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Upland erosion: evaluation and measurement*

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ABSTRACT The author describes the connection between experimental research and mathematical models in assessing and forecasting upslope soil erosion. The objectives and scale of quantitative evaluations of erosion effects are considered. The "state of the art" of modelling upslope water erosion is briefly reviewed considering the progress from the first generation models (USLE) obtained by analysis of plot data, to the second generation mathematical models (Foster *et al.*, 1977a) which need parameterization and validation from experimental tests. Field and laboratory experiments and their relationship to the needs of model parameterization and validation are discussed.

Erosion à l'amont des versants: estimation et mesure L'auteur décrit les rapports entre recherche RESUME expérimentale et modèles mathématiques en vue de déterminer et prévoir l'érosion du sol à la partie supérieure des versants. Les considérations fondamentales concernant les objectifs et l'échelle de l'évaluation quantitative des effets de l'érosion sont mise en évidence. On effectue une revue de l'état actuel des méthodologies pour la mise en modèle de l'érosion à la partie supérieure des versants en considérant les progrès realisés depuis les modèles de la première génération (USLE) obtenus par l'analyse des données des parcelles jusqu'aux modèles de la seconde génération (Foster et al., 1977a) qui nécessitent la paramétrisation et le contrôle par l'expérimentation. L'organisation des expérimentations sur le terrain et au laboratoire est étudiée aussi que les besoins de paramétrisation du modèle et de son contrôle par l'expérimentation.

INTRODUCTION

Soil erosion is a natural phenomenon influencing soil genesis and landscape dynamics and, through them, playing a fundamental role in the evolution of the ecosystem. Soil erosion assumes a negative role only in connection with land utilization by man. In fact, already in its natural expression (geological erosion) it may represent a constraint to land utilization, while human activity often increases the intensity of the process (accelerated erosion) bringing a progressive and sometimes

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permanent degradation of the basic resources fundamental for the development of human society in a given environment. Therefore the understanding and measurement of water erosion factors and processes is important both for the evaluation and measurement of their effects on the evolution of the natural ecosystem, and for assessment and planning of conservation measures necessary when man's intensive exploitation of the natural ecosystem accelerates these phenomena.

The scientific knowledge of water erosion has progressed through the understanding, definition, classification and measurement of the factors and processes involved; establishing the relationships between them; and finally the modelling of the complex systems for forecasting purposes. From such forecasting models, conservation measures have been derived and tested for different environmental conditions.

From the beginning the study of water erosion has followed two fundamental methods common to every physical science:

(a) The theoretical understanding and classification of the physical factors and processes and the determination of the mathematical relationships between them for forecasting models.

(b) Experimental quantitative measurements of the "effects" of the factors and processes involved, aimed at the parameterization and testing of the mathematical relationships and the comparative empirical evaluation of experimental results.

MEASUREMENT OF SOIL EROSION BY WATER; OBJECTIVES AND SCALES

When we try to assess the factors and effects which have been used as "quantitative indices" of the water erosion process, it can been seen that they depend largely on the spatial scale at which the phenomena is studied.

Using evidence from sediment concentration in rivers, measurements of soil loss from hillsides, and investigation into the relationships between scale and erosion rate and scale and drainage density, Morgan & Keech (1976) reported that the factors mainly influencing soil loss by water erosion are climate at a broad regional scale (macroscale); while local variations (mesoscale) are mainly a result of relief; and variation at field scale (microscale) reflect differences in crop cover, slope and the use of conservation measures. An attempt to classify the kind of measurement data available as indices of soil erosion "effects" at these three scales is summarized below:

Macroscale and mesoscale Sediment transport in rivers and streams Distribution and density of surface drainage system Geomorphological mapping system for soil erosion Factorial scoring of erosion intensity

Microscale

Soil loss from hillslopes Soil natural profile curtailment Surveys of soil depth losses of different erosion forms Evaluation of soil fertility indices

