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"An Experimental Model for Evaluating Soil Erosion on a Single-Rainstorm Basis"

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An experimental model for evaluating soil erosion on a single-rainstorm basis

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Soil erosion is widespread and severe in Italy. During recent decades, new agricultural techniques accelerated erosion, while traditional soil conservation measures were neglected, especially in hilly areas.

Research on soil erosion in Italy began in the late 1960s at a few experimental centers that were not representative of the whole nation (3). These efforts remained isolated until the National Research Council (CNR) started a 5-year project on soil conservation, which ended in June 1982.

The CNR project was developed along the lines of the universal soil loss equation (USLE) (*16*). Erosivity, erodibility, slope-length, and crop factors were investigated.

Notable results of the soil conservation project (5) include the following:

1. Italy has at least five climatic zones, from the Alps, where rainfall mainly occurs in summer, to Sicily, where rainfall is unequally distributed during the winter.
2. Heavy rainstorms occur often, making any sort of mean unrepresentative of the real situation (9).
3. Most of the total annual erosion occurs during a few rainstorms.
4. Because soil loss is concentrated within a few storms, sediment contribution to the river system is often critical, affecting the infrastructure of downstream towns and villages.
5. The hazard of localized, severe loss of soil fertility is high.
6. The USLE does not apply everywhere in Italy (*4*, *8*).

Statistical models are not suitable because of the many climatic zones;

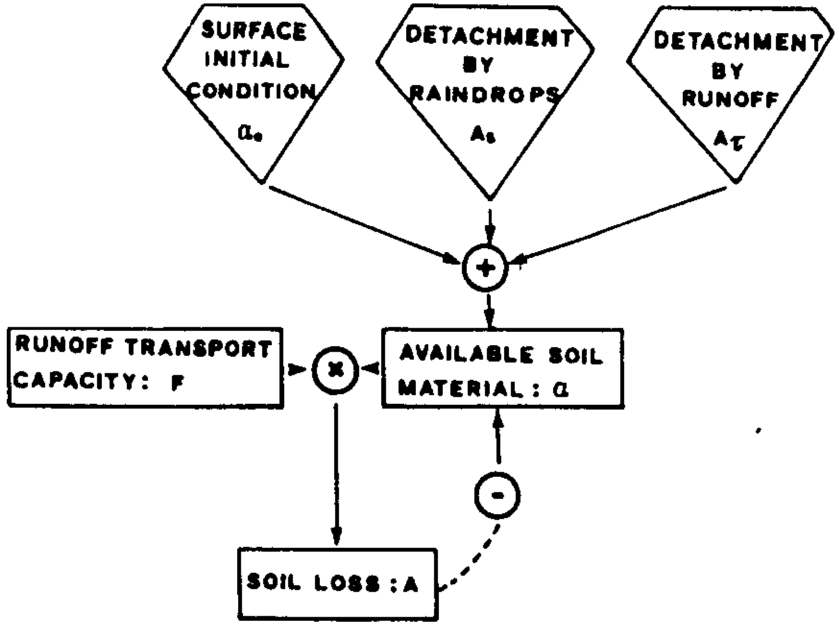

Figure 1. Scheme of the model.

moreover, such models are unfeasible because of funding and organizational limitations.

A deterministic model could be more feasible, but recent research indicates that models based on erosion mechanics could be more useful in forecasting soil loss (*6*). Whether statistical or deterministic models are used, equations are needed that can forecast erosion during critical events. The soil conservation project sponsored a first study of soil erosion mechanics with this aim in view (*5*). This paper discusses some early results.

Conceptual model and mathematical layout

The model is based on the fact that runoff transports particles and aggregates available to be transported. Therefore, transport capacity of runoff is one of the main factors of erosion. The quantity of material available is variable in space and time. It mainly depends upon the balance between the amount of material detached by raindrop impact and runoff shear strength and the transport capacity of runoff.

Figure 1 is a scheme of the model. It shows that the material available is a balance between input (essentially, material detached by raindrops and runoff) and output (washed-off material). The amount of material al-

ready detached decreases with time as runoff washes it away. It can affect the beginning of the erosion-versus-time curve.

