning for soil and water conservation.

Modeling Approaches for Soil and Water Conservation

Requirements of more quantitative results in probabilities and risks of soil degradation and its influence on crop production and environmental damage for planning soil and water conservation practices (Pla, 1994) may be partially satisfied with the use of modeling, 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 for understanding degradation processes and their interactions, and for setting research priorities (Nearing *et al.,* 1994). They are used in conservation planning when site-specific physical and socioeconomic conditions can be matched with technical requirements (Lu and Stocking, 1998).

Research must be directed to produce useful models for predicting the impact of changes in use or in 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. Models require a balance between technical, productivity and social-economic impacts, for the specific purpose of assisting decision making in soil conservation.

Direct measurements of runoff and soil loss in the traditional erosion field plots, generally associated to the collection of data 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 non practical in places where the resources are scarce and there are required short term solutions (Pla, 1991). Therefore, the current complete dependence on runoff plots for the measurement of soil erodibility has to be substituted by a more flexible, less expensive and more efficient methodology, leading to an approximate and more useful prediction of infiltration and runoff of field soils under rainfall (Rose, 1994).

The prediction of water erosion is presently generally done using mostly empirical, and much less process based methods end models. Among these, the USLE and its derivatives and adaptations, has been by far the model more widely used worldwide since 1960. USLE is the statistical summary of data from field plot experiments in the Great Planes of the USA Mid West, where the effectiveness of various practices or treatments in preventing soil loss are compared to a bare uncropped reference plot. Therefore USLE, or any other empirical model based solely on collected data, is not universal in its application, and limited to the extent of that data set. Besides, empirical models like USLE and the revised version RUSLE do not consider adequately the complex interactions of soil, climate, changes in cropping and management, topography and conservation practices (Laflen, 1998).

Empirical models with a purely experimental statistical approach require a local data base not available in most of the cases, which is frequently being substituted by information generated through submodels and regression equations developed under conditions very different to the ones where they are applied. This 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.

Even though the relative and absolute significance of different processes of soil erosion may vary, they are universal. Therefore, it is required to develop process-based models, with a structure from which the movement of water and sediments over the land surface can be simulated. While they are developed, the main benefit of these models is the identification of gaps of knowledge and data, for setting research priorities, and the understanding of the degradation processes (Morgan and Nearing, 2000). Models must rely on hydraulic parameters of rainfall and runoff generation as direct predictors of erosion processes (Kirkby, 1980). In modeling runoff generation, we may use infiltration or storage approaches. The infiltration velocity changes with time, and runoff generation is estimated from rainfall intensities in excess of the current infiltration capacity. In this case runoff is strongly related to the process of soil surface sealing by rainsplash, which my reduce effective infiltration by a factor of 10 or more (Pla, 1986, 2000). Such large variations in runoff are correspondent with differences in sediment yield, which may outweigh all other factors and therefore must be considered ion modeling (Kirkby, 1980; Pla, 2000).

It may be concluded that in general process based models will require a good 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, 1997, 1998, 2000). 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 specificity, limited transferability and others. Also, models based on hydrological processes may be easily adapted to the present changes in emphasis from sustaining better the soil resource as such, to sustaining the soil resource for protection of the environment (Laflen, 1998).

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 methods and techniques applicable for predicting soil hydrological behavior under field conditions 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 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 actualized 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. In any case it is desirable to keep the information that must be obtained simple, so that basic objectives can be achieved (IBSRAM, 1995).

We always have to take into account that models are not only to help the understanding of a complex situation by a quantitative description of the more significant processes, but they may also serve as decision-making tools to reduce or to avoid negative environmental impacts under different and changing scenarios (Richter and Streck, 1998). Hydrological approaches allow to combine the characteristics of climate with the characteristics of soils and landforms and land-use types, for interpretation and prediction of land degradation hazards. When applied to a series of scenarios of land use and potential environmental and climate change impacts, the results can be used by decision makers for future land use planning and implementation. This approach makes the extrapolations more soundly based and provides a scientifically solid base which leaves little space for subjective interpretations leading to alternatives for different land use and management for agricultural and non-agricultural purposes. Modeling hydrological processes has proved to be a very reliable tool for evaluation and prediction of land degradation processes for guiding planning strategies for soil and water conservation and management practices, under very different climate, topography, soils, cropping and management conditions (Pla, 1994, 1997, 1998, 2000). Figure 1 shows the flow diagram, which was the basis for the development of the simulation model SOMORE (Pla, 1997), based on hydrological processes. It 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 predictions may be used to identify the more probable degradation processes, and for the selection of the best alternatives, with more probabilities of success and for the assessment of environmental impacts of soil and water conservation practices for each combination of soils, climate and topography.

Figure 2 shows how simulation models based on hydrological processes may play a fundamental role in the evaluation and prediction of potential soil and water degradation processes for planning strategies leading to sustainable land use, management and soil and water conservation practices, under different and changing scenarios.

