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"Modelling Soil Erosion by Water: Why and How"

Prof. Giancarlo CHISCI
Prof. R.P.C. MORGAN
Università degli Studi di Palermo
Istituto di Agronomia Generale e Coltivazioni Erbacee
Palermo, Italy

# MODELLING SOIL EROSION BY WATER: WHY AND HOW

G.CHISCI (*) AND R.P.C.MORGAN (**)

* Istituto Sperimentale per los Studio e la Difesa del Suolo, Piazza d'Azeglio 30, 50100 Firenze, Italy.

** Silsoe College, Silsoe, Bedford MK45 4DT, U.K.

## ABSTRACT

There is a need for a model that can be used to evaluate the risk of soil erosion by water within the countries of the European Community and which can provide a basic tool for the design of erosion control measures. Rather than adapt a model from the U.S.A., it is proposed that a European model be developed which can be applied to the critical conditions that give rise to the dominant erosive events and also to the extreme event. A framework for a model is presented comprising three components: a runoff generator, an estimator of soil detachment and a transport capacity function that incorporates an index of the likelihood of rilling. Possible operating functions based on European research are reviewed. The model can be extended spatially by linking it with the SHE (Systeme Hydrologique Europeen) hydrological model. The model includes several parameters which may be manipulated to evaluate the effects of vegetation or crop cover, tillage practices and other soil conservation measures.

## 1. INTRODUCTION

The last decade has seen an increasing awareness of the importance of soil erosion within the European Community. Two workshops, at Firenze in 1982 (Prendergast, 1983) and at Cesena in 1985 (Chisci and Morgan, 1986), have been held on the topic. Data presented at these workshops show that rates of soil erosion by water are high enough for concern, especially when compared with rates necessary to maintain acceptable standards of water quality and agricultural productivity. Considering the shallowness of many European soils and the demand to protect the environment from pollution as a result of inputs of sediment and solutes to rivers, lakes and reservoirs, it may be necessary to maintain mean annual erosion rates below 1 t/ha. Yet in many areas of Mediterranean Europe and in the undulating loamy and sandy lands of northern Europe annual erosion rates of more than 20 t/ha are recorded, enough to threaten the useful life of some of these soils within the next 75 years (Morgan, 1986).

The total area of the European Community presently subject to soil erosion at unacceptable rates is not known and no standardised technique exists for determining it. Methods of erosion assessment based on scoring systems for rainfall erosivity, soil erodibility, slope and landuse (Giordano, 1986; Rubin, 1986) provide good information on the spatial distribution of erosion and areas at risk but yield only limited data on erosion rates. Also they do not produce the information required to design erosion control measures or to evaluate their effect. These deficiencies can only be rectified by combining the assessment techniques with erosion models such as the Universal Soil Loss Equation.

American scientists developed the Universal Soil Loss Equation (Wischmeier and Smith, 1978) as a method of assessing erosion and evaluating the effects of different soil conservation practices. Although the Equation has served its purpose well over the years, being both simple to use and arguably the most effective predictive tool available to date, it has a number of weaknesses. First, it is designed to predict mean annual soil loss whereas for assessments of the effects of erosion on pollution, it is necessary to know what happens in individual storms or even in shorter periods of time. Second, the equation applies only to a field scale and it has proved difficult to link it to catchment scale models to assess sediment yields. Third, the equation does not take account of runoff explicitly. Yet a knowledge of runoff is essential for understanding the timing of sediment and solute inputs to rivers. Fourth, it is now appreciated that the various factors that influence erosion cannot be simply multiplied together to obtain an erosion rate; there are important interactions which can only be taken account of by a



less empirical approach with greater emphasis on the mechanics of erosion. These shortcomings of the Universal Soil Loss Equation are recognised and have caused American workers to concentrate on producing a new generation of models with a stronger physical base.

This paper is concerned with the development of a model for erosion assessment and design of soil conservation measures in the European Community. It is not the intention to propose a specific model but rather to outline an approach, present some ideas for debate and review current European work.