The selection of what kind of measurement is better suited to

Aim of analysis	Factor
Macroscale and mesoscale Quantitative modelling of sediment transport Evaluation of the erosion hazard Definition and planning of general conservation measures and design of mechanical and land use measures for conservation Water quality evaluation and control Financial allocation of funds for conservation	Climate Topography Lithology Land use
<i>Microscale</i> Quantitative modelling of erosion on slopes Evaluation of soil degradation hazard Definition and planning of mechanical and agrobiological measures for soil conservation on slopes Evaluation of soil material contribution to the transport system	Rainfall erosivity Length, gradient and form of slopes Soil erodibility Crop management Soil management Land management

Table 1 Factors and aims of analysis of water erosion phenomena

assess water erosion depends also on the purposes for which the measurement is intended. Table 1 shows a tentative classification of such purposes.

We shall confine this paper to a review of upslope microscale measurements of water erosion factors and effects, keeping in mind two general aspects for which water erosion assessment and forecasting at such a scale is important in the study of the overall water erosion process in a basin: (a) the evaluation of changes in soil fertility on a given unit of slope, (b) the evaluation of the contribution of soil sediment from a unit slope source to the stream transport system, relevant to water quality, bank and bed erosion in channels, deposition in channels, reservoirs, flood plains and the sea. Such evaluations provide the information necessary to develop plans and conservation measures to control both soil loss and erosion damage in upland areas and the sediment contribution to the stream system and lowland areas.

STATEMENT OF THE PRINCIPLES

The amount of soil erosion by water depends basically upon the combination of the power of the rain to cause erosion and the ability of the soil to withstand the rain. In mathematical terms erosion (E) is a function of the rain erosivity (R) and of the soil erodibility (K):

$$E = f(R,K)$$

(1)

Other factors certainly influence this basic relationship, reducing or increasing rain erosivity and soil erodibility and, consequently, soil erosion rate. However, in relation to erosion rate, generally only the factors R and K are measured in derived units, since such factors as soil morphology, vegetation cover, crop and land management are taken as subsidiary factors and normally expressed as ratios, which describe conditions other 334 G. Chisci

than the standard conditions given by the basic equation (Hudson, 1971).

The erosion rate (E) from a slope can be evaluated by measuring either the amount of sediment transported by water across a transverse section or the lowering of the soil surface. Erosivity (R) is defined as the potential ability of the rain to cause erosion, while erodibility (K) is defined as the vulnerability of the soil to be eroded. The complexity of erodibility and erosivity is illustrated in Fig. 1.



Fig. 1 Basic factors affecting sediment loss on a slope due to water erosion.

Considering the main phases of soil erosion by water as defined by Ellison (1947), i.e. detachment and transport of soil particles, it is possible to separate the total erosion into: splash erosion (E_S) due to the impact of rainfall drops which detach soil particles and translocate them by saltation; overland flow erosion (E_O) due to the detachment and translocation of particles of sediment by overland flow of water; and rill erosion (E_r) due to the removal and translocation of soil material by the shear force of concentrated rill flow (Alberts et al., 1980).

The effects of these separate components vary according to the size and other characteristics of the experimental plot, particularly slope angle and downslope length. Splash erosion is not influenced by the length but only by slope angle; while overland flow erosion occurs on the areas between rills and is influenced only slightly by the distance of the sheetflow to the rills and influenced much more by slope steepness. Rill erosion is a linear process depending largely on the length and steepness of the slope.

Erosivity can be subdivided into splash erosivity $(R_{\rm S})$ due to raindrop impact, inter-rill flow erosivity $(R_{\rm O})$, and rill erosivity $(R_{\rm r})$ that are due to the shear force of the overland

and channelled flow and its transport capacity.

Erodibility can be subdivided into soil detachability $({\rm K}_{\rm d})$ which depends mainly on the soil matrix characteristics; soil rillability $({\rm K}_{\rm r})$, the susceptibility of the soil to rilling, which depends on the soil matrix characteristics; and soil transportability $({\rm K}_{\rm t})$ which is the susceptibility of the detached soil particle to be transported in overland and rill flow and depends on the physical characteristics of the transported material.

