SOIL ERODIBILITY INDICES FOR SOUTHERN QUEBEC SOILS DERIVED UNDER VARIABLE INTENSITY RAINFALL SIMULATION

by

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ABSTRACT

M.Sc. Aubert R. Michaud Renewable Resources

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SOUTHERN QUEBEC SOILS DERIVED
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A stationary, variable-intensity rainfall simulator was conceived, calibrated and used in a soil erodibility study on southern Quebec soils. The apparatus simulates rainfall at any range of intensities up to 127 mm/h with drop-sizes and impact velocities near those of natural rainfall.

A standard simulated rainstorm composed of four consecutive rainfall runs of decreasing intensity was applied to eight experimental runoff plots in agricultural fields of the Montreal and Eastern Townships regions. Rainfall energies required to initiate runoff, runoff rates, sediment concentrations in runoff and cumulative soil losses were measured for each rainfall run at each site. Soil erodibility indices for each soil were evaluated by linear regression of soil loss and simulated rainfall erosivity data. Soil erodibility indices were found consistently higher when evaluated by combinations of rainfall runs applied on wet soil as opposed to dry storm combinations. The aforementioned dependent variables were related to site and soil physico-chemical properties using correlation and regression methods. Soil particle-size distribution, organic matter content and bulk density were found significant contributors in explaining rainfall energies required to initiate runoff and runoff rates among the sites tested. Soil aggregation stability, particle-size distribution and slope gradient significantly accounted for variability in sediment concentrations in runoff and soil losses.

RESUME

M.Sc. Aubert R. Michaud Ressources Renouvelables

Un simulateur de pluie stationnaire à intensité variable fut conçu, calibré et utilisé au cours d'une étude d'érodabilité des sols du sud du Québec. Le simulateur reproduit sensiblement les grosseurs de goutelettes d'eau, la vitesse à l'impact et l'énergie de la pluie naturelle jusqu'à une intensité de pluie de 127 mm/h.

Une pluie-type composée de quatre sessions de pluie simulée à des intensités décroissantes fut appliquée sur huit parcelles expérimentales installées dans des champs agricoles des régions de Montréal et de l'Estrie. Les taux de ruissellement, de concentration du ruissellement en sédiment et de perte de sol étaient mesurés sur chaque site à chaque session de pluie simulée. Les indices d'érodabilite du sol étaient estimés par regression linéaire des données de perte de sol en fonction des érosivités des pluies simulées. Les indices d'érodabilité des sols pour des combinaisons de sessions de pluie sur sol détrempé se sont avérés supérieurs aux indices évalués par des combinaisons de pluie sur sol sec à tous les sites. Les variables dépendantes mentionnées ci-haut ont été mises en relation avec les propriétés physico-chimiques des sols. La granulométrie, le contenu en matière organique et la densité apparente des sols à l'étude ont contribué significativement à expliquer les variabilités observées dans l'énergie de pluie requise pour initier le ruissellement et les taux de ruissellement. La stabilité des agrégats, la granulométrie des sols et l'inclinaison de la pente des sites ont contribué à expliquer significativement les variabilités observées dans les concentrations du ruissellement en sédiments et les pertes de sol.

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FOREWORD

This thesis contains an introductory chapter, followed by a ~~literature~~ literature review. Chapter 3 and 4 discuss, respectively, the development of the rainfall simulator and its use in a soil erosion study. General conclusions are reported at the end of the thesis.

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1. INTRODUCTION

In the last thirty years, technological advances in most industrialized countries have lead to drastic intensification and concentration of agricultural production. Fewer farmers cultivate larger areas more intensively; economic incentives favoring wide-row cropping has greatly reduced and sometimes eliminated crop rotations. In Quebec today, the total farmland area in production is half of what it was in the 1950's, while the average producer cultivates twice as much land. The last ten years have seen a rise in popularity of row-cropping in Quebec: grain-corn seeded farmland has nearly tripled during this period.

These pressures on farmland have been recently associated with degradation of the soil resource, not only in Quebec, but all across Canada. The cost of soil degradation in the country was priced at 1.3 billion dollars per year, which represents 38% of the net revenue generated by each hectare of Canadian land (Science Council of Canada, 1986). In that perspective, 1.1 million hectares of farmland in Canada could be lost due to water erosion by the year 2008.

Soil erosion by water faces the Canadian agricultural communities with a double problem. Besides jeopardizing the quantity and productivity of tomorrow's farmland, sediments and runoff exported from the fields constitute a major "non-point" source of pollutants. Thus, sediment and associated lost plant nutrients not only represents an economic loss to the Canadian farmer in the order of 15 to 30 dollars/ha annually, in terms of fertilizers (Agricultural Institute of Canada, 1980), but also become both a physical and chemical pollutant in waterways.

The most efficient and practical tool for soil loss prediction was developed by U.S. researchers over the past half-century. The "Universal Soil Loss Equation" (USLE) was used successfully by the U.S. Soil Conservation Service to develop individual farm plans for controlling soil erosion. The prediction model considers the rate of rainfall erosion to be determined by climate, soil, topography, and plant cover. The two major limitations for the adaptation of the USLE to Canadian conditions are the lack of proper estimations of both climatic and soil influences on soil loss.

Although some soil loss data have been collected in the past on runoff plots in Quebec, no direct measurements of soil erodibility have been reported. The main purpose of this research project was to obtain soil erodibility indices compatible with the USLE for typical agricultural soils of southern Quebec. A rainfall simulation procedure was selected in order to accumulate soil loss data under standard rainfall conditions in a short-term experiment. An original variable-intensity rainfall simulator was conceived with the purpose of respecting, as much as possible, the common range in rainfall intensities of southern Quebec.

2. Literature Review

2.1. The Universal Soil Loss Equation

2.1.1. Concept, development, and limitations

The basis for using mathematical relationships to describe soil erosion began about the mid-thirties in the U.S. Cook (1936) listed three major factors to describe soil loss: soil erodibility, rainfall and runoff erosivity including the slope effect, and the protection afforded by vegetal cover.

The use of equations to calculate field soil loss began in the Corn Belt when Zingg (1940) published an equation relating soil loss rate to length and gradient of slope. The following year, Smith (1941) added crop (C) and supporting practice (P) factors to the equation. The C-factor then included the effects of weather and soil as well as cropping system. This soil loss estimating procedure, referred to as the slope-practice method, was used throughout the Corn Belt in the 1940's. The introduction of extensive tables of factor values for different soils, rotations and slope lengths (Browning et al. 1947) enhanced the field use of the equation.

In an effort to broaden the applicability of the Corn Belt equation, a national U.S. committee reappraised the factor values and added a rainfall factor. The so-called Musgrave (1947) equation included factors for rainfall, slope gradient and length, soil characteristics, and vegetal cover effects. However, the adequacy of the 2-year, 30-minute rainfall to the 1.75 power, adopted as the rainfall factor in the Musgrave (1947) equation, was not confirmed by subsequent research.

From computerization of over 7,000 plot-years and 500 watershed-years of basic precipitation, soil loss, and related data (Wischmeier, 1959), a rainfall factor for the U.S. east of the Rocky Mountains was made possible (Wischmeier and Smith, 1958). Following the combination of crop rotation and management factors into a crop management factor (Wischmeier, 1960), the "Universal Soil Loss Equation" was first introduced in its present form by Wischmeier and Smith in 1960. Up to 1978, several thousand additional plot-years and watershed-years of data augmented by data from erosion-plot research using simulated rainfall were added to the original USLE data bank as they became available. The complete presentation of the USLE was revised by Wischmeier and Smith (1978) to include these latest data. Additional developments to the 1960's USLE included a soil erodibility nomograph (Wischmeier et al., 1971), topographic factors for irregular slopes (Foster and Wischmeier, 1974), cover and management effects of conservation tillage practice (Wischmeier, 1973), cover factors for range and woodland (Wischmeier, 1975), erosion prediction on construction areas (Meyer and Ports, 1976), improved evaluation of erosion control support practices (Laflen and Johnson, 1976), and rainfall erosivity data for the western U.S. and Hawaii (Brooks, 1976; McCool et al., 1976).

The current Universal Soil Loss Equation (Wischmeier and Smith, 1965; 1978) as converted to SI metric units (Foster et al., 1981) is:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where: $\underline{A}$ is the predicted soil loss in t/ha.y. It estimates the average annual rill plus interrill erosion from rainstorms for field-sized areas. It does not include erosion from gullies and streambanks but does include eroded sediment subsequently deposited before it reaches downslope streams.

R is the rainfall and runoff erosivity factor for a specific location, expressed as average annual erosion index units (EI) in MJ.mm/ha.h.y and derived from individual storm rainfall energies and 30-min maximum intensity products.

K is the soil erodibility factor for a specific soil horizon, expressed as soil loss per unit of area per unit of R for a unit plot (t.ha.h/ha.MJ.mm). A unit plot is 22.1 m long with a uniform 9% slope maintained in continuous fallow with tillage when necessary to break surface crusts.

LS is the dimensionless slope-length and gradient factor,, expressed as the ratio of soil loss from a given slope length and gradient to that of a 22.1 m long, 9% gradient slope under the same conditions.

C is the dimensionless cover and management factor, expressed as a ratio of soil loss from the condition of interest to that from a tilled unit plot condition.

P is the dimensionless supporting erosion-control practice factor, expressed as a ratio of the soil loss with practices such as contouring, strip cropping, or terracing to that with farming up and down the slope.

The mathematical relationship between each of the USLE factors and soil loss was determined from statistical analyses of the assembled data. It utilizes four dimensionless factors to modify a basic soil loss that is described by dimensional rainfall and soil factors; regression lines and correlation coefficients were key aspects of its development. Thus, the relationships within the USLE are primarily statistical in form rather than physical. The equation computes long-term average annual soil losses for specific combinations of physical and management conditions (Wischmeier, 1971). Since the primary need was a relatively simple technique for predicting average annual soil losses as a working tool for conservationists, technicians, and planners, refinements needed only for short-run predictions were sacrificed in the interest of conciseness and simplicity. Direct use of the USLE for soil loss prediction on an individual runoff-event basis, for example, is basically a misuse (Wischmeieir, 1976), since soil losses during specific storms and in specific years are greatly influenced by irregular, temporal fluctuations in secondary parameters.