## 2. CHOICE OF MODEL

Several studies have been carried out to test the validity of the Universal Soil Loss Equation (Zanchi, 1978; Schwertmann, 1981, 1986; Chisci, Giordano, Indelicato, Li Destri-Nicosia, Sfalanga and Torri, 1982) in the European Community. They show that great care is required in the selection of input values, particularly for the rainfall (R) (Chisci and Zanchi, 1981; Richter, 1983) and soil (K) (Richter, 1980; De Ploey, 1986; Schwertmann, 1986) factors before the equation can be made to work effectively. Studies with another American model, CREAMS, show that it gives quite reasonable predictions of mean annual runoff and erosion but requires considerable input data, including daily rainfall amounts, to achieve these. Much more could and should be expected of its ability to predict the effects of individual events than seems to be the case in practice (Morgan, Morgan and Finney, 1985).

Given that these models are not readily transferable to European conditions and that the Americans are intent on replacing the Universal Soil Loss Equation in the near future, it is difficult to justify continued effort on their validation for the European Community. Instead, attention should be paid to developing a model from within Europe designed specifically to meet European needs and based on European research.

## 3. CONCEPT OF A EUROPEAN MODEL

The design requirements of a European model for soil erosion by water are that it should (1) enable the risk of erosion to be assessed; (2) be applicable at field and catchment scales; (3) allow the contribution of sediment and solutes from the land surface to water bodies to be determined; (4) provide reliable estimates of erosion and solute concentrations for comparison with standards of what is acceptable; (5) operate on an event basis; and (6) be useful as a tool for selecting erosion control measures.

In developing a model to meet these requirements, the following challenges arise. First, predicting erosion for an individual event is extremely difficult because of the large number of factors that interact to influence how much soil loss takes place and the soil and land use conditions at the start the storm. Second, the equations used to describe the erosion, being based on the mechanics of the processes involved, are strictly applicable to instantaneous conditions. They cannot be applied to average conditions without loss of accuracy. The maximum time period for which averaging is feasible is about one hour. Third, many factors cannot be expressed in a suitable way for inclusion in a model. This is why many recent American models still rely on the K and C factors of the Universal Soil Loss Equation to describe soil and land use. Fourth, the structure of many new models is so complex that it is difficult to determine the main factors giving rise to a particular erosion prediction. Fifth, the complexity of the models means that they are very demanding of input data. Sixth, since erosion risk is still perceived by many people in terms of mean annual conditions, event models have to be run for a long period of time so that mean annual rates of erosion can be calculated from a series of individual storm predictions.

Many of these problems can be overcome by simplyfing the model to consider only particular events and selected erosion processes. The keys to simplification for the countries of the European Community are the frequency of erosion, the dominance of specific erosion processes and the need to rethink the basis on which erosion risk is assessed and soil conservation measures designed.



Measurements of soil erosion on hillside plots and in small watersheds (Sfalanga and Franchi, 1978; Boschi and Chisci, 1978; Richter, 1979; Morgan, 1980; Raglione, Sfalanga and Torri, 1980; Boschi, Chisci and Ghelfi, 1984; Tropeano, 1984; Chisci, Boschi and Ghelfi, 1985) show that most erosion takes place in what may be termed dominant events with a frequency of two to three times a year. Erosion risk assessment can therefore be approached by predicting the effects of these dominant events. This does away with the need to model the conditions at the start of the storm since it is reasonable to assume a saturated soil and the tillage and crop cover conditions for the time of year the event is expected to occur. The response to extreme events which, as shown by Thornes (1976) in southern Spain, can irreparably scar a landscape, can be approached in the same way by applying the model to an event with say a hundred-year return period.

Present approaches to modelling soil erosion derive from a scheme described by Meyer and Wischmeier (1969) in which erosion is viewed as a two-phase process of detachment of soil particles from the soil mass and their transport downslope. Both detachment and transport take place by raindrop impact on the soil surface and by runoff. This scheme can be simplified by neglecting soil particle transport by raindrops and soil detachment by runoff. Erosion is then a function of the soil material made available for transport through detachment by raindrops and the transport capacity of the runoff.