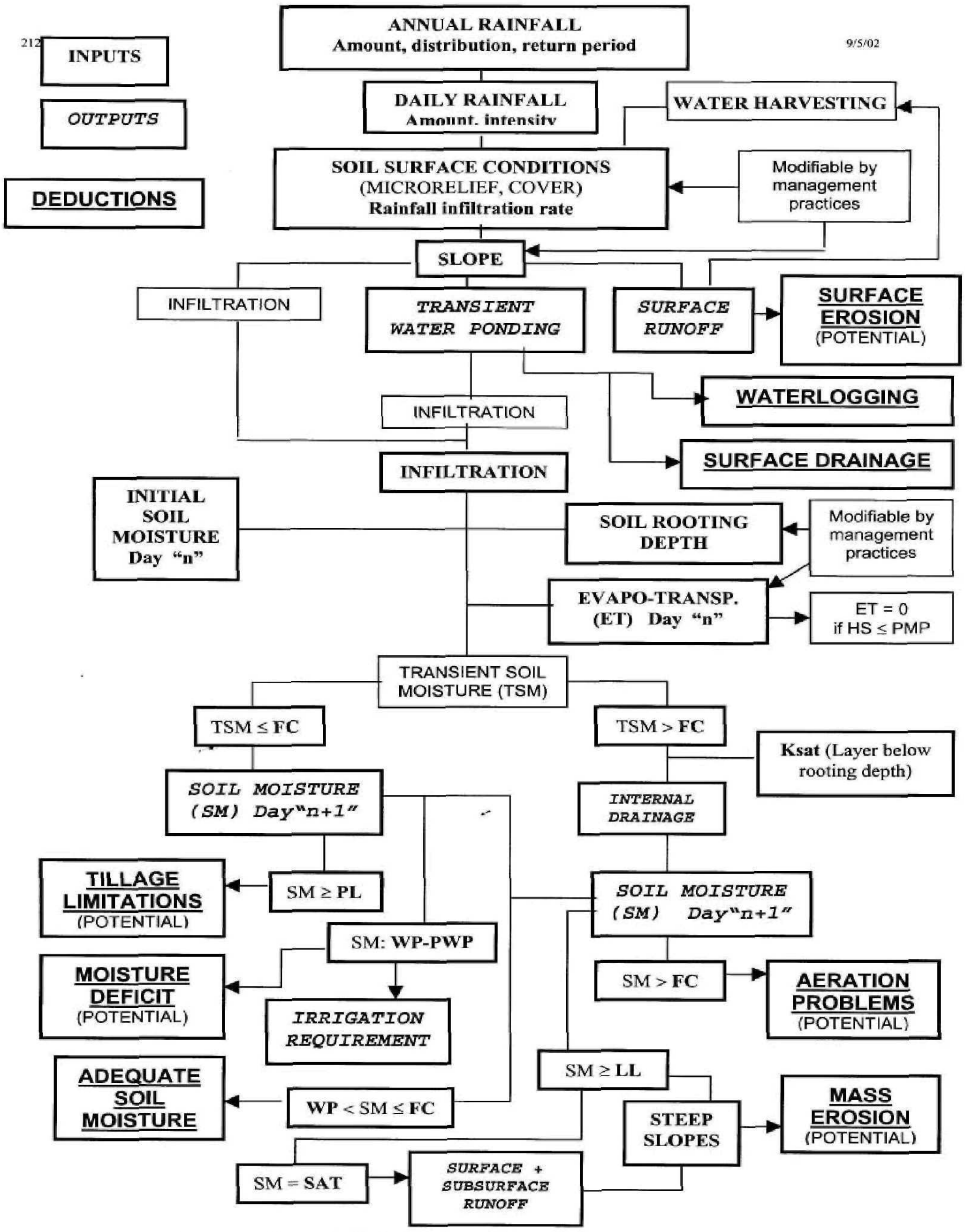
Conclusion

The modelling of soil and water degradation processes must allow the design of sustainable and productive land use and management strategies which guarantee protection of the environment, previewing the effects of different combinations of climate, soil, slope and management, including extraordinary events with low return period. That requires changing the present mostly empirical, subjective and qualitative approaches, to more quantitative modeling approaches based on hydrological processes. The modeling must take into consideration that soil degradation not only causes problems in site, but it may cause serious problems off-site. An hydrological approach does facilitate a more integral evaluation at both levels.

In modeling we must pursue an equilibrium among accuracy, simplicity and flexibility. Models have to include all important factors and processes, but to be efficient and of practical use it is necessary to identify the ones with greater influence in order to simulate them in greater detail. As no practicable model is valid for all conditions, flexibility in the structure of the model must allow to introduce other parameters or processes if it is found that they are locally important.