Considering all the above mentioned factors, the following basic conceptual model can be formulated for the erosion process:

 $E = f(E_{s}, E_{o}, E_{r}) = f(R_{s}, R_{o}, R_{r}, K_{d}, K_{r}, K_{t})$ (2)

From this general equation, conceptual submodels can be derived in which the dimensions of the experimental plot play an important role in determining the main factors causing soil loss.

Many different experiments are necessary to understand the interrelationships between all the factors in (2). In practice, in quantitative water erosion studies the various factors, processes and effects have been combined in a number of ways, so that they may be given a quantitative expression for use in digital models for forecasting soil loss. Wischmeier & Smith (1965) who elaborated the well known universal soil loss equation (USLE) analysing annual average soil loss from runoff plots, utilized an integrated rainfall erosivity factor (EI_{3O}) and also an integrated erodibility factor (K). The more recent mathematical models developed by Meyer et al. (1975), Foster & Meyer (1975), Foster et al. (1977a, 1977b), taking into account the main phases of detachment and transport, have divided the erosion process into inter-rill and rill erosion. Following this concept, they have subdivided the erosivity factor into rainfall erosivity (I_t), depending on kinetic energy of the rainfall as the Wischmeier & Smith factor does, and runoff erosivity (F_+) , depending on the volume and peak discharge of runoff (Williams, 1975). Also the soil erodibility factor was subdivided into: inter-rill erosion (K_i) , which takes into consideration soil characteristics related to detachability by splash and transportability by overland flow; and rill erosion (K_r) , which takes into consideration soil characteristics related to rillability by channelled flow and transportability in the rill flow.

WATER EROSION IN UPLAND AREAS: STATE OF THE ART

The study of water erosion in upland areas is a relatively young science, especially in relation to quantitative measurements of erosion data. From about 1915 runoff, soil loss and related field conditions were measured continuously at 42 stations in 23 states of the USA for periods ranging from 5 to 30 years. In 1954 the Agricultural Research Service (ARS) of the US Department of Agriculture (USDA) established a National Runoff and Soil Loss Data Center at Purdue University. The USLE, obtained using these data (Wischmeier & Smith, 1965) has been used operationally since then by planners to determine the average annual soil loss from slopes and the potential soil loss reduction from alternative crop and soil management systems. This equation has the form

(3)

A = R K S L C P

where A is the average annual soil loss in tons per acre; R is a rainfall erosivity index calculated for each erosive event; K is a soil erodibility factor whose units depend upon the amount of soil loss for a unit of erosivity R, under specific conditions; (continuous cultivated bare fallow); L is the unit length factor, a ratio which compares the soil loss of the given unit length with that of a field of specified length (72.6 ft); S is the slope factor, a ratio which compares the soil loss from a given slope to that of a field of a specified slope (9%); C is the crop management factor, a ratio which compares the soil loss of a given crop management system with that from a field under a standard treatment (continuous cultivated bare fallow); P is the conservation practice factor, a ratio which compares the soil loss for a land management system with that from a field with no conservation practices (i.e. ploughing up and down the steepest slope).

The USLE has been adapted for forecasting average soil loss in many countries outside the USA by modifying some of the factors in the equation to fit climate, soil and management conditions elsewhere (Hudson, 1965; Lal, 1977; Kowal & Kassam, 1977; Roose, 1977; El-Swaify, 1977; etc.).

From its inception, consistent improvements in the USLE model have been made in connection with the evaluation of the erodibility factor K from soil matrix characteristics (Wischmeier & Mannering, 1969; Wischmeier *et al.*, 1971; El-Swaify & Dangler, 1977; Roth *et al.*, 1974), and for the quantitative evaluation of the crop management factor (C), also for construction areas, pasture, rangeland, wasteland and woodland (Wischmeier, 1975). Moreover, the evaluation of the topographic factor LS was improved by a better parameterization of the power coefficient for the effect of slope length (L) on increasing steepness (Foster *et al.*, 1977b), and for applications to irregular slopes (Foster & Wischmeier, 1974).