The "universality" of the USLE was commented on by Wischmeier (1972; 1976) in response to criticism of the term "Universal" in the USLE. Wischmeier stated that application of the USLE is limited to areas where information is available for local evaluations of the equation's individual factors. Wischmeier (1972) also recognized exceptions to the validity of the EI parameter (rainfall energy times the 30-min. peak intensity) as a measure of the combined erosive forces of rainfall and runoff. The work by McCool et al. (1982) and Evans and Kalkanis (1976) in California, Zuzel et al. (1982) in the Pacific Northwest, and Pall et al. (1982) in Southern Ontario clearly demonstrates that a more accurate predictor of runoff-erosion potential needs to be substituted as the value of R in their regions respectively. In all three areas, runoff derived from rainfall and/or snow was shown to contribute a major portion of the erosive potential that is not adequately accounted for by the rainfall kinetic energy and intensity parameters used to evaluate the R factor in the central and eastern U.S.

Although the indicated nature of effects of topography, cover, and management variables was suggested universal by Wischmeier (1972), it has not been shown that the specific ratios for L, S and C derived in the central and eastern U.S. are necessarily accurate in vastly different areas. McCool et al. (1982) obtained markedly lower exponent values for L and S than those from central and eastern U.S. data. In California, Evans and Kalkanis (1976) could not justify the assumption that LS is uniquely related to the length and steepness of the slope; the soil moisture-soil temperature regime was used as an indicator for selecting a proper LS relationship to soil loss. The effect of slopes with gradients appreciably in excess of 20% is also a serious void in research information recognized by Wischmeier (1972).

2.1.2. Beyond the USLE

Current research on soil erosion by water is putting emphasis on obtaining a better understanding of the basic principles and processes of erosion and sedimentation. Erosion prediction in the future will likely be based more on fundamental, as opposed to empirical, relationships derived on the basis of mathematical descriptions of the erosion process. In terms of modelling, the need for information about the basic erosion processes led to two major research trends: the experimental modification of the USLE and the derivation of new equations.

A system of subfactors for computing the C factor in the USLE was introduced by Mutchler et al. (1982). These subfactors are multipliers that represent the effects of land use residual, incorporated residue, tillage intensity and recency, macroroughness, canopy and cover. Since the use of a single value for K in the original USLE resulted in a soil erodibility component concealed in the "C" factor, it became necessary to represent the hidden erodibility component in the division of the cover and management factor "C" into subfactors. Mutchler and Carter (1983) proposed the use of coefficients "Kc" to be applied to the conventional K factor based on the monthly variation of soil erodibility to enable the effective study and use of the "C" subfactors.

Using data from slope lengths up to 183 m under simulated rainfall, Mutchler and Greer (1980) proposed a new equation for the slope length factor "L" of the USLE better adapted to gentle slopes:

$$L = (\lambda/22.13)^m \quad (2)$$

where λ = slope length in m

$m = 1.2 (\sin \theta)^{1/3}$

$\sin \theta$ = % slope/100

Following this research, a correction factor to reduce the USLE erosion prediction on gentle slopes, "Rc", was proposed (Murphree and Mutchler, 1981).

A major weakness of the USLE for short-term soil - loss prediction was highlighted in the 1970's when erosion models for individual storms were developed. The failure of the rainfall erosivity factor (R) to adequately express hydrology, particularly antecedent conditions, led to its modification. Williams (1975) proposed a replacement for the erosivity factor of the USLE using watershed area, volume of runoff, and peak flow rate data. Since the equation was derived using watershed sediment yield, the erosivity factor expressed the effect of a delivery ratio. The Onstad-Foster (1975) replacement for "R" was expressed as:

$$Ro = 0.5\ R + 3.42\ Q\ qp^{1/3} \quad (3)$$

where R is the annual USLE "R", Q is the volume of runoff (mm) and qp is the peak flow rate (mm/h).

The Onstad and Foster (1975) concept of "R" was integrated as a runoff erosivity factor for a new erosion equation framework derived from basic erosion principles (Foster et al. 1977a,b). The proposed equation is based on the concept of dividing the erosion process into rill and interrill erosion according to the source of the eroded sediment (Meyer et al., 1975; Foster and Meyer, 1975). Considerable research based on basic erosion principles will be required to develop an operational equation from the sophisticated framework of Foster et al. (1977a,b). However, it is felt by the authors that improved soil loss estimates for single storm events and for specific time periods can be obtained from an operational equation of this type.

2.2. The definition of soil erodibility in the USLE (K)

In early soil loss equations derived from runoff plot data, the effect of soil was first represented by subjectively chosen constants and confounded with the rainfall effect (Zingg, 1940) and the cropping effect (Smith, 1941). A first expression of a soil factor relative to standard conditions for topography and rainfall was put forward by Musgrave (1947). The factor system for soil loss computation, later introduced by Smith and Whitt (1948), first expressed the soil erodibility as a dimensionless multiplier together with slope, cropping practice and conservation practice.

The definition of a rainfall index by Wischmeier (1959) made it possible to compare erodibilities of soils from different climatic regions, and develop the current form of the soil erodibility factor of the USLE (Wischmeier and Smith, 1960). Although similar in format to the Smith and Whitt (1948) factor approach, the USLE introduced substantial changes in the soil erodibility evaluation. The cropping management reference was changed from continuous corn to fallow, the gradient reference increased from 3% to 9% and the length of slope shortened from 27.6 m to 22.1 m. The final expression for K, the soil erodibility factor in the USLE, was then defined as the soil loss rate per erosion index unit for a specified continuously tilled fallow soil as measured on a unit plot 22.1 m long with an uniform 9% slope (Wischmeier and Smith, 1960). Instructions for establishment and maintenance of cultivated fallow plots were also issued (Smith, 1961) and proved to reduce considerably measured soil loss variations resulting from differences in soil manipulation. Recommended plot preparation was as follows:

- plowing to normal depth and smoothing immediately by disking and cultivating two or more times

- annual plowing at time row crop plots are plowed
- cultivation routine of row crop and also when necessary to eliminate serious crust formation
- chemical weed control if necessary
- up-and-down slope plowing and cultivation.

The fallow plot standards also required the removal or decomposition of surface and subsurface organic crop residue. Generally, a 2-year fallow period for eliminating organic residues was judged adequate for the warm, humid regions of the U.S. and tropical areas. The definition of K was also temporarily linked to climatic factors. The proposition that a rainfall cycle in the continental U.S. averaged 20 to 22 years (Wischmeier and Smith, 1965) emphasized the need for long-term determinations of K. In practice, an average period of record for fallow plots slightly less than 7 years has been used by Wischmeier and Smith (1965) in the publication of K values.

Implicit in Wischmeier and Smith's (1965) definition, the USLE K value appeared thus as a lumped "parameter" that integrated soil response to several erosion and hydrologic processes over variable storm frequencies and intensities, and variable conditions of antecedent moisture and surface roughness through a season or a year. The USLE K value thus remains empirical in nature and cannot be interpreted as a process-specific constant. As such, the K value lumps together the soil response to all specific erosive mechanisms, as described in deterministic approaches to soil erodibility (i.e. detachment and transport by raindrop impacts and overland flow shear forces).

2.3. Field evaluation of the USLE soil erodibility factor

2.3.1. K values from natural runoff plots

The evaluation of soil erodibility factors for benchmark soils has been particularly helpful in the estimation of K values for soils with similar characteristics and to verify estimations from rainfall simulation or modeling. However, only a limited number of direct measurements from natural runoff plots in fallow condition have been published. In fact, only eight soils on fallow plots, with periods of record ranging from 3 to 10 years and slopes from 5 to 18 % constitute the published data bank on soil K from fallow plots (Olson and Wischmeier, 1963). The "second generation" of benchmark K values given by Olson and Wischmeier (1963) were computed from cropped-plot data on 20 soil series. The data were adjusted on the basis of C values for each crop given by Wischmeier (1960), contouring factors, and length-slope factors. Direct comparisons of K values from the fallow plots with those from cropped plots yielded similar estimations for three soils, while the K values for two soils differed by 0.013 and 0.016 t.h/MJ.mm, respectively.

2.3.2. Rainfall simulation-based K values

The need for rapid and reliable estimates of USLE parameters has favored over the years the replacement of natural runoff plots by rainfall simulator experiments. Besides its widespread use in the study of the effects of cropping and tillage on soil erosion, rainfall simulation has also been extensively used to collect soil erodibility data. Larger plot-size studies (plots with a minimum of 10 m length) all used the same type of rainfall simulator (the "rainulator") developed by Meyer and McCune (1958) but differed in plot preparation and in the method of computing K values (Barnett et al., 1965; Wischmeier and Mannering, 1969; Barnett et al., 1971; Wischmeier et al., 1971; Romkens et al., 1975; Dangler et al., 1976; Young and Mutchler, 1977). Rainfall simulator storms, however, have been somewhat similar. Most storms in North American studies have been applied at an intensity of 6.4 cm/h in two storm periods 24 h apart. Barnett et al. (1965) used two 30-min storms at 6.4 cm/h with 10 min between storms, followed by an identical session 24 h later. Wischmeier and Mannering (1969) and Romkens et al. (1975) applied a 60-min storm at the same intensity followed the next day by two 30-min storms 15 min apart. Young and Mutchler (1977) followed a similar procedure, except on the second day when their rain was continuous for 1 h. Dangler et al. (1976) applied 2 h of continuous rainfall on each of two consecutive days.

Soil erodibility values have been determined in several different ways by using soil loss data from a series of rainfall simulator storms. Most data have been adjusted by using USLE length-slope and cropping management factors, except in the Wischmeier and Mannering (1969) study where regression equations derived from the individual storm soil losses were used to adjust data to unit plot specifications and average values of time-dependent variables. After linear regression of the adjusted soil loss on EI from four rain periods of 0.5, 1, 1.5, and 2 h, Wischmeier and Mannering (1969) represented the soil erodibility factor by the slope of the regression equations, while the negative intercept was primarily associated with surface detention and infiltration. Barnett et al. (1971) also determined soil erodibility values by using a similar regression method, but using data adjusted by USLE parameters.