If dA/dt is the erosion rate, transport capacity is estimated through the force of transport (F) and α is the material available (*12*), then

$$\frac{dA\,(t)}{dt} = \alpha\,(t)\;F\,(t) \qquad [1]$$

where

$$\alpha(t) = f\,(\alpha_0(t),\,A_s(t),\,A_\tau\,(t),\,A(t))$$

is the material available: $\alpha_0(t)$ = material available since the beginning of the event; $A_s(t)$ = material detached by raindrops; $A_\tau(t)$ = material detached by runoff shear strength; $A(t)$ = washed-away material; and t = time.

Materials and methods

Laboratory experiments. The rainfall simulator is described elsewhere (*1*). Rainfall is produced by nozzles sprinkling downwards.

The soil was collected from the plow layer. The methodology used to prepare the samples for the tests is described in Torri and Sfalanga (*11*). In short, air-dried material was sieved through a 4-mm net and then used to prepare the surface of the soil samples.

The containers in which the soil material was settled were 50 cm wide and of variable length (47 to 200 cm) and slope (5 to 31%). The soil was usually saturated by capillary rise for 48 hours before testing.

Field simulator experiments. The simulator (*13*) produces rain sprinkling upwards. The plots (24 m long, 3 m wide) were prepared as for a seedbed and wetted to bring the upper layer near saturation.

Field natural experiments. The field trials were carried out on two small watersheds at Guiglia Experimental Center (Modena) in the north central

Table 1. Laboratory experiments.

Approximate Experimental Plan	*Equation 2*		*Equation 3*	
	Degree of Fitting	*Number of Data*	*Degree of Fitting*	*Number of Data*
3 soils x 3 intensities x 4 slopes	0.980	41	0.944	56
6 soils x 3 intensities (slope = 10%)	0.843	21	0.802	25

Appennines (2). Each watershed was 1.5 ha and had a uniform slope of about 13 percent and a length of 135 m along the maximum gradient line. The watersheds were hydraulically isolated. Rainfall, runoff, and sediment rates were measured.

Each watershed was subdivided into four sections 33 m long by ditches on the contour. Summer row crop and lucerne were cultivated alternatively on the two units.

The data presented here correspond to rainfall, runoff, and soil losses per event in the period when there was no soil cover and the soil was tilled for seedbed preparation.

Results and discussion

Laboratory experiments. The laboratory experiments were planned to control separately the mechanics of detachment caused by raindrop impact, mechanics of detachment caused by runoff shear stress, and relationship between F and runoff discharge rate.

Soil containers 48 cm long with variable slopes were used to measure splash and sheet erosion. (Shear stress was negligible.)

Complete results of this first stage of the research are described elsewhere (*12*); only a summary is given here.

The results showed that detachment by raindrop impact can be expressed by the following equation (*10*):

$$\frac{dA_s}{dt} = \beta \frac{(\mathrm{tn}\,\gamma + \frac{4}{\pi}\mathrm{tn}\varphi)}{1 + \mathrm{tn}^2\varphi}\left(\frac{E(t)}{Eo} - 1\right) \quad [2]$$

where β = an empirical constant; tnφ = the initial slope of the trajectory of the splashed particles (tn$\varphi \approx$ exp (− Ds)); E = the kinetic energy of rain per unit of surface and time; Eo = dissipated energy per unit of surface and time (Eo $\approx$ exp (− Ds)); tnγ = slope of the plot; Ds = dry bulk density; and t = time.

The data on sheet erosion illuminate the relationship between the force F and the runoff discharge rate. If we suppose α constant in a certain situation (constant rainfall rate and constant runoff rate), then equation 1 can be integrated with time as

$$A = cP \quad [3]$$

where c = constant and P = runoff momentum (F = dP/dt).

With formulas linking discharge rate and runoff speed, P can be evaluated.

The formulas giving the estimator of P that was the best related to erosion were derived from the Navier-Stokes equation (7, pp. 75-76). The equation relating P and the runoff discharge rate (q) is as follows:

$$P = \left(\frac{g}{3\nu}\right)^{1/3} \frac{w}{\varrho^{2/3}} \int q^{5/3}\,dt \quad \sin^{1/3}\gamma \quad [4]$$

where: g = acceleration of gravity; ν = kinematic viscosity of the fluid; w = width of the plot; ϱ = density of the fluid; γ = slope angle; and q = runoff discharge rate per unit of width.