Plot studies have enabled the major erosion factors to be identified, and have provided a wealth of information on control measures. However, plot studies have some inherent limitations: the effects of rainfall characteristics and soil properties cannot be isolated in a "one location" study, where rainfall and soil are either constant for a plot series or vary in unison; also many secondary variables interact with the controlled variables and such interactions can substantially bias the evaluation of soil loss over short periods.

The USLE is probably the most accurate field operational model at hand for forecasting average annual soil loss on a unit slope basis. It remains, however, essentially an erosion control planning tool for conservationists in the USA and other countries to devise conservation measures to maintain cropland productivity.

Some of the shortcomings of the USLE are:

(a) The limited capacity to evaluate soil loss on a unit storm

basis.

(b) Integration of water erosion processes without any knowledge of the sediment sources and the phases of detachment, transport and deposition of sediment.

(c) Inherent difficulty of integrating soil loss from unit slopes into an overall sediment load transport system.

(d) Insufficient information on the physical and chemical characteristics of the sediment load along the transport system.

Fundamental studies of erosion mechanics conducted concurrently with the development of the USLE and receiving increased emphasis since 1960, have attempted to overcome some of these shortcomings. Basic mathematical models (second generation models) are being developed, separating the erosion process into rill and inter-rill erosion according to the source of the eroded material (Meyer *et al.*, 1975; Foster & Meyer, 1975), and considering the phases of soil detachment and transport in the general erosion process in upland areas (Ellison, 1947). Moreover, the principle of continuity of sediment transport by overland flow was assumed (Bennett, 1974), taking into account also the continuity in time, for the calculation of soil loss and sediment load on a storm to storm basis.

It has been shown (Foster et al., 1977a, 1977b) that the accuracy of estimates for individual storms can be significantly improved by using a soil loss equation having separate terms for rill and inter-rill erosion. However such models have not yet become field operational because additional research is needed to bridge certain information gaps. In particular, research is needed to define precisely the relationships between rill erosion and runoff erosivity and between inter-rill erosion and rainfall While in relation to the rainfall erosivity factor, erosivity. the EI_{3O} index seems the best estimator available, the evaluation of runoff erosivity based on runoff volume and peak discharge (Williams, 1975) requires a simple reliable method for estimating runoff from rainfall and soil characteristics. The soil factors K_i and K_r need to be defined and related to easily measurable soil properties; the separate effects of cover, management and conservation practices on rill and inter-rill erosion need to be established.

Forecasting the sediment contribution from slopes to the stream system is very important for devising sediment control measures. One of the first methods for estimating upslope contributions to basin sediment yield using average soil loss from unit slopes, was the gross erosion sediment delivery method based on the USLE (US Department of Agriculture, 1971). By this method, the detachment, transport and deposition phases of the erosion process on slopes are integrated in the evaluation of gross erosion, while the transport and deposition phases along the stream system of the basin are integrated in a sediment delivery ratio which is the ratio between the estimated gross erosion for a basin area to the experimentally measured sediment yield at the outlet section of the basin. From an analysis of runoff and soil loss data in small basins covered by a single crop, Williams (1975) concluded that the sediment delivery ratio could be eliminated by using the basin runoff volume times peak rate for the value of R

in the USLE. An advanced simulation model taking into account an evaluation of sediment load and rill and inter-rill erosion based on a single storm was developed by Onstad & Foster (1975). It is substantially an erosion deposition model which involves the calculation of soil detachment and transport potential on a storm by storm basis.

Another important aspect of the upslope water erosion contribution to the stream system is pollution by sediment and chemicals, mineralogical clay and water stable aggregates being the main vehicles of pollutants. Eroded material normally has a higher organic matter content than the soil matrix because organic matter particles are lighter than most mineral particles and tend to remain in suspension. Also the organic matter content of aggregates in the sediment is high.