Barnett et al. (1965) introduced the storm weighting procedure for the derivation of K values from simulated storms in the southeast United States. The adjusted soil loss and erosivity of the simulated rainstorms were weighted based on the storm frequency distribution relative to the erosivity of the storms at each soil location and an arbitrary 50% probability that storms of less than 45 erosion index occur on dry soil. A similar procedure was used by Wischmeier et al. (1971) in the development of a soil erodibility nomograph. Using the Wischmeier and Mannering (1969) data base from the Corn Belt, soil loss from dry runs was more heavily weighted than that from less frequent storms on wet soil to yield weighting factors of 13, 7, and 3, respectively, for storms on initially dry, wet, and very wet soils. Romkens et al. (1975) and Young and Mutchler (1977) used the same weighing factors (Wischmeier and Mannering, 1971) for studies on Corn Belt soils. Relatively close agreement of K values obtained with the rainfall simulator and from fallow natural runoff plots from Minnesota (Young and Mutchler, 1977) gave further credence to the weighting procedure.

Unfortunately no direct comparison between the regression and storm weighting procedures for determining erodibility from simulated rainfall data have been published. While the regression procedure strictly expresses the linear relationship between soil loss and rainfall erosivity as defined by Wischmeier (1959), it does not discriminate among soils for rainfall energy required to initiate soil loss. The regression procedure may then fail to express the soil erodibility factor variations among soils of widely different water regime. The storm weighting procedure, on the other hand, has merit for the estimation of average annual or average seasonal K values since it accounts for antecedent soil moisture conditions. The problem of estimating K values, however, becomes one of selecting weighting factors for each simulated storm, an approach that remains partially subjective and requires an extensive network of data on storm frequency distribution. The extrapolation of the narrow band of information from simulation experiments to the wide variety of storms and antecedent soil conditions that occur over a year or a season thus remains the major difficulty of simulation-based K values estimation.

2.3.3. The relationship of soil properties to erodibility

The erosion ratio concept derived by Middleton (1930) is one of the earliest attempts to determine the erodibility of a soil from its soil properties. The index expressed the quotient of the dispersion ratio over the ratio of colloid-to-moisture equivalent and was designed to reflect erosional characteristics and ability to absorb water by the soil. Organic matter content and silica-sesquioxide ratio were also identified as soil erodibility indicators. Following Ellison's (1947) identification of the four phases of the erosion process, research on the relation of soil properties to erodibility was mainly process-specific and largely dominated by the study of splash detachment and transport phases (Ellison, 1944; Mihara, 1951; Free, 1960; Bubenzer and Jones, 1971; Quansah, 1981; Savat and Poesen, 1981). The contribution to detachment by overland flow, as a specific erosion process (Ellison, 1947) has received very little attention. Quansah (1983), however, examined the relative contribution in soil loss from overland flow and raindrop impact. Soil texture was noted as a major factor in the erosive processes; the contribution to soil loss by splash as compared to overland flow was noted to double from a sandy soil to a clay on a 7% slope.

The development of the USLE, favoring an empirical rather than a deterministic expression of soil erodibility, has led to several field studies aiming at the modelling of K values based on soil properties (Barnett and Rogers, 1966; Wischmeier and Mannering, 1969; Wischmeier et al., 1971; Romkens et al., 1975; El-Swaify and Dangler, 1976; Young and Mutchler, 1977). All studies were performed under similar rainfall-simulation experimental conditions reported earlier in section 2.3.2.

Barnett and Rogers (1966) identified 34 independent variables in explaining the dependence of the K value. Slope steepness, however, was included as an independent variable, thus obscuring the effect of the intrinsic soil properties. Particle-size fractions, soil-water terms and combinations thereof were used. The study by Wischmeier and Mannering (1969) involved 24 independent variables consisting mostly of interaction terms of particle-size fractions, organic matter, structure, and aggregation index. The effect of specific soil properties appeared highly dependent on interacting properties. The effect of silt in increasing the soil K value, for example, depended on the other particle-size fractions, the organic-matter content, and the soil pH. From the same data base, Wischmeier et al. (1971) derived the soil erodibility nomograph in which a storm weighting procedure was used in the derivation of the simulation-based K values. Now widely accepted, the nomograph made it possible to predict K values from standard soil profile descriptions, and particle-size and organic-matter laboratory analyses. The textural parameter "M" of the nomograph (% "corrected" silt) x (% "corrected" silt + % "corrected" sand) could account alone for 85% of the K value variation of the medium-textured Corn Belt soils under study. The finding that very fine sand behaved like the silt fraction in the erosion processes precludes the merging of both fractions into a "corrected silt" class. The variation in K values among the 55 Corn Belt soils under study could be explained by the following algebraic equation with a 95% confidence interval of ± 0.005 t.h/MJ.mm:

$$759K = 2.1 \times 10^{4}(12-OM)M^{1.14} + 3.25(S-2) + 2.5(P-3) \quad (4)$$

where – S and P are indices for structure and permeability (U.S.D.A., 1951)

– OM is the organic-matter content

– M is the textural parameter "Corrected silt x (corrected silt + corrected sand)" (Wischmeier and Smith, 1978).

The accuracy of the Wischmeier et al. (1971) nomograph was tested by Young and Mutchler (1977) on 13 Minnesota surface soils using similar experimental procedures. Current nomograph values were shown to underestimate the erodibility of six and overestimate the K values of three of the 13 soils tested. Young and Mutchler (1977) indicated that the differences between measured and nomograph K values were due to differences in clay fraction (montmorillonite was dominant) and the degree of aggregation between the soils used in Wischmeier et al. (1971) and their study. Young and Mutchler (1977) further suggested that the erodibility of Upper Midwest soils could be more accurately predicted with an expression which takes into consideration the degree of soil aggregation and type of clay. A regression of the measured K values on ten soil physical characteristics explained 93% of the variations in K using bulk density, dispersion ratio, aggregate index, percent silt and very fine sand, and amount of montmorillonite as independent variables. Aggregate index and percentage of montmorillonite, although highly intercorrelated (r^2=0.70), alone explained 75% of the variation in K, while the textural parameter "M" showed a simple correlation coefficient of 0.30 with K. It was thus concluded that aggregation characteristics rather than textural soil parameters appeared as the important predictors of soil erodibility for the well-aggregated soils in the Upper Midwest.

The importance of soil aggregation to the K value was also stressed by Romkens et al. (1977) in their erodibility study on high-clay subsoils. Under standard rainulator tests on seven clay subsoils, citrate-dithionite bicarbonate (CDB) extractable percent of Al_2O_3 plus Fe_2O_3 was shown as having an important erosion controlling effect and was related to parallel findings (Kemper and Koch, 1966) of enhanced aggregate stability and reduced soil erosion as sesquioxide levels in soils increased. Together with "M", CDB extractable aluminium and iron oxides accounted for 90% of the variation in the subsoil K values. The study confirmed the importance of "M" for estimating K values and favored the use of textural parameter-binding agent combination as primary parameters of soil erodibility factors.

In their study of Hawaiian soils under standard rainulator procedures, El-Swaify and Dangler (1976) ranked "M" as only the seventh most significant variable in explaining K variability. Mineralogical class parameter, mean weight diameter, suspension percentage, base saturation, and percent unstable aggregates all yielded simple correlation coefficients with erodibility values higher than "M". The nomograph had limited validity for the tropical soils under study because of the low correlation coefficients between measured K and organic matter or structural/permeability classes as well as the high clay contents associated with the soils.

From the various studies relating measured soil erodibilities to soil properties, it appears difficult to predict K values from specific soil properties across a wide range of soils. Consequently, the aforementioned rainfall simulation studies appeal to prudence in adopting soil erodibility prediction equations developed within a definite "soils region" in a widely different edaphic environment.

2.4. Rainfall simulation technique

Rainfall simulators for studying infiltration, runoff, erosion, and sediment yield have proliferated. Several devices have been used for forming raindrops under energy levels and intensities simulating natural conditions. The size of simulators has varied from small laboratory systems to those covering several acres. All models however have a common goal: the closest possible reproduction of natural rainfall characteristics. This section reviews the studies on rainfall characterization that have been used as guidelines for rainfall simulator development, followed by a review of the main design criteria and concepts used in rainfall simulation over the past half-century.

2.4.1. Rainfall characteristics important for simulation

2.4.1.1. Raindrop size and velocity

Kinetic energy computations depend on the mass and velocity of raindrops. It was shown that both mass and drop fall velocity of natural rain are functions of its intensity. The reproduction of rainfall kinetic energy thus requires the expression of drop fall velocity and drop size spectrum of natural rainfall with respect to intensity.

DROP SIZE DISTRIBUTION

Studies of raindrop size characteristics as related to rainfall intensities have been conducted at various locations throughout the world

(Laws and Parsons, 1943; Hudson, 1963; Rogers et al., 1967; Carter, 1974). The most widely used study in rainfall simulator development is that of Laws and Parsons (1943) performed in Washington D.C. The data were also used by Wischmeier and Smith (1959) in the development of the energy-intensity factor in the USLE. Laws and Parsons (1943) showed curves of drop size - volume distribution that appear to be normal for intensities up to 90 $mm.h^{-1}$ which was the highest intensity curve they gave. The following exponential equation expresses the relation of median drop size (D_{50}) in mm and rainfall intensity (I) in $mm.h^{-1}$ given by Laws and Parsons (1943):

$$D_{50} = 4.018\ I^{0.182} \qquad (5)$$

Hudson (1963) presented smoothed curves for southern Zimbabwe that appear to be normal for intensities up to 100 $mm.h^{-1}$. For higher intensities, the drop-size distribution approached a log-normal scale. Rogers et al. (1967) compiled data that appear to fit the exponential model for D_{50} up to about 50 $mm.h^{-1}$, while D_{50} remains relatively constant at higher intensities. For the south-central U.S., Carter et al. (1974) found a cubic equation of D_{50} versus intensities up to 250 $mm.h^{-1}$, while indicating an increasing D_{50} up to 75 $mm.h^{-1}$. McGregor and Mutchler (1976) developed a three-term exponential relationship to relate D_{50} to intensity for the Holly Springs data of Carter et al. (1974). The equation expressed a rapid rise in D_{50} for intensities up to about 40 $mm.h^{-1}$ followed by a slowly decreasing drop size at the higher intensities. The continuous expression of D_{50} in mm for all rainfall intensities in $mm \cdot h^{-1}$ reported by McGregor and Mutchler (1976) is:

$$D_{50} = \frac{2.76 + 11.40\ e^{(-26.42\ I)} - 13.16\ e^{(-29.72\ I)}}{25.4} \qquad (6)$$

Following Carter et al. (1974), Wischmeier and Smith (1978) apparently recognized the bias in Laws and Parsons (1943) prediction that D_{50} increases continuously with intensity and limited its application up to 64 $mm.h^{-1}$ in rainfall energy evaluation.