The design of erosion control measures can be approached by considering protection of the soil against a particular event rather than an annual condition. The extreme event would probably be too costly for most farmers to consider protection and the dominant event would be too small in magnitude to guarantee protection without an unacceptable risk of failure. Protecting against the event with a ten-year return period may be a suitable compromise. This approach would place the design of field-scale erosion control measures on the same basis as that used in the design of terraces and grass waterways.

## 4. FRAMEWORK FOR A MODEL

A proposal for a simple model is shown in Figure 1. Only surface hydrology and sediment production are considered. No attempt is made to include sub-surface flow or movement of solutes although the model is constructed in a way which would allow modelling schemes for these components to be added. The model requires three operating functions: a runoff generator, a soil detachment estimator and a transport capacity determinator.

4.1. Runoff generation

Scientists from the Danish Hydraulic Institute, the Institute of Hydrology and SOGREAH have already developed a deterministic, distributed and physically-based hydrology model, Systeme Hydrologique Europeen (SHE), capable of predicting runoff at points or over small hillslope areas in a catchment and routing it downslope to the channel (Danish Hydraulic Institute, 1985). The model takes rainfall data and calculates net rainfall at the soil surface after allowing for interception storage on the vegetation cover and evapotranspiration. If the model is applied to the critical conditions of a dominant or extreme erosion event, it may be reasonable to neglect evapotranspiration and to assume that interception storage has been satisfied so that all the rainfall reaches the ground surface either directly or as plant canopy drainage.

Water accumulating on the ground surface responds to gravity by flowing downslope so that the runoff can be described by the following equations:

$$\partial h/\partial t + \partial (uh)/\partial x = q \qquad (1)$$

$$\partial h/\partial x = Sx - Sfx \qquad (2)$$

$$uh = (h^{5/3}\ Sx^{1/2})/n \qquad (3)$$

where h = water depth
t = time
x = horizontal (downslope) direction
u = flow velocity in the x direction
q = net precipitation minus infiltration
Sx = ground slope in the x direction
Sfx = friction slope in the x direction
n = Manning's coefficient of roughness.



The model solves these equations in an explicit procedure.

4.2. Soil detachment

The rate of soil detachment depends upon the properties of the rainfall, the resistance of the soil, slope steepness, the depth of ponded or running water on the surface and the vegetation cover. Styczen and Høgh-Schmidt (1986) demonstrate that a model which considers soil detachment by raindrop impact as proportional to the sum of the squared momentum of each raindrop in the rain event is capable of explaining observed detachment rates with and without vegetation. Their model is thus an improvement over models based on raindrop kinetic energy which are poor at explaining some vegetation effects (Morgan, 1985). Adapting the model in the light of research on the other factors influencing soil detachment suggests that a suitable equation to determine detachment rate (D) will have the form:

$$D = K\, e^{-qh} \tan^{a} S\ (A - C) \sum^{d} Nd\ Md^{2} + C \sum^{d} Ndc\ Mdc^{2} \qquad (4)$$

where K = a soil parameter expressing detachability
h = depth of water on the soil surface
S = ground slope in the x-direction
A = area affected by raindrop impact
C = area of canopy cover in plan view
Nd = number of raindrops of size class d in the rainstorm
Md = momentum of raindrops of size class d in the rainstorm
Ndc = number of raindrops of size class d in the rain under the canopy
Mdc = momentum of raindrops of size class d in the rain under the canopy
q, a = experimental constants

Several approaches have been used to define K. Styczen and Høgh-Schmidt (1986) relate it to the energy required to detach one soil aggregate. Poesen (1985a) uses a soil resistance parameter expressed as the kinetic energy required to detach 1 kg of material and has produced a graph showing how this parameter changes with the median grain size of the soil. Quansah (1981) expresses it as the weight of soil detached per unit of kinetic energy and gives values for sandy, clay and clay loam soils. Torri, Sfalanga and Del Sette (in press) attempt to describe it in terms of cohesion of the soil, as measured with a shear vane. They find that the percentage clay content of the soil also needs to be considered to explain the effect of soil on detachment rate.