The use of models in conservation planning has to consider that in most of the cases our objective is not so much to precisely predict soil loss under field conditions, but to design effective land use and management strategies and to select the soil and water conservation practices with more probabilities of being effective. We must not forget that in many cases the spatial variability of soil hydrological properties would be much larger than the error related to the approximations incurred by a model, making the use of more accurate and complex models irrelevant.

Before selecting any model, the users must be always aware of the limitations and range of applicability of it. That requires a knowledge of the main assumptions and simplifications made by the modeler. In any case it has to be clear that models are not substitutes of experience, but only tools to help experience and research to reach results useful for conservation planning, Experience is required to assess the applicability of the results of a model to a particular situation.



(**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)

Figure 1 Flow dragram of a conceptual simulation model, bases on hydrological processes, to predict the soil moisture regime and to assess the potential soil degradation processes (adapted from: Pla, 1997).

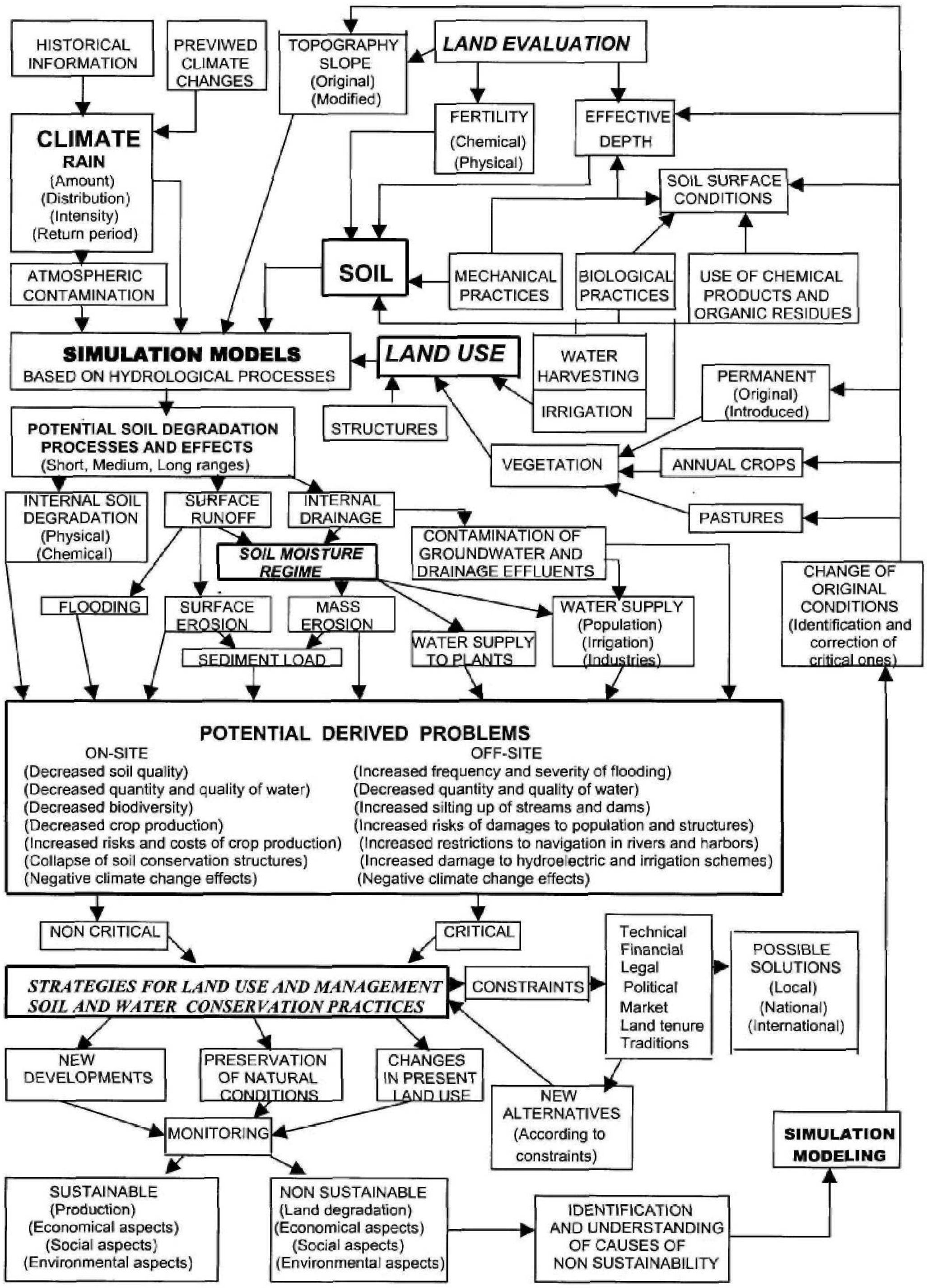


Figure 2 Simulation modeling for evaluating potential soil degradation prodcesses, causes and effects on site and off site, and for planning land use, management and soil and water conservation practices.

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