Despite the variation encountered in various drop size measurement studies, the overall results clearly indicate a rapid increase in mean drop diameter with intensity for rainfall rates up to about 50 $mm.h^{-1}$. There is also considerable evidence that the mean drop diameter tends to remain nearly constant or decrease slightly at higher intensities.

FALL VELOCITY

Raindrop impact velocities have generally been assumed to be equal to terminal vertical velocity in studies of raindrop erosion, thus neglecting wind effects and effects of non-normal impact. Terminal velocities of waterdrops based on measurements by Laws (1941) and by Gunn and Kinzer (1949) have been particularly well accepted by rainfall simulator designers.

Laws (1941) conducted his extensive study of the fall velocity of water drops through still air as a function of fall distance for drops with diameters from 1.2 to 6.1 mm. Gunn and Kinzer's (1949) work, although using a different technique, substantiated Laws' data in the drop size range from 0.08 to 5.8 mm. Since most simulators have been designed on the basis of these data, most simulated rainfall thus represents minimum impact velocities of similar sized drops in natural storms, the actual velocity of a raindrop being function of wind speed (Van Heerden, 1964). It remains questionable however if wind velocity makes an appreciable change in the raindrop fall vector near ground level where wind velocities are generally the lowest in the surface air mass (Mutchler and McGregor, 1979).

2.4.1.2. Rainfall intensity and storm characteristics

Rainfall intensity has been reported to depend on storm type, location, season, and other factors. Thunderstorms are generally associated with summer months and high rainfall intensities while stagnate cold front storms have lower intensities (Stol, 1971). Orographic storms and combinations of the aforementioned types of storm have intensity patterns depending on the particular combinations of atmospheric influences (U.S.D.A., 1941). These temporal and geographical variations in intensity are known to have an effect on both the amount of erosion and runoff but remain poorly documented.

The main contribution on the effects of regional differences in intensity and storm characteristics on soil loss has been made by Wischmeier (1959), studying individual storms. The best single variable evolved from multiple correlation analysis for prediction of soil loss from cultivated fallow plots was the total energy of a storm and its 30-min intensity. The "EI" interactive variable was then selected as the rainfall erosivity factor of the USLE (Wischmeier, 1959). However, when the intensity distribution within rainstorms was studied by Wischmeier (1959), the division of storms as advanced, intermediate, and delayed intensity storms did not help him in explaining the variability between "EI" and soil loss.

The U.S. Soil Conservation Service generalized storm intensity distributions with two long-term average representations (U.S.D.A., 1968). The storm patterns were later updated to four (U.S.D.A. 1973). These storm intensity distributions, appearing closely associated with climatic regions and seasonal variations in rainfall intensity, were used by Ateshian (1974) in the development of a rainfall erosion index based on a 2-year 6-h rainfall.

However, the realism of using one-dimensional rainfall was seriously criticized by Renard and Simanton (1975) who compared the Wischmeier (1959) and Ateshian (1974) methods of evaluating erosivity for various rainfall events.

Elaboration of guidelines for selection of simulated rainfall intensities have thus been primarily restricted by the lack of documentation on temporal variations of intensity and its effect on soil loss. In fact, the selection of a design intensity or a design test storm for simulator development has been primarily oriented by the objectives of the investigators. For erosion and hydrology studies, very low and very high intensities are not of major interest, due respectively to the former's low contribution to annual soil loss and the latter's rare occurrence. Meyer (1979) identified intensities of about 10 to 100 $mm.h^{-1}$ as having the greatest importance for rainfall simulation. However, most simulators in use today do not allow researchers to vary storm characteristics during a rainfall event and since the most severe erosion problems have been associated with high intensity storms in the U.S., most American simulators have been designed to apply water at relatively high intensities. The concept of a universal rainfall simulator remains, however, closely associated with considerations of regional differences in rainfall intensity and storms characteristics. In areas such as southern Quebec where a major portion of the annual soil loss may be associated with low intensity rain on thawing or snow-covered fields (Kirby, 1985), climatologic and hydrologic considerations are likely to be critical.

2.4.2. Design criteria for rainfall simulation

The first step in the design of a rainfall simulator for runoff plots involves the development of a list of criteria to be met. As rainfall simulation techniques improved and research needs evolved over the years, the list of design criteria grew. Past and current criteria can be sorted into two groups: rainfall characteristics criteria and technical criteria; the first group being closely associated with experimental findings on natural rain and the latter linked to the technical imperatives of runoff plot research in the field.

2.4.2.1. Rainfall characteristics criteria

If a rainfall simulation study is to produce reliable indications of natural rainfall effects, the equipment should closely approach natural rainfall characteristics. A first extensive series of rainfall design criteria was formulated by Meyer and McCune (1958) in the development of their rainulator:

" - Drop size distribution of natural rainfall
- Drop velocity at impact near terminal velocity
- Uniform rainfall and random drop-size distribution
- Rainfall intensity corresponding to natural conditions"

The physical characteristics of natural rainfall used as guidelines were those of Laws and Parsons (1943) and Laws (1941). Meyer (1965) published two additional desirable rainfall characteristics:

" - An angle of impact not greatly different from vertical for most drops

- A rainfall application nearly continuous throughout the study area"

Although implicit in Meyer and McCune's (1958) criteria, Bertrand and Parr (1961) retained the total energy values of simulated raindrops as a design criterion. Finally, in the development of a rainfall simulator for erosion research on row sideslopes, Meyer and Harmon (1979) included the production of a wide range of rainfall intensities as a desired characteristic. The rainfall continuity criterion was obtained by minimizing intervals between intermittent rainfall to 10 s.

In a survey of 28 developers and/or users of rainfall simulators, Bubenzer (1979) reported that 90% of all responses indicated that mean drop size, intensity, and uniformity of coverage were selection criteria for their research. It appears, therefore, that the basic rainfall criteria for simulation are generally well established. Moreover, this apparent unanimity on rainfall criteria is highly desirable since the perfect nozzle or drop-forming device has not been developed yet.

2.4.2.2. Technical criteria

The need for economic, rapid and realistic runoff plot data from field research under simulated rainfall has also imposed design criteria on simulator designers. Early but still up-to-date technical criteria include minimum wind distortion, portability and ease of handling, use on standard-size runoff plots, and ability to reproduce a given storm (Meyer and McCune, 1958). Minimization of wind disturbance has been achieved in most runoff plot studies by the use of windbreaks or by limiting field trials to a threshold wind velocity. Since rainfall simulators are generally expensive to construct and use, complete portability in minimal time has also been a prime concern of all designers.

Application area criteria vary somewhat among various simulator models. Initial rainulator experiments were carried on plots of 85 to 22 m^2 by Meyer (1960). However, much smaller areas have been used with field simulators, but it is generally agreed that simulators which apply rain to experimental areas smaller than 10 m^2 are unacceptable for direct evaluations of the terms in the USLE (Römkens, 1979). The use of an adequate buffer area around the runoff plot was also identified as a technical criterion by Meyer (1960) and Bertrand and Parr (1961). Finally, a technical concept that enables reproducibility of a standard test storm over varying plot and slope conditions remains an essential design criterion of rainfall simulator models developed to date.

2.4.3. Conception of rainfall simulators for runoff plot research

During the past half century of rainfall simulation, several different concepts of simulators have evolved. These can be divided into two groups by their means of producing rainfall: drop formers and nozzle types.

2.4.3.1. Drop-former models

Early rainfall simulators used small pieces of yarn to form rainfall (Parsons, 1943; Ellison and Pomerance, 1944; Barnes and Costell, 1957). More recent simulators have used glass capillary tubes (Adams et al. 1957), polyethylene tubing (Chow and Harbaugh, 1965), brass or stainless steel tubes as drop formers (Blackburn et al., 1974), and hypodermic needles (Romkens et al., 1975). Most drop-former simulators produce drops of constant size; reported ranges vary from 2.5 mm diameter (Blackburn et al., 1974) to 5.6 mm (Adams et al., 1957). Various sizes of raindrop, however, were produced by Brakensiek et al. (1979) by using compressed air blowing around the drop formers. Most plot sizes associated with drop-former simulators are relatively small (up to 2 m^2). Notable exceptions include simulators developed by Chow and Harbough (1965) and the laboratory simulators located at Purdue and Utah State Universities (Bubenzer, 1979), which respectively cover plot sizes of 144, 21, and 96 m^2.

Although capable of producing rainfall kinetic energy close to its natural range, the use of drop-former simulators in outdoor conditions has been very limited. The main handicap has been the fall height required for water droplets to achieve terminal velocities (up to 10 m for a 4-mm drop). The relatively small coverage area of most models has also been a serious limitation for use in outdoor runoff plot research.

2.4.3.2. Nozzle models

Several different rainfall simulators with varying nozzles and interception mechanisms have been used for runoff plot research. Four nozzles, however, seem to predominate in modern simulators: the Spraying Systems 80100 and 80150 Veejets, the Spray Engineering 7LA, and the Rainjet 78C.

The Meyer and McCune (1958) rainulator used the Spraying Systems 80100 Veejet nozzle. Lateral movement of the nozzles across the slope by motorized carriage was used to limit rainfall intensity. Delays of up to 40 s between successive applications were made necessary for a 64 $mm.h^{-1}$ rainfall intensity. Swanson (1965) used the same nozzle on a rotating boom, while Bubenzer and Meyer (1965) developed an oscillatory laboratory simulator out of the 80100 Veejet nozzle. Seimens and Oschwald (1978) constructed a modified version of the rainulator which was self-propelled. The oscillating nozzle concept, which effectively reduces the rainulator intermittency, has also been incorporated into the inter-rill simulator of Meyer and Harmon (1979) and the new rainulator developed by Foster (1979), both using the 80150 Veejet nozzle. The kinetic energy level of the latter nozzle was found somewhat greater than that of the 80100 model.

Bertrand and Parr (1961) introduced the use of the Spray Engineering Company's 7LA nozzle for a stationary, continuous application rainfall simulator. Several variations of the "Purdue Sprinkling Infiltrometer" have been used since then. Amerman et al. (1970) and Rawitz et al. (1972) used slotted rotating disk units to reduce rainfall intensity. The concept of using a rotating disk was introduced some years before by Morin et al. (1967) in connection with the Spraying Systems 1.5H30 Fulljet nozzle.