The coefficient c was shown to be dependent on (a) the amount (ψ) of soil aggregates stable at 48 hours of saturation and passing through a 63 μ sieve and (b) on dry bulk density (D_s):

$$c \approx \exp(\psi/D_s)$$

The coefficient c showed no significant variation due to changes in rainfall intensities or plot slope. In this simplified situation, c has a meaning similar to that of the erodibility factor K of the USLE. It is in agreement with the main subfactors determining K. This agreement is evident in that c is partially determined by an index depending on structural stability of the soil. K depends on particle size distribution and organic matter content (*14*), which are correlated to structural stability.

Equations 2 and 3 were calibrated on three soil types (Table 1). Control tests were made on six other soil types in the same laboratory conditions. These tests obtained fairly good results.

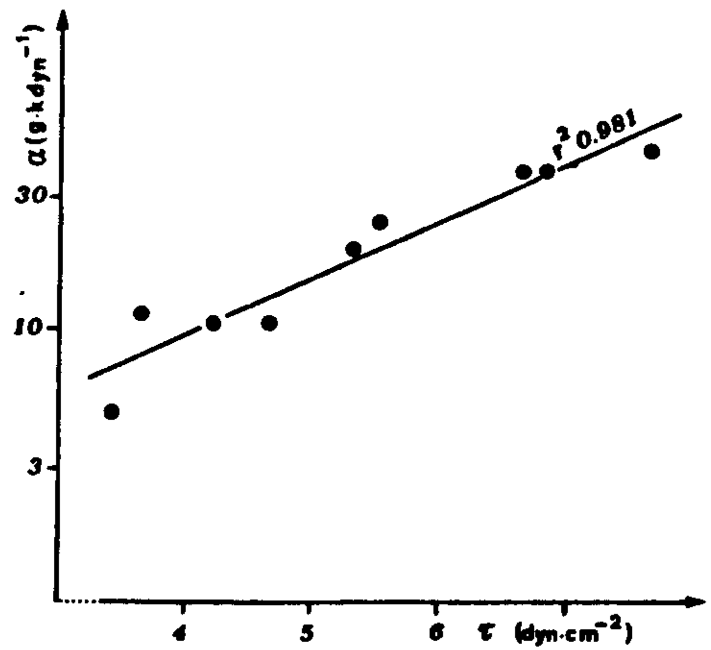

Figure 2. Relationship between α and the shear stress.

Table 2. Field experiments.

Kind of Test	*Approximate Experimental Plan*	*Degree of Fitting*	*Number of Data*
Field simulation	1 soil x 3 intensities x m* replicates (seedbed condition – length = 24 m)	0.837 (S. Benedetto)	9
		0.997 (Vicarello)	8
		0.775 (Albugnano)	9
		0.576 (Fagna II)	5
Natural plots	1 soil x 1 slope x 1 length (seedbed condition)	0.820 (Guiglia)	20

*m is a variable number.

In another set of experiments, still in progress at the time of writing, containers 2 m long are used in gathering information about shear stress. Preliminary results are presented here for one of the soils that is highly erodible by rills. Shear stress was estimated through the following equation derived from Landau and Lifchitz (7):

$$\tau = (\varrho g)^{2/3} (3\nu)^{1/3} \sin^{2/3}\gamma \, q^{1/3} \quad [5]$$

Figure 2 shows the relationship between measured values of α (equation 1) and the calculated values of τ. The fairly good agreement seems to indicate that equation 5 is a good estimator of shear stress, but it has not yet been sufficiently tested.

Field experiments. The soil conservation project gave us an opportunity to test the model with data collected in the field, using both simulated and natural rains. Because the field experiments were planned before the model was sketched, some field information necessary to control the model was not collected. Still, a comparison was made to see whether the estimate of runoff force was related to erosion. The degree of fitting varied by soil. One soil (Fagna II) was strongly affected by rill erosion at the highest rain intensities, but its determination coefficient was low because the model is not yet sufficiently developed to describe rill erosion.

Another test was made using data collected in natural plots (2). The model was tested for 20 winter rains (Table 2).

Conclusion

The model is based mainly on soil availability (α) and force of transport of runoff (F). Availability is a balance between some subfactors, namely, raindrop and runoff detachment rates and erosion rate. An estimator of F was proposed and tested. It obtained satisfactory results, although further tests are needed.