The location of the source areas of the sediment and the erosive agent dominant in detaching and transporting the sediment, can significantly affect the particle-size distribution of the resulting sediment. The size distribution of both sediment aggregates and primary particles may differ from those of the original soil (Sfalanga & Franchi, 1978). The size and the density of aggregates are particularly important in sediment transport analysis; the range in sizes and densities of detached soil material that is available for transport may result in selective erosion (Meyer et al., 1975). Differences in particle size distribution and selection of material during transport to the stream system are dependent on the energy of the rainfall, season, vegetation cover and soil management (Chisci et al., 1977; Sfalanga & Franchi, 1978). An attempt to predict the particle size distribution of sediment from soil matrix characteristics was done by Young & Onstad (1976), based on specific soil surface area and texture and considering organic matter enrichment and rillability of the soil.

The latest available mathematical model for chemical, runoff and erosion from an agricultural management system on a field scale is CREAMS (US Department of Agriculture, 1980).

The detailed models available may be quite useful in studies of sediment and chemical transport on a particular field or basin, but field data for calibrating or testing these models are quite limited. Consequently, much more research is needed to make the second generation simulation models field operational.

MEASUREMENTS OF WATER EROSION ON EXPERIMENTAL PLOTS

Erosion data are needed for (a) validation of general water erosion models; (b) parameterization of factors and mathematical equations to be used in the models.

Experiments on water erosion can be performed in the field or in the laboratory (Table 2), depending on the factors and processes to be evaluated.

Rainfall erosivity as defined by Wischmeier & Smith (1958) depends on the total kinetic energy of raindrops. Many devices have been proposed to measure it. Some indirect; assuming the raindrops'speed at the impact moment almost equal to the terminal

Rainfall	Soil
Field experiments Natural Simulated	Undisturbed under different experimental treatments Undisturbed under different experimental treatments
Laboratory experiments Simulated Simulated	Soil cores under different experimental treatments Soil completely disturbed under different experimental treatments

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velocity of droplets in stagnant air (Laws, 1941; Gunn & Kinzer, 1949), it was necessary to determine the raindrop size distribution vs. intensity. Many methods were used to do this: flour pellets (Laws & Parsons, 1943), filter paper, cryo-pellets (Bazzoffi, 1980), etc. Direct methods to measure the impact energy of raindrops have been proposed using devices such as drums, disdrometers, piezoelectric discs (Joss & Waldvogel; Kowal & Kassam, 1977; Gori, 1978), which give direct continuous measurements of the energy of impact of raindrops during a storm or at any chosen interval of time. However, while the latter methods give information about the impact energy, they do not directly give the raindrop distribution, which is quite important because the energy of large impacting drops is dissipated on the soil differently from the energy of small drops due to different shapes and collapsing times. Many factors other than rainfall intensity affect raindrop distribution and velocity in natural conditions; i.e. type of storm, wind speed and direction, temperature (Laws & Parsons, 1943; Hudson, 1963; Lyles, 1976; Zanchi & Torri, 1980; Torri, 1979).

Following the evolution of mathematical modelling, rill erosivity is the second and perhaps most important measure of rain aggressiveness. Rill erosivity is not yet well defined, mainly because of a lack of experimental data. In fact runoff plots under natural rain, data from which were used to obtain the USLE model, generally give information about the combined effects of splash, sheet, and rill erosion. Rainfall simulator experiments are better suited to give the kind of data needed at present, because it is easier to divide rill from inter-rill Following the model set up by Foster et al. (1977a, erosion. 1977b), a measure of flow shear stress was used by Alberts et al. (1980) to estimate rill erosivity. It consisted of measuring flow velocity by timing the movement of a food colouring dye and in determining the cross section of the rill by a profilimeter, the density of runoff and the slope of the rill.

Therefore, rill erosivity is a difficult parameter to measure and especially to forecast. Rill erosivity is described in terms of shear stress of the rill flow and critical shear stress that is the minimum value over which rill erosion will occur. The critical shear stress obviously depends on the soil characteristics but also on the soil conditions such as soil wetness, tillage practices etc. when the process of rilling starts. The evaluation of runoff erosivity and soil erodibility are strictly connected with runoff and soil loss measurements and will be discussed later with the experimental techniques actually in use for the empirical measurement of the effects of water erosion.