Rainjet 78C nozzles have also been used on large-plot stationary simulators (Holland, 1969; Lusby, 1977). Energy levels of the droplets, however, are smaller than those of simulators using the Veejet 80100 and 80150 nozzles. The same problem has been reported for other simulator models using the type F nozzle (Wilm, 1953), the Spraying Systems 14 WSQ (Bubenzer, 1979) and the Bete Fog SRW 303 (Shriner et al., 1977).

It appears that the main handicap for realistic and efficient simulation of rainfall with nozzles has been the overcapacity of nozzles which are able to reproduce natural rainfall drop size and energy levels. Such overcapacity required either highly sophisticated intermittence mechanisms or the selection of nozzles with lower capacity that reproduce only a fraction of the energy level of natural rainfall.

3. Conception, design and calibration of a stationary, variable intensity rainfall simulator for outdoor runoff plot research.

3.1. Introduction

The collection of adequate research data for soil erosion studies involving natural rainfall is very time consuming because hydrologic processes are so variable. The need for rapid and efficient data collection for soil erosion has led to the development of rainfall simulators. In field studies, nozzle-type rainfall simulators have been primarily used over drop former type for practical purposes and also to simulate drop size distributions close to natural rainfall. Available nozzles producing drop and energy characteristics comparable to those of natural rainfall have limited use in rainfall simulation, however, due to their high flow rates. The problem of high nozzle capacity has been resolved in most field simulator designs by either intercepting a major portion of the spray (Morin et al., 1967) or increasing the coverage area by lateral or rotational movement of the nozzles (Meyer and McCune, 1958; Swanson, 1965). However the intermittency of water applications in rainfall simulator studies has been shown to have a significant effect on the amount of rainfall or energy a soil can absorb before runoff begins (Sloneker and Moldenhauer, 1974; Sloneker et al, 1974). Delayed surface sealing and variable soil water pressure have also been associated with soil shear strength increases and resulting soil splash decreases (Towner and Childs, 1972). Consequently, the need to relate rainfall simulator data to natural conditions favors a minimization of the on-off time in the nozzle-type simulators as a performance criteria in simulator design (Foster et al., 1979; Meyer and Harmon, 1979).

With the growing interest in soil erosion estimates based on individual storms (Onstad and Foster, 1975) and separation of rill from interrill erosion (Foster et al., 1977a,b), the understanding of the effect of rain intensity variations within rainstorms becomes increasingly important. The new emphasis on soil erosion research demands more flexibility in rainfall intensity from rainfall simulation equipment. Together with the minimization of spray intermittence, the ability to vary the rainfall intensity from rainfall simulation apparatus constitutes a design characteristic adapted to most current research needs.

This paper outlines the design, construction and calibration of a new nozzle-type variable-intensity rainfall simulator for runoff plot research. The apparatus was used in a soil erodibility study in southern Quebec.

3.2. Materials and methods

3.2.1. Design Considerations

The concept of a stationary, intermittent nozzle spraying system controlled by 3-way solenoid valves was retained as the basic design for the simulator. Such design presents many advantages, namely:

- It enables the operator to achieve complete control over simulated rainfall intensity, by alternating flow to the nozzle or to a return line.
- It makes possible the recycling of unsprayed water.
- It excludes mobile parts from the apparatus design.

Desired characteristics and performance criteria retained for the design, construction and calibration of the rainfall simulator included:

1. Wide range of intensities,
2. Minimum time between raindrop applications,
3. Drop size, fall velocity and impact energy of simulated raindrops similar to that of natural rainfall,
4. Uniform rainfall and random drop-size distribution,
5. Complete portability and economy of construction.

3.2.2. Construction

Following a first selection of pressure regulation parts for an experimental simulator unit, preliminary tests were carried out to study the performance of various three- and four-way ASCO solenoid valves. Four-way valve 8342A1, modified to three-way, was finally selected for the rainfall simulator unit. Its relatively high friction flow factor (Cv), minimizing pressure variation in the system, and compatibility with desired discharge range led to its selection.

Individual units of the simulator were then assembled using the following principal parts:

- 51 mm schedule 40 galvanized steel piping network
- 51 mm pressure regulator 20-350 kPa, Watts 26A
- 0-200 kPa pressure gauge, Solfrunt series 1900 6"
- 51 mm 60-mesh two-way brass strainer, ASCO 8600 A2
- 51 mm four-way solenoid valve, ASCO 8342A1, modified to three-way.

Gauges had to be equipped with screw-checks in order to achieve full protection and proper reaction time in reading pressure, since alternating flow from return line to nozzle causes minor pressure changes. Figure 3.1 illustrates the design of an individual simulator unit.

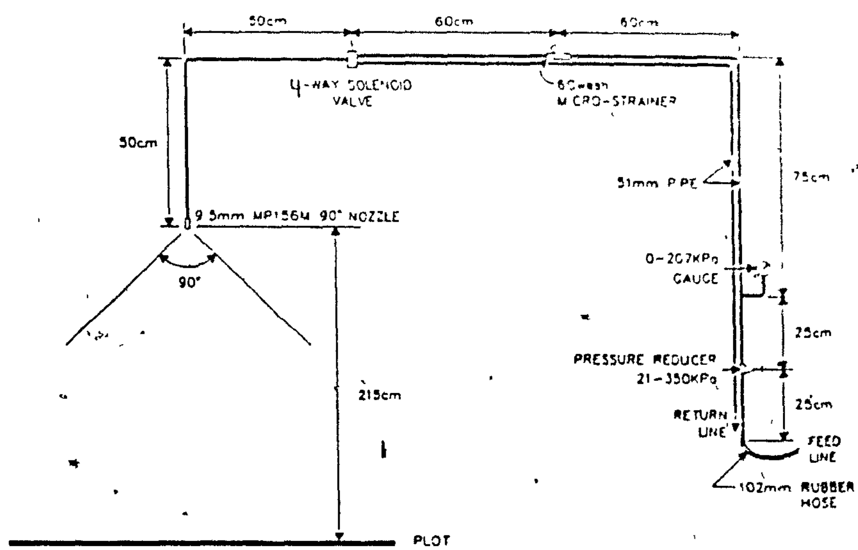


Fig. 3.1 Design of the stationary, variable-intensity rainfall simulator unit.

3.2.3. Nozzle spray characteristics evaluation

The main problem in developing a stationary, intermittent simulator was the selection of a small capacity nozzle with acceptable spray characteristics. Commercially available nozzles used in past rainfall simulator models (Meyer and McCune, 1958; Morin et al., 1967; Holland, 1969; Meyer and Harmon, 1977) appeared not suitable for a stationary design due to excessive discharge and/or flat spray patterns. In order to select a nozzle compatible with the prescribed design, preliminary testings of intensity, uniformity and drop size spectra at various operating pressures were performed on selected full cone nozzle models from "Spraying Systems Fulljet series" and "Bete Fog MP and WL series".

Drop-size spectra, spray intensity and coefficient of uniformity of selected nozzles, mounted on a simulator unit providing 185 or 215 cm fall height, were measured on a 2 X 2 m reference area. Coefficients of uniformity (Cu) were computed using the Christiansen (1942) index from 49 sampling points which were replicated three times. Spray intensity was expressed as the average of rainfall intensities measured at all sampling points. Spray drop-size spectra were measured using Laws and Parsons (1943) flour pellets method for drop size measurement. The method consists of allowing simulated rainfall droplets to fall into a layer 3 cm deep of freshly sieved flour, with a smooth surface, contained in a shallow receptacle. Resulting spherical pellets are air-dried, collected by sieving and finally oven-dried. Detailed pellet size distribution is then obtained by sieving the pellet samples through a set of standard sieves. Flour used for simulated droplets collection was calibrated to relate pellet mass to the droplet/pellet mass ratio. Calibration yielded the following regression equation at terminal velocity of droplets, using reference droplets ejected from paraffin coated syringues and micro pipettes mounted on a vortex shaker 12 m above reception pans:

$$M = 0.89 + 0.21 \log (Mp) \qquad r^2 = 0.86 \qquad (7)$$

where M = mass ratio = droplet mass/pellet mass
Mp = pellet mass

Triplicate samples of simulated raindrops were collected on the 2 x 2 m reference area at four distances away from spray center. Spray drop-size was expressed as the average of these four determinations weighted for rainfall intensity measured at these four sampling points.

When spray characteristics from a given nozzle at a specific operating discharge were acceptable, drop impact velocity from the 215 cm fall height was computed. The computations were based on measured drop-size spectra, nozzle aperture, discharge rate, and a mean fall angle against vertical of 22.5 degrees. The computing program used for droplet fall simulation was provided by Schuepp (1984).

3.3. Results and discussion

3.3.1. Nozzle selection

Preliminary estimations of drop-size spectra, Cu and intensity of tested nozzles are reported in appendix 1. All nozzles designed with ratio of free passage diameter to orifice size equal or smaller than 50% were characterized by much too small drop-size when drop fall velocity was desirable. The 9.5 mm MP156M model from Bete Fog Nozzle Inc. was finally selected for the rainfall simulator because its drop-size distribution was close to that of natural rainfall at low operating pressures. Free passage diameter equal to nozzle orifice diameter in the "MP series" was believed responsible for the production of relatively large droplets at low pressure.

3.3.2. Design nozzle discharge selection

A detailed drop-size spectra evaluation was undertaken on the "~~Bete~~- MP156M" nozzle at the design fall height of 215 cm to evaluate the effect of nozzle discharge on drop size distribution and its spatial variability. Five discharge rates and four distances away from nozzle spray center were investigated in triplicates. Drop-size spectra measured at the five discharge rates are illustrated in appendix 2. Analysis of variance in a 5 x 4 randomized complete block design of the overall drop size data confirmed significant effects, at the 0.01 level, of nozzle discharge and distance from spray center, and their interaction on median drop size (Table 3.1). Spray median drop size (D_{50}) over the 2 x 2 m reference area at each nozzle discharge level were obtained by normalization of individual median drop size data for intensity and surface area associated with each sampling point. Spray D_{50} was found related to nozzle discharge by the following second degree regression equation (Fig. 3.2):

$$D_{50}' = 12.0-2.8(Q)-0.19(Q)^2 \qquad r^2 = 0.91 \qquad (8)$$

where D_{50} is the spray median drop-size in mm,
Q is the nozzle discharge in liters per minute.