Fewer studies have investigated the effects of surface water and slope but likely values for q and a are 1.9 (Torri and Sfalanga, 1986) and 0.2–0.3 (Quansah, 1981; Torri and Sfalanga, 1986) respectively.

Equation (4) does not consider soil detachment by rills which may sometimes need to be allowed for once the surface runoff becomes channelled. Detachment in rills is more related to rill wall collapse than to scouring effects of the runoff. This in turn is dependent upon the characteristics of the soil and the slope angle of the rill wall.

4.3. Transport capacity of runoff

Torri, Sfalanga and Chisci (in press), in a laboratory study designed to examine the threshold conditions for rill formation, show that the depth of erosion increases with the ratio $\tau/\tau_s$ where $\tau$ is the shear stress of the runoff and $\tau_s$ is the cohesion of the soil measured with a shear vane under saturated conditions. Although data were collected mainly for clay soils, the relationship should hold in principle for all soils. The authors were also able to define a critical level of the ratio $\tau/\tau_s$ at which rills developed and to demonstrate that this was compatible with other studies relating the onset of rills to critical values of runoff shear stress (Govers, 1985; Govers and Rauws, 1986) and slope steepness (De Ploey, 1983).

Developing a transport capacity equation from this approach has the advantages of incorporating a readily measurable soil property, taking account of the likelihood of rilling and providing a simple relationship similar in concept to Du Boys' formula. The exact nature of the equation is yet to be determined but it is expected to take the form of:

$$R = f\left[T\,(T - Tc)\,W\right] \qquad (5)$$



where R = transport capacity of runoff
T = shear stress ratio ($\tau/\tau_s$) of runoff
Tc = critical shear stress ratio of runoff for rills to form
W = other factors helping water to concentrate, e.g. stemflow, tractor wheelings

If the shear stress of runoff is defined by the Landau and Lifchitz (1971) relationship

$$\tau = (\rho g)^{2/3}\,(3\nu)^{1/3}\,\sin^{2/3}\theta\; q^{1/3} \qquad (6)$$

where $\rho$ = fluid density
g = acceleration due to gravity
$\nu$ = kinematic viscosity of the fluid

and other terms are as already defined, it is possible to allow for the effects of soil detachment by assuming that the detached particles contribute to the sediment load of the runoff and adjusting the fluid density accordingly. In this way, the critical shear stress ratio for rilling is affected by a critical level of sediment concentration in the flow as proposed by Boon and Savat (1981). Inclusion of kinematic viscosity which depends upon the temperature of the fluid, allows account to be taken of the retarding effects on velocity of a heavy sediment load (Savat, 1979).

4.4. Interactions

The proposed model, if operated for short successive time periods, will allow for changes taking place during a storm. Thus, if soil detachment is followed by crusting or sealing of the soil surface, the rate of infiltration can be reduced, resulting in greater runoff. An increase in flow depth will cause a decrease in soil detachment later in the storm. Increased runoff and higher sediment concentrations will increase the likelihood of rilling and raise the sediment transport capacity.

It may be feasible to model these changes using De Ploey's (1981) consistency index to determine whether a soil is likely to crust under raindrop impact. The index reveals that a reasonably consistent top soil with a high aggregate stability and low crustability absorbs more water and energy than an unstable top soil. From laboratory tests and field observations it is found that the values of the consistency index are closely correlated with the texture and organic matter content of the soil. De Ploey and Poesen (1985) show how soil crustability affects infiltration and runoff generation. Govers and Poesen (1985) found a relationship between the ability of the soil to seal and its cohesiveness as measured by a torvane. The areal extent of surface sealing and changes in the roughness and compaction of the soil surface all followed a similar temporal evolution controlled, either directly or indirectly, by the texture of the top soil, slope angle and microrelief (Poesen, 1985b; 1986). The link between soil sealing, textural characteristics and infiltration rate was also demonstrated by Poesen (1985b) who formulated a sealing index (SI) defined as:

$$SI = \Delta P / \Delta T \quad (7)$$

where $\Delta P$ = difference in percolation rate (mm/h) between peak percolation and terminal percolation rates