Field measurements of runoff, soil loss and physical and chemical characteristics of the exported material are generally obtained experimentally using:

(a) small plots on which runoff does not play any consistent role in soil loss;

(b) bounded runoff plots of known area, slope steepness, slope length and soil type, from which both runoff and soil loss are monitored;

(c) laterally open plots of slope length, bounded only at the downward transverse section to monitor both runoff and soil loss. The physical and chemical characteristics of the exported sediment can be measured on any of these plots by sampling runoff.

There are many ways to monitor soil loss by splash erosion, all of which are applications to field conditions of the Ellisontype splash cup (Ellison, 1944). Two such devices were designed by Bollinne (1975) and by Gorchichko (1976).

Bounded runoff plots vary in size depending on both the type of experiment and the method of data collection. The number of runoff plots to be used for soil loss measurement depends on the purpose of the experiment and usually allows for at least two replications, to compromise between the necessity of controlling random variability and of reducing the considerable efforts and expense necessary for such experiments. In relation to the size of the experimental plot, one must take into account (a) that by reducing the size of the plot, and particularly its length, the soil loss is increasingly less dependent on runoff parameters; and (b) certain treatments of soil, crop and land management to be evaluated (i.e. farming operations, soil tillage practices, conservation measures, etc.) require more space (Table 3). The lead in the design and operation of bounded runoff plots for measurement of runoff and soil loss has unquestionably come from the USA. A standard layout for bounded runoff plots is described by Hudson (1965).

Type of plot	Size	Experiment
Micro-plots	1-2 m ²	Relative erodibility of soil Comparison of ground covers Comparison of other "no space" dependent treatments
Standard plots	40 m ² (22.6 m \times 1.8 m)	Evaluation of standard erodibility on a 9% slope Cropping and rotation experiments
Macro-plots	> 200 m ²	Field scale operation treatments Tillage treatments Tree covers Mechanical protection measures

Table 3	Size of	bounded	runoff	plots and	d the	type of	experiment
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Actually, field experiments on soil erosion have been done in many countries other than the USA, so a large amount of information is available on the design and operation of bounded runoff plots.

Measuring devices for runoff, soil loss, and sediment sampling have different design characteristics depending on the plot size and the data to be collected. The most important considerations in choosing such devices are measurement accuracy and operative layout, especially when they are required to function automatically for a certain time (Table 4).

Although bounded runoff plots, when correctly designed for the experiment to be carried out, give the most reliable data on runoff and soil loss from a unit area, there are several sources of error involved with their use. These include silting of the collecting trough and pipes leading to the measuring devices, inadequate covering of the trough against rainfall and the maintenance of a constant level between the soil surface and the rill or lip of the trough. Other problems are that runoff may collect at the boundaries of the plot and form rills which would not develop otherwise, and that the plot itself is a partially closed system separated from the input of upslope water and sediment (Hudson, 1957). Nevertheless, the effect of the errors outlined above decreases with increasing plot size.

Laterally open units for measuring runoff and soil loss were devised by Gerlach (1967) using a simple metal gutter with an outlet pipe draining to a collecting bottle. Because there are no plot boundaries, edge effects are avoided but the definition of the catchment area of the plot is uncertain. When it is important to state runoff and soil loss per unit area instead of that per unit width of gutter, it is necessary to assume that any lateral loss of water and sediment is balanced by inputs from adjacent areas. This assumption is reasonable only when the plane of the slope is straight (Morgan, 1979).

Measurement of soil loss can be achieved also by measuring the lowering of the soil surface on an experimental unit in its different erosion forms. This method normally provides a very crude estimate of soil erosion as pointed out by Hudson (1971). The direct measurement of changes in soil level is most suitable in the case of localized erosion forms, to evaluate changes in morphology and rillability. Moreover, the measurement of soil lowering under natural rainfall conditions is practicable only for long intervals of time.