Raindrop detachment rate was mainly dependent on rain kinetic energy and soil characteristics. Runoff detachment rate was proportional to runoff shear stress. Both detachment rates need to be tested further, especially that for runoff.

The balance between the factors has yet to be defined. Only some experimental evidence has been collected at present and elaboration is still in progress.

The model has some weak points: (a) The force of transport and the shear stress are estimated through formulas derived in conditions of uniform flow at a steady state; (b) runoff characteristics strongly affect the model. However, since the model is intended to forecast soil loss during critical events, simplifications in forecasting runoff are to be expected.

The experimental results indicate that the main factors and subfactors defining the USLE (namely, kinetic energy of rain, particle size distribution, and organic matter content) are strongly related to erosion as all of them are implicitly or explicitly present in the model.

The model is far from operative but the results obtained so far indicate that it shows promise for forecasting soil loss during critical events. This kind of forecasting is of great importance in the Italian environment.

REFERENCES

1. Bazzoffi, P., D. Torri, and C. Zanchi. 1980. *Stima dell'erodibilità dei suoli mediante simulazione di pioggia in laboratorio.* Nota I: simulatore di pioggia. Annali Istituto Sperimentale Studio Difesa Suolo II: 129-140.
2. Boschi, V., and C. Chisci. 1978. *Influenza delle colture e delle sistemazioni superficiali sui deflussi e l'erosione in terreni argillosi di collina.* Genio Rurale 41(4): 7-16.
3. Chisci, G., L. Lulli, G. Ronchetti, and C. Zanchi. 1972. *Ricerche parcellari sulla conservazione dei suoli argillosi. I. Impostazione sperimentale, metodologie, strumentazione.* Ann. Ist. Sper. Studio e Difesa del Suolo, Firenze, vol. III: 51-72.
4. Chisci, G., and C. Zanchi. 1981. *The influence of different tillage systems and different crops on soil losses on hilly silty-clayey soil.* In R.P.C. Morgan [ed.] *Soil Conservation: Problems and Prospects.* Wiley Interscience Publ., Chichester, Eng. pp. 211-217.
5. Chisci, G., A. Giordano, S. Indelicato, O. Li Destri Nicosia, M. Sfalanga, and D. Torri. 1982. *Acquisizioni per la previsione dell'erosione idrica sui versanti.* Atti Convegno comelusivo P.F. "Conservasione del Suolo." pp. 187-202.
6. Foster, G. R., F. Lombardi, and W. C. Moldenhauer. 1982. *Evaluation of rainfall-runoff erosivity factors for individual storms.* Trans. Am. Soc. Agr. Eng. 25(1): 124-129.
7. Landau, L., and E. Lifchitz. 1971. *Mécaniques des fluides.* MIR, Moscow. pp. 672.
8. Li Destri Nicosia, O. 1981. *Indagine sperimentale sui fattori dell'erosione idrica superficiale.* Congresso Intern. su "Problemi idraulici nell'assetto territoriale della montagna," Milano, 11-13 Maggio.
9. Santoro, M. 1983. *Aggressività della pioggia nello studio dell'erosione idrica del territorio siciliano.* Publ. Quad. 164. Istituto di Iobraulica, Palermo, Italy.

10. Sinai, G., D. Zaslavsky, and P. Golany. 1977. *Excess runoff caused by raindrop splashes*. Winter meeting, Am. Soc. Agr. Eng. Dec. 13-16, 1977, Chicago, Illinois.
11. Torri, D., and M. Sfalanga. 1980. *Stima dell'erodibilità dei suoli mediante simulazione di pioggia in laboratorio*. Nota II: Preparazione dei campioni di suolo. Annali Istituto Sperimentale Studio Difesa Suolo 11: 141-157.
12. Torri, D., and M. Sfalanga. 1982. *Some aspects of soil erosion mechanics: Laboratory experiments*. Annali Istituto Sperimentale Studio Difesa Suols XIII: 75-89.
13. Turi, G. 1979. *Progetto e taratura di un simulatore di pioggia*. Genio Rurale 42(9): 31-36.
14. Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. *A soil erodibility nomograph for farmland and construction sites*. J. Soil and Water Cons. 26(5): 189-193.
15. Wischmeier, W. H., and D. D. Smith. 1978. *Predicting rainfall-erosion losses from cropland east of the Rocky Mountains*. Agr. Handbk. 537. U.S. Dept. Agr., Washington, D.C.