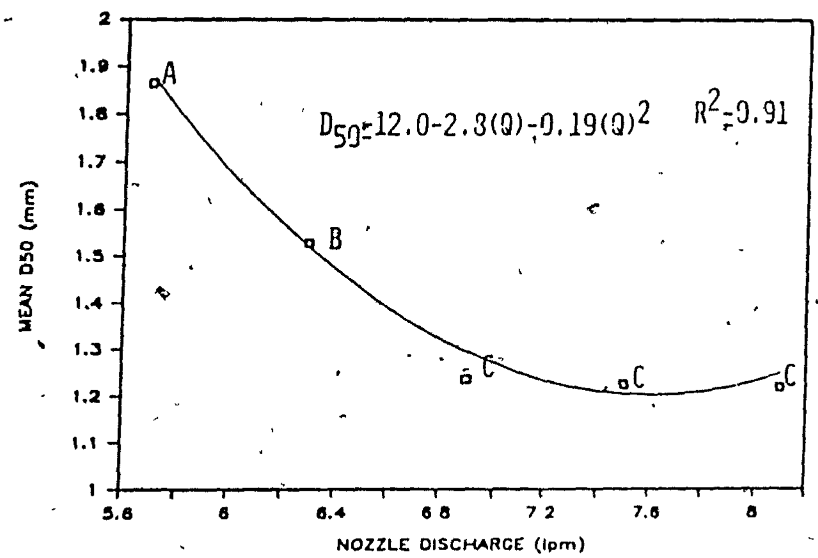


Figure 3.2 Spray median drop-size response to nozzle discharge.
Means with different letters are significantly different at the 0.05 level using the l.s.d. test.

Table 3.1 Analysis of variance of nozzle discharge and distance from spray center effects on D_{50} of Bete Fog nozzle MP156M.

SOURCE	Df	F value	Pr>F
Block	2	1.08	0.3492
Nozzle discharge (Q)	4	42.46 **	0.0001
Distance from spray center (d)	3	38.90 **	0.0001
Q * d interaction	12	6.11 **	0.0001

** Significant at the 0.01 level

The 5.7 $L.min^{-1}$ nozzle discharge rate was selected as the design discharge for the rainfall simulator since a spray drop size spectra most comparable to high intensity rainfall was obtained (Fig. 3.3), while giving droplet impact velocities from a 215 cm fall height close to terminal fall velocity. Figure 3.4 illustrates the impact velocities associated with the various class sizes of the drop size spectra from a 5.7 $L.min^{-1}$ nozzle discharge, and respective terminal velocities in still air. Up to a drop diameter of 2.5 mm, the vertical fall velocity from 215 cm exceeds slightly the theoretical terminal velocity, while larger drops achieve fall velocities slightly lower than terminal.

The kinetic energy of the spray at 5.7 $L.min^{-1}$ was evaluated by combining drop size spectra data and fall velocities simulation results to yield a figure of 0.201 MJ/ha.mm. Referring to Wischmeier and Smith (1978) estimation of rainfall kinetic energy per unit of rainfall, the simulated rainfall at 5.7 liters per minute nozzle discharge is reproducing 80% and 72% of the kinetic energy of natural rainstorms of respectively 25 and 100 mm/hr.

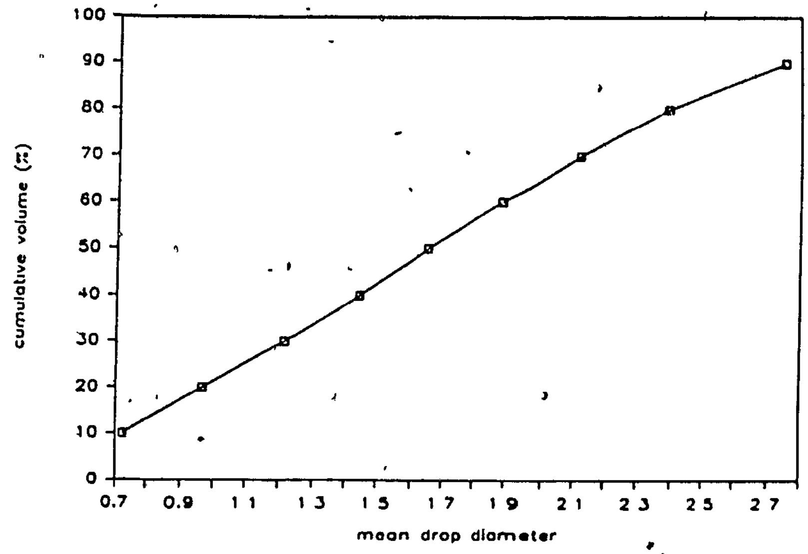


Figure 3.3 Mean spray drop-size distribution for Bête Fog MP156M 90 deg. full cone nozzle at 5.7 liters per minute discharge rate.

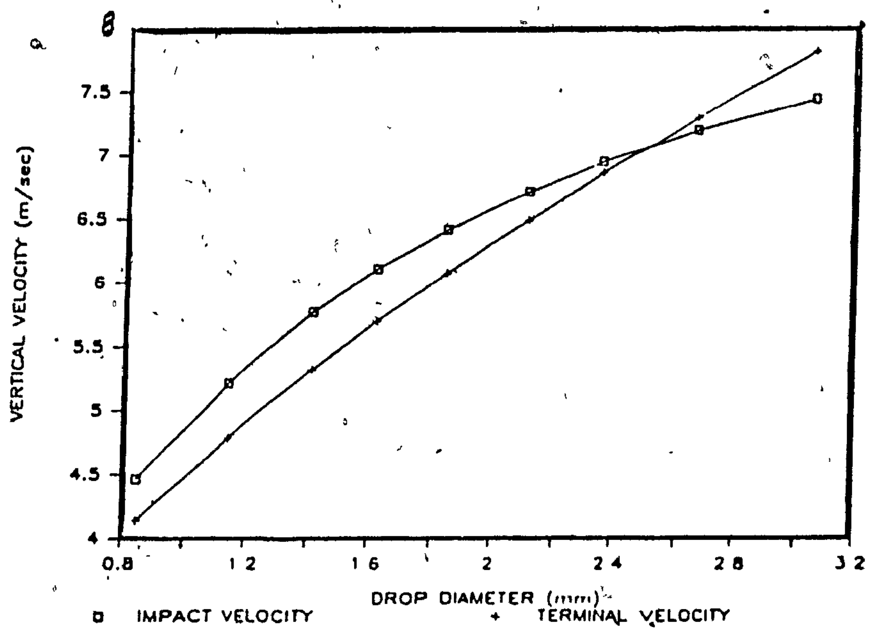


Figure 3.4 Drop impact vertical velocities as function of drop diameter from a fall height of 215 cm, 7.7 m/sec initial spray velocity and a mean spray angle against vertical of 22.5 degrees, as compared to terminal fall velocities for Bete Fog nozzle MP156M at a discharge rate of 5.7 liters per minute.

3.3.3. Multiple-nozzle operation

A 1.50 m spacing between nozzles was selected following optimization of the intensity distribution at various spacings. Spray intermittence levels were selected as 25, 50, 75, and 100 % of full flow directed at the nozzle (on-time). Adjacent nozzle lines were paired on different solenoid valve circuits (normally open and normally closed) in a total 40-second cycle (Table 3.2). Time delays between plot exposition to nozzle spray could thus be limited to 10 seconds at the lowest rainfall intensity (32 mm/h). Individual simulator units were connected in parallel to return and feed water lines. To compensate for variations in nozzle capacity, the gauge pressures of the simulator units were individually calibrated against nozzle discharge.

Table 3.2 Simulated rainfall characteristics response to spray intermittence.

Cycle duration (sec) ON	OFF	Intermittence (% flow at the nozzle)	Rainfall Intensity (mm/hr)	% Energy of [1] natural rainfall (%)
10	30	25	32	80.3
20	20	50	66	72.3
30	10	75	97	71.5
40	0	100	127	71.5

(1) Based on the kinetic energy of the spray (0.201 MJ/ha/mm) and Wischmeier and Smith (1978) estimations of rainfall kinetic energy of natural rainfall (e) relation to intensity (i):

$$e = 0.119 + 0.0873 \log(i)$$, where e is in MJ/ha.mm, i is in mm/h

Intermittence was noted to have a significant effect on average spray pattern. Shortening on-time was responsible for directing more droplets in the spray center (Fig. 3.5). Overall multiple nozzle coefficient of uniformity averaged 75% for single-row nozzle arrangement spaced at 1.5m.

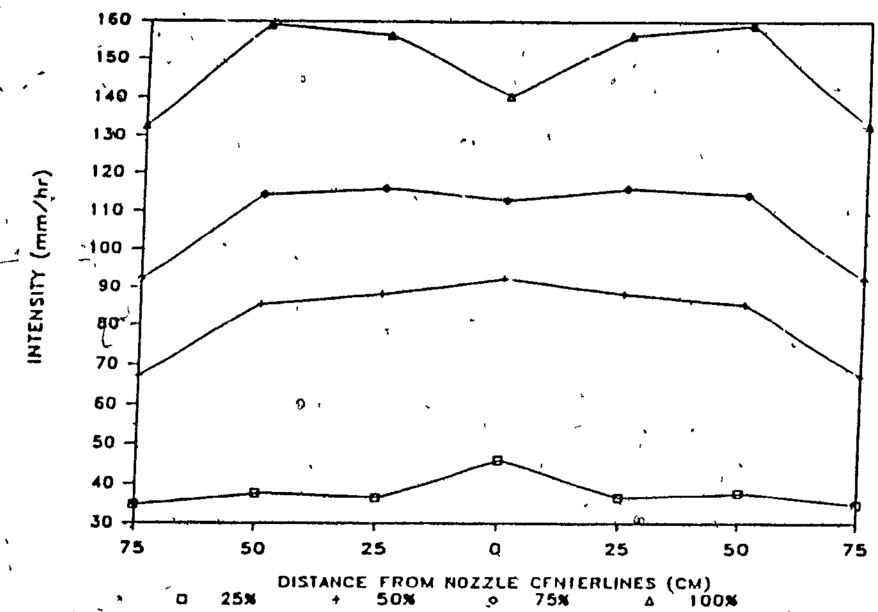


Figure 3.5 Average rainfall intensity distribution response to spray intermittence at 5.7 liters minute discharge rate from Bete Fog nozzle MP156M 90 degrees nozzle.