Piest *et al.* (1977) in attempting to monitor surface microchanges on a slope, used a low-altitude photogrammetric procedure. The measurement was possible with an accuracy of about 0.6-1 cm so that it was not possible to detect soil changes in a cornfield for a period less than 5 years.

Several devices for measuring changes in the surface level of soil subject to erosion have been described by Gleason (1957), Hudson (1965) and Panicucci (1972). The profilimeter presented by Meyer *et al.* (1975) was made of a close set of metal pins (0.64 cm apart) freely movable vertically on a metal framework, which can measure the cross sectional geometry of a rill bed, so that both the lowering of the soil surface and changes in the rill

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		Devices				
		For runoff		For sediment rate		
Type of plot	Plot size	Continuous measurement	Total for a storm or longer period	Continuous measurement	Chosen time intervals during a storm	Total for a storm or longer periọd
Micro-plots	1-2 m²	Calibrated weir, triangular or logarithm, with hydrometer or hydrograph devices	Collecting tanks	Turbidimeters	Manual sampling Pumping sampler	Collecting tanks
Standard plots	40-100 m²	Calibrated weirs with hydrograph device: HS flumes, Venturi-type flumes (i.e. Parshall) Weighing tanks with recording devices (Linsalata-Cavazza type)	Collecting tanks with divisors: Geib-type or Coshocton-type	Turbidimeters Weighing tanks with recording device	Manual sampling Pumping sampler	Collecting tanks
Macro-plots	> 200 m²	Calibrated weirs with hydrograph device: H and HL flums, Venturi- type flums (i.e. Parshall) Weighing tank with recording device (Linsalata-Cavazza type)	Collecting tanks with divisors: Coshocton- type	Turbidimeters Weighing tanks with recording device	Manual sampling Pumping sampler	Collecting tanks

bed can be evaluated.

Field measurements of runoff and soil loss under natural rainfall conditions are necessary to obtain a reliable historical series of data either to validate forecasting models or to assess factors related to crop, soil and land management.

The effect of management practices on water erosion and sediment contribution to the stream system has usually been studied (a) by intensive experimental measurements on plots or basins; (b) by analysis of the data using statistical models; (c) by generalization of results for more extensive application.

Statistical models need many data and much time to collect them: unfortunately, we can no longer afford this luxury of time. Policy decisions must often be made quickly and by the time statistical significance has been obtained, the practice could be obsolete.

Alternatively more detailed mathematical models may be used in analysing data, obtained by specifically designed experiments in a shorter time. The experimental data can be used to estimate model parameters and techniques must be developed for predicting from readily obtainable physical measurements. Simulation can then be used to evaluate the stochastic properties of the system and to examine the long term effects. In this context, laboratory experiments could be very useful, but field experiments using rainfall simulators are also a great help.

Laboratory experiments are particularly suited for the study of the mechanics of erosion because the effects of many factors can be controlled. However, because of the artificiality of laboratory experiments, some confirmation of their applicability to field conditions is desirable (Morgan, 1979). The most difficult, if not impossible, problem is the layout of the soil sample. Depending on the aim of the experiment, depth and slope of the sample are very important parameters. Morover, in relation to soil conditions, the experiment could be performed using either an undisturbed soil core or soil disturbed in a lot of different Many examples of laboratory experiments on water erosion ways. mechanics could be quoted from the literature. Here we mention only laboratory experiments on the effect of rainfall impact on soil detachment and transport by Ellison (1947), Mutchler & Young (1975), Young & Mutchler (1969), Young & Wiersma (1973), and laboratory experiments on the particle size distribution of eroded material (Moldenhauer & Koswara, 1968; Gabriels et al., 1975; Gabriels & Moldenhauer, 1978).