$\Delta T$ = difference between time of peak percolation and time terminal percolation rate is reached

Values of the sealing index correlate with soil texture and soil shear strength as measured by a torvane (Poesen, 1986). These studies provide a suitable basis for modelling changes in infiltration rates and runoff generation through a storm.

Another scheme for evaluating sealing dynamics and its influence on infiltration and runoff has been developed by Boiffin (1985) and Boiffin and Monnier (1985). This predicts the reduction in infiltration rate in relation to the surface area affected by crusting. The latter depends upon soil properties and rainfall energy.

## 5. APPLICATIONS

If future research is concentrated on developing procedures to estimate input parameter values, the type of model described here has potential for several



applications. First, by applying it to selected storms, the risk of erosion can be evaluated. This can be achieved most easily by predicting the erosion in dominant and extreme events.

Second, by changing the input parameter values in accordance with the effects of different soil conservation practices, the model can be used as a design tool. Agronomic measures will affect the volume of runoff through changes in interception storage and infiltration, the velocity of runoff through Manning's n, the rate of soil detachment through changes in the raindrop sizes and therefore momentum of the rainfall as it passes through the plant canopy, and both soil detachment and transport capacity, indirectly through effects on runoff and directly through changes in soil cohesion brought about by the root system and the soil's organic content. Approaches to modelling these vegetation effects are discussed in Rickson and Morgan (1986). Different tillage practices will alter soil cohesion and, through changes in microtopographic roughness and depression storage, affect Manning's n and therefore runoff velocity. Changes in infiltration will affect runoff volume. Runoff volume and velocity together will change surface water depth and therefore influence soil detachment.

Third, by combining the erosion model with the SHE distributed hydrological model, a scheme is provided for extrapolating point or small area determinations of erosion to a larger area or catchment. As pointed out by Nielsen and Styczen (1986) who are developing their own soil erosion model to superimpose on SHE, such a scheme can simulate spatial variations in sediment yield within a catchment. This means it can help to identify the locations of sediment sources and sinks, vital information for planning soil conservation works on a regional scale.

## 6. CONCLUSIONS

The objective of this paper has been to present ideas for discussion and not to propose a definitive model. The selection of processes to include in the model, the choice of variables and the operating equations are all open to criticism. The philosophy underlying the paper, however, is that greater benefit will be achieved by developing an erosion model from within Europe based on the approaches and framework described here rather than continuing to test and apply American models to European conditions. The large number of citations made in support of the framework indicate that European scientists have more than laid the foundation for model development. Indeed, in at least three aspects European work would appear to be ahead of American research. These are the modelling of soil detachment under vegetation covers, the prediction of rilling and the study of soil conservation practices in a way that simulates their effect on soil erosion processes.

By simplifying the erosion system to three components, runoff generation, soil detachment and transport capacity, and by choosing to apply the model to selected storms for which the starting conditions can be fairly easily determined, many of the problems associated with complex, daily simulation models have been avoided. Instead, the scheme presented should be easy to use for both assessing erosion risk and designing soil conservation measures.

Much research still needs to be done to make the scheme operational. Procedures need to be developed for estimating input parameter values. The model needs to be validated against field data. Progress may well depend upon the enthusiasm of European scientists to coordinate their research, not just in modelling but also in linking models to other methods of erosion assessment and in collecting through field measurement suitable data for model validation. Given the increasing recognition of soil erosion and the lack of precise information on the area of the European Community that is in danger of serious physical degradation through erosion, this coordination effort should be afforded a high priority. The success of recent European work on the understanding of soil erosion processes causes the authors to be optimistic on the development of a European model for soil erosion.

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