3.3.4. Field operation

Six units mounted in parallel were used on 1.75 m by 7.50 m plots on slopes ranging from 1 to 25 % gradient. Typical test storms included four simulated rainfall intensities (Table 3.2). A "U-lock" type aluminum structure supports the nozzle assembly lines and provides a frame for a polyethylene wind shield, used to prevent spray drift. Accessory equipment includes a 5,000-L portable water tank, a 1.13-kW pump, a pressure tank, an electric generator, two independent electric timers and a quick-connect rubber hose network. The runoff collection unit includes a steel flume and a 20 L/min capacity plexiglass tipping bucket. An electric immersion pump is used to drain the collector pit. Two persons can readily assemble, operate and disassemble the equipment. Figure 3.6 illustrates the rainfall simulator setup for an outdoor runoff plot experiment.

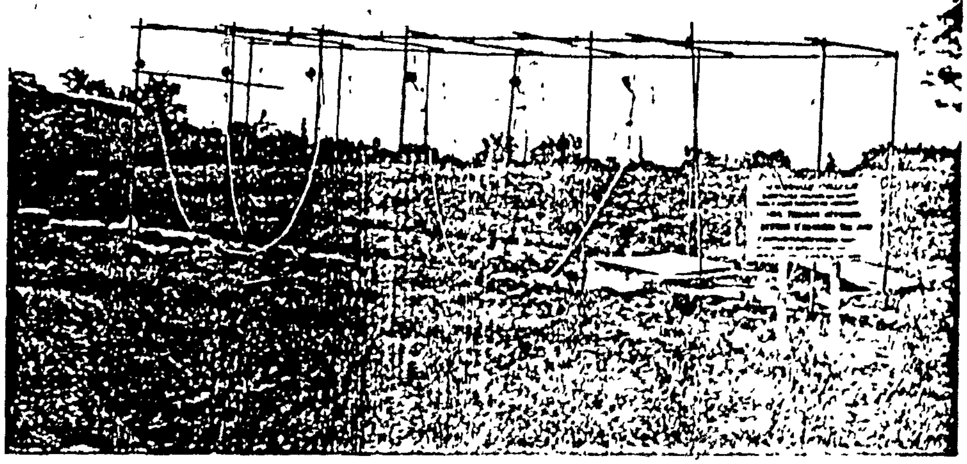


Figure 3.6 Rainfall simulator setup for an outdoor runoff plot experiment.

3.4. Conclusions

The use of a nozzle with orifice diameter equal to its free passage has made possible the development of a readily portable stationary rainfall simulator. The apparatus simulates rainfall at any range of intensities up to 127 mm/h with drop-sizes and impact velocities near those of natural rainfall. Field studies using this equipment have shown that it can provide useful data on rill and interill erosion as affected by rainfall intensity.

4. DETERMINATION OF SOIL ERODIBILITY INDICES USING A VARIABLE-INTENSITY RAINFALL SIMULATOR

4.1. Introduction

The need for rapid and reliable data on soil erosion by water led to the development of rainfall simulation techniques as early as the 1930's. Much of the more recent research on the estimation of USLE parameters using rainfall simulation began with the development of field rainulators by Meyer and McCune (1958) and later by Swanson (1965). Advantages provided by the use of simulators are numerous; rapid results, control of soil surface characteristics and standard test storms. Rainfall simulation thus largely contributed to the development and refinement of the USLE.

In the area of field research, rainfall simulators have been particularly well suited for the study of the effects of surface covers and tillage on soil erosion. Studies of slope effects on soil loss, water pollution from cropland, infiltration, soil particle movement and erosion mechanics are other current applications of rainfall simulation technology.

Simulators were extensively used to study the effect of soil characteristics on erosion and to refine the soil erodibility factor of the USLE (Barnett and Rogers, 1966; Wischmeier and Mannering, 1969; Romkens et al., 1975; El-Swafy and Dangler, 1976; Young and Mutchler, 1977). From many years of field rainulator measurements, Wischmeier et al. (1971) developed the "K nomograph", widely used for the prediction of soil erodibility factor (K) from soil properties in the American Midwest ever since.

The rainulator developed by Meyer and McCune (1958) has been used for most determinations of K in simulated rainfall studies. Most test storms in North American experiments also consisted of two 60 min storm periods 24 h apart at an intensity of 64 mm/h. Two methodologies, however, have been used in the determination of K values. Soil erodibility has been expressed as the slope of the regression of soil loss data on simulated rainfall erosivity (Wischmeier and Mannering, 1969; Barnett et al., 1971), and also by weighting soil loss and storm erosivity on the basis of natural storm frequency distribution (Barnett et al., 1965; Wischmeier et al.,1971; Romkens et al., 1975; Young and Mutchler, 1977). Although both methods present conveniences and disavantages, no discussion or direct comparison of procedures has been published to date.

This study used a variable-intensity rainfall simulator to collect runoff and soil loss data on outdoor runoff plots. The main purpose of the study was to characterize the soil erodibility of selected southern Quebec soils. Specific objectives of the study were:

- to estimate soil erodibility factors, compatible with the USLE, using a variable-intensity rainfall simulation procedure; and
- to study the relations of soil properties of the selected soils to runoff production, sediment concentration in runoff, soil loss, and K value, under standardized storm conditions.

4.2. Materials and Methods

4.2.1. Site selection and preparation

Eight soils were tested using a variable-intensity rainfall simulator on plots equipped with runoff measuring equipment. Table 4.1 lists the site and selected physico-chemical characteristics of the soils tested. A single plot, 7.5 m long by 1.75 m wide, was prepared at each site. Although duplication was judged highly desirable from a statistical standpoint, the rainfall simulation runs were not duplicated in order to collect plot data on the widest range of soils possible. Four of the selected sites on the Macdonald College Farm, namely the Arboretum, Dump, Highway, and Radar sites were previously studied over a continuous 2-year period by Kirby (1985), thus providing valuable comparison data for the simulation trials. The Rudy and Coleman sites were also located on the Macdonald College Farm, while the Sheldon and Coaticook soil series were studied on the Agriculture Canada Experimental Farm in Lennoxville, Quebec.

All sites were either seeded to row crops under conventional tillage or kept fallow for the preceeding two growing seasons. All crop residues and vegetation were removed from the plot surfaces and pre-run surface treatment included several passes with a five-tooth harrow up-and-down slope to a depth of approximately 7.5 cm in order to simulate a conventional seedbed preparation. Pre-run soil surface preparations and rainfall simulations were performed at a soil moisture content approaching field capacity. After harrowing, plots were covered with plastic sheets to avoid bias of results by natural rainfall.

Table 4.1a. Site characteristics: soil classification

SITE	ARBORETUM	COATICOOK	COLEMAN	DUMP	HIGHWAY	RADAR	RUDY	SHELDON
SOIL CLASSIFICATION	Orthic Melanic Brunisol	Humic Luvic Gleysol	Gleyed Sombric Brunisol	Gleyed Sombric Brunisol	Orthic Humic Gleysol	Orthic Humo-ferric Podzol	Eluviated Melanic Brunisol	Not Available
SOIL SERIES	St-Bernard	Coaticook	Chicot	Chicot	Rideau	St-Damase	Chateauguay	Sheldon[1]
SOIL PHASE	Sandy loam	Silty loam	Sandy clay Loam	Sandy loam	Clay	Loamy sand	Sandy clay loam	Loam
SLOPE (%)	1.2	4.2	6.2	6.5	11.5	26.0	8.0	12.0

(1) Soil series identification at Sheldon site provided by Pesant (1985).

Table 4.1b. Site characteristics: soil physical and chemical properties (0-15 cm depth)

SITE	ARBORETUM	COATICOOK	COLEMAN	DUMP	HIGHWAY	RADAR	RUDY	SHELDON
STRUCTURE	Medium granular	Fine-medium granular	Fine-coarse granular	Medium granular	Fine sub-angular blocky	Single grain	Fine-medium sub-angular blocky	Medium-coarse granular
TOTAL SAND (%)	60.6	18.0	46.0	56.2	29.1	76.9	50.5	29.0
V.C. SAND (%)	0.7	1.5	1.5	0.4	0.1	0.1	4.0	7.0
C. SAND (%)	3.0	1.0	3.0	2.5	0.5	0.6	9.0	5.0
M. SAND (%)	0.0	2.0	9.5	14.2	4.0	21.3	27.0	8.5
F. SAND (%)	50.2	9.5	21.0	31.4	16.5	51.2	6.5	4.5
V.F. SAND (%)	6.7	4.0	11.0	7.7	8.0	3.7	4.0	4.0
TOTAL SILT (%)	26.4	59.5	27.0	35.7	25.8	14.1	26.0	48.0
TOTAL CLAY (%)	13.0	22.5	27.0	8.0	45.0	9.0	23.5	23.0
DRY MEAN WEIGHT DIAMETER (mm)	0.60	1.47	2.43	0.31	1.04	0.26	0.91	2.53
WATER-STABLE AGGREGATES > 1.0 mm	8.3	42.0	13.0	16.2	12.3	7.8	15.5	45.9
DRY BULK DENSITY ($Mg.m^{-3}$) 0-5 cm	1.31	1.14	1.49	1.28	1.33	1.37	1.46	1.51
20-25 cm	1.13	1.13	1.41	1.20	1.22	1.15	1.33	1.46
SOIL MOISTURE (% by mass)	26.6	35.4	14.6	19.4	28.4	20.5	13.7	21.8
WATER RETENTION AT 10 kPa (% by mass)	26.1	42.6	21.9	26.3	24.2	13.1	20.6	20.8
AVAILAIBLE WATER AT 10 kPa (% by mass)	7.0	7.8	6.5	8.4	5.7	3.8	6.3	6.8
ORGANIC MATTER (%)	3.75	4.87	1.53	3.13	3.07	2.56	1.93	2.35
C.E.C. (meq/100 g)	15.80	33.28	4.11	7.56	14.30	4.48	8.72	5.22
EXCH. Ca	12.41	25.59	3.19	5.73	9.24	3.19	6.23	3.45
EXCH. Mg	2.89	5.19	0.30	0.91	3.43	0.71	1.38	0.82
EXCH. Na	0.31	1.57	0.46	0.50	1.31	0.28	0.69	0.39
Fe+Al (%) PYRO. EXTR.	0.23	0.52	0.14	0.39	0.15	0.39	0.32	0.31
D.C.B. EXTR.	1.05	1.06	1.83	0.82	1.10	0.89	1.00	1.08

4.2.2. Rainfall simulation and runoff collection procedures

The design test storm used was composed of four runs of decreasing rainfall intensity. The first application was made under existing soil moisture conditions (dry run) at a simulated rainfall rate of 127 $mm.h^{-1}$ for 15 min. The other three applications (wet runs) lasted 30 min each, with respective intensities of 97, 66 and 32 $mm.h^{-1}$. Runs were separated by a 10 min break. Duration-rainfall intensity combinations were selected upon long-term high intensity rainfall statistics for the Montreal meteorological station (Segal, 1979).