Zanchi (1979) summarized the "state of the art" of the construction and use of rainfall simulators, indicating the most important physical characteristics for such a device to be operational. The main problem with rainfall simulators is that they have to represent natural rainfall, both in impact velocity and the size distribution of drops at a certain rainfall intensity. Simulators can be divided in two main groups according to whether drops are formed: (a) using capillary tubes or hypodermic needles, or (b) using nozzles. The working principles of several types of rainfall simulators are well illustrated in Hudson (1971).

Capillary tube-hypodermic needle simulators require a dense arrangement of drop formers per surface unit so they can only have small dimensions, especially suitable for laboratory experiments. However, they cannot produce small drops and consequently, they cannot simulate correctly the raindrop distribution of natural rain. The impact velocity of the drops is usually less than in natural rainfall because with this device the initial velocity of droplets is zero and 8-10 m of free fall are needed to gain terminal velocities found in the range of drop sizes most common in natural rain.

To overcome this problem water is released from low heights under pressure. For this, nozzle simulators are more commonly used and these can sprinkle water upwards or downwards. Sprinkling water upwards is possible only in the field, because in this case there is also the problem of the height of fall. Moreover, simulators sprinkling upwards, are particularly subject to malfunctions in relation to wind problems. Nozzle simulators sprinkling upwards or downwards normally produce rain intensities which are too high, but this effect can be reduced by sprinkling intermittently. Intermittency, however, must be as short as possible because it affects infiltration and consequently the quality of simulation.

At the present time many simulators are available but none accurately reproduces all the properties of natural rain (Hall, 1970).

In field applications, other considerations have to be taken into account that can limit the quality of simulation and its operativity, such as the surface covered by simulated rainfall, ease of handling, costs, etc.

In laboratory applications, where the target is a small soil plot, the rainfall simulator can be supplemented by a device to supply a known quantity of runoff at the top of the plot, instead of relying solely on runoff resulting from rainfall. This facility is helpful for studies of overland erosion (Savat, 1977) and to simulate length in rill erosion (Gabriels & Moldenhauer, 1978; Alberts *et al.*, 1980).

Plots and laboratory experiments using simulated rainfall have been particularly useful in the assessment of soil erodibility, also in its more specific forms of rill and inter-rill erodibility, and in formulating mathematical equations which relate soil erodibility to the physical and chemical characteristics of the soil matrix (Wischmeier & Mannering, 1969; Wischmeier *et al.*, 1971; El-Swaify, 1977; Roth *et al.*, 1974).

The parameterization of mathematical equations for evaluation of rill and inter-rill erosion factors in simulation models for forecasting soil loss and sediment transport can be done more quickly by using rainfall simulators in the near future.

CONCLUSIONS

The erosion hazard on large areas of productive land has greatly increased everywhere due to population pressure, increased export demands for agricultural products, use of large machines, enlargement of fields with continuous long slopes and the increasing practice of extensive monoculture which reduces the protective effect of sod-based rotation systems on cropland.

Besides the increased sediment contributions to the stream system, the widespread use of chemicals to sustain crop production has enhanced the hazard of water pollution from nonpoint sources (Chisci, 1980).

The solution of those problems lies in the evaluation of the erosion rate on slopes and sediment contribution to the stream system and in applying conservation measures to keep both erosion rate and sediment contribution within carefully established tolerance limits. However, to be effective such measures must be integrated in planning basin development.

We saw that average annual soil loss from slopes can be predicted with reasonable accuracy using the USLE. Recent progress in developing mathematical models has demonstrated their potential in predicting temporal and spatial distribution of erosion and sedimentation. However, some basic relationships, assumed in these models, need further research so they can be parameterized and validated for a wide range of field conditions.

Development of new agronomical and mechanical measures for conservation of soil fertility on slopes and for pollution control need to be devised and tested. On the other hand, the quality and characteristics of the sediment reaching a continuous stream system cannot yet be soundly forecast. The knowledge of the sediment contribution process from slopes to the stream system is, in fact, unsatifactory and requires further research.

Mathematical modelling and experimental measurements are complementary in the advancement of our knowledge on water erosion representing the master-keys of its assessment and forecasting and in finding conservation measures to keep it under control.

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