A 20-$L.min^{-1}$ capacity tipping bucket was calibrated in situ and used to collect and measure runoff at each site. Appendix 3 reports calibration data of the tipping bucket for the eight sites. Simple linear regressions between plot runoff volume and "pairs of $tips.min^{-1}$" of the tipping bucket were significant at the 1% level with r^2 greater than 0.99 at all sites. The number of a bucket's pair of tips was recorded manually together with time using a stopwatch. Runoff was sampled at maximum intervals of 1 and 2 min for the dry run and the wet runs, respectively, at all sites. Full volumes of the tipping bucket were collected in a 4-l pail when the bucket emptied out, without interferring with the bucket movement. The collected runoff sample was then homogenized by quick rotational movement of the collection pail, and a 750-ml fraction of the sample was immediately transferred to a glass jar. Sediment concentration in runoff was determined by oven drying the runoff samples. After evaporation of most of the runoff water, sediments were left in the oven at 105°C for 24 hours before final weighing.

4.2.3. Measurement of soil properties

Selected soil chemical and physical properties were measured on soil samples from each plot. Samples for aggregate-size distribution and stability determinations; 0-15 cm depth moisture content, textural and chemical analyses were collected immediately prior to the first rainfall simulation run, while the soil profile bulk density was measured using Troxler gamma-ray probe a few days following the rainfall simulation session. A description of the surface physico-chemical properties of the eight sites studied is given in table 4.1.

Soil particle-size distributions were determined in duplicate using the hydrometer method. Triplicate size-distributions of dry aggregates smaller than 8 mm were measured using a nest of 4.75-, 2.00-, 1.00- and 0.75-mm sieves operated mechanically for two minutes by a motor giving 40 strokes per minute. A Yoder (1936) type sieving machine using the same nest of sieves was used to determine water-stable aggregates. Duplicate samples, where lumps of soil greater than 8 mm were broken to pass through the 8 mm sieve but retained on the 4.75 mm sieve, were wetted at atmospheric pressure within 3 seconds. Sieving was started 10 min after the samples were wetted, for a period of 10 min at 50 $strokes.min^{-1}$ and a 2-cm amplitude. After dispersion in sodium hexametaphosphate solution, material retained in each size class was hand sieved to allow correction for sand and coarse fragments.

Organic carbon was determined in duplicate using the Leco combustion method. Pyrophosphate and citrate-dithionite bicarbonate extractable iron and aluminium were analysed in duplicate following Agriculture Canada (Sheldrick 1984) standards.

4.2.4. Data analysis

4.2.4.1. Soil loss computations

Runoff hydrographs and temporal variation of sediment concentration in runoff for each simulated rainfall run were computed based on in situ manual recordings of the calibrated tipping bucket and the sediment concentration data determined in the lab. By pooling instantaneous data on runoff and sediment concentration for identical time intervals, soil loss estimates as a function of time were obtained. Runoff hydrographs, temporal variation of sediment concentration in runoff and evolution of cumulative soil loss with time for all sites under the four runs of the test storm are reported in Appendix 4.

4.2.4.2. Soil erodibility indices computation

Since estimates of percentage distribution of storm sizes for the areas under study were not available, a representation of annual soil loss per unit of rainfall erosivity by a storm weighting procedure (Barnett et al., 1965; Wischmeier et al., 1971; Dangler and El-Swaify, 1976) was not possible. Site erodibilities therefore were computed through linear modelling by a least squares technique as suggested by Barnett et al. (1966) and used by Wischmeier and Mannering (1969). After correction for the slope length and gradient factors of the USLE (Wischmeier and Smith, 1978), the slope of the soil loss - EI linear regression, was interpreted as the erodibility factor K as defined for the USLE (Wischmeier and Mannering, 1969).

The following computational procedure was adopted for the derivation of the K factor for each site.

(1) - Data sets including measured soil losses in $t.ha^{-1}$ and associated storm erosivities (EI) in $MJ.mm.ha^{-1}h^{-1}$ for all possible combinations of the rainfall simulation runs were created. Table 4.2 summarizes the storm erosivity computational procedure for each run combination. A constant rainfall energy per unit of rainfall (e) of 0.201 $MJ.ha^{-1}mm^{-1}$ was used throughout storm energy (E) computations in order to reflect the actual kinetic energy of the simulated rainfall.

(2) - The data for the ten possible storm combinations were split into two data subsets. One subset, designated as the dry run data set, is composed of all run combinations that include the first simulator run on dry soil. The wet run data set includes all other possible run combinations. The data for the four storm sizes provided by the dry run data set and the six storm sizes provided by the wet run data set were then fitted by a least-squares technique to the linear model:

$$A = m\,EI + b \qquad (9)$$

where "A" is the soil loss in t/ha and "m" is the apparent erodibility of the site, as estimated by the dry or wet run combinations.

(3) - The apparent site erodibility values were subsequently adjusted to the standard of 9% slope gradient and 22.1 m slope length to be compatible with K as defined in the USLE.

Table 4.2 Storm erosivities associated with each combination of simulated rainfall runs.

Run # combinations	Ppt (mm)	$E^{(1)}$ ($MJ.ha^{-1}$)	$I_{30}^{(2)}$ ($mm.h^{-1}$)	$EI^{(3)}$ ($MJ.mm.ha^{-1}h^{-1}$)
Dry run subset[4]				
1	31.75	6.38	64	405
1 +2	80.25	16.13	112	1807
1 + 2 + 3	113.25	22.76	112	2549
1 + 2 + 3 + 4	129.25	25.98	112	2910
Wet run subset[4]				
2	48.50	9.75	97	947
2 + 3	81.50	16.38	97	1590
2 + 3 + 4	97.50	19.60	97	1901
3	33.00	6.63	66	438
3 + 4	49.00	9.85	66	650
4	16.00	3.22	32	103

(1) Storm energy (E) = Ppt . e
where Ppt = total runs combination precipitation (mm)
e = rainfall energy per unit of rainfall
= 0.201 $MJ.ha^{-1}mm^{-1}$ for the simulated raindrops

(2) I_{30} is the maximum 30-min rainfall intensity.
For a duration less than 30 min, I_{30} = 2 x Ppt
(Wischmeier and Smith, 1978)

(3) Storm erosivity (EI) = E . I_{30}

(4) Run #1, 2, 3, and 4 were applied at the respective intensity of 127, 96, 66 and 32 $mm.h^{-1}$. Run #1 has a duration of 15 minutes, runs #2, 3, and 4 last 30 min. each

4.2.4.3. Soil properties in relation to erodibility

To attempt to understand how particular properties of the soils studied affected their erodibilities, the following dependent variables were studied: (i) rainfall energy required to initiate runoff, (ii) end-of-run runoff rates, (iii) end-of-run sediment concentration in runoff, (iv) total soil loss for the run, and (v) soil K. End-of-run runoff rates and sediment concentrations were computed by averaging the ponctual data sampled in the last 3 and 5 min of the dry and wet runs respectively.

The merits of the various soil properties as indicators of the aforementioned dependent variables were explored by simple correlation and multiple-regression techniques. The final parameters and transformations used in the analysis were selected by intuitive judgement, trial runs, and review of previous rainfall simulation studies (Barnett and Rogers, 1966; Wischmeier and Mannering, 1969; Wischmeier et al., 1971; El-Swaify and Dangler, 1976; Young and Mutchler, 1977; Luk, 1979). Table 4.3 summarizes the variability of the soil properties used in the correlation and regression analyses. When studying a given dependent variable, the probability level of 50 % was the threshold level for accepting an independent variable in the correlation/regression analyses. In the derivation of multiple linear regression equations, care was taken to exclude parameters that were intercorrelated or were subjective. Numerically-coded soil properties, i.e. soil structure or permeability class, were thus excluded from the statistical analysis.

Table 4.3 Variability in selected physico-chemical properties of the eight soils analyzed for the erodibility study.

Variable	Mean	Standard deviation	Range in values least	Range in values greatest
Organic matter (%)	2.90	1.06	1.53	4.87
Very coarse sand (%)	1.9	2.4	0.1	7.0
Coarse sand (%)	3.1	2.8	0.5	9.0
Medium sand (%)	10.8	9.5	0.0	27.0
Fine sand (%)	23.8	18.7	4.5	51.2
Very fine sand (%)	6.1	2.7	3.7	11.0
Total sand (%)	45.8	19.5	18.0	76.9
Silt (%)	32.8	14.5	14.1	59.5
Clay (%)	21.4	12.0	8.0	45.0
Dry mean weight diameter (mm)	1.19	0.89	0.26	2.53
Water Stable agg. > 1 mm (%)	20.2	15.0	7.8	45.9
Soil moisture 0-15 cm (% by mass)	22.6	7.3	13.7	35.4
Water retention at 10 kPa (% by mass)	25.5	8.4	13.1	42.6
Available water at 10 kPa (% by mass)	6.5	1.4	3.8	8.4
Dry bulk density 0-5 cm ($Mg.m^{-3}$)	1.36	0.12	1.14	1.51
Dry bulk density 20-25 cm ($Mg.m^{-3}$)	1.25	0.13	1.13	1.46
Dry bulk density ratio (0-5 cm/5-10 cm)	1.106	0.032	1.041	1.149
Exchangeable sodium (meq/100 g)	0.69	0.49	0.28	1.57
Exchangeable magnesium (meq/100 g)	1.95	1.71	0.30	5.19
Exchangeable calcium (meq/100 g)	8.63	7.58	3.19	25.59
Cation exchange capacity (meq/100 g)	11.68	9.76	4.11	33.28
DCB exchangeable Fe + Al (%)	1.10	0.31	0.82	1.83
Pyro. exchangeable Fe + Al (%)	0.31	0.13	0.14	0.52
Slope (%)	9.5	7.6	1.2	26.0

4.3. Results and discussion

In order to ease the presentation and interpretation of the results, the data and associated statistical analyses were split in three sections. In a first section, hydrologic data are presented and discussed. The second section focuses on sediment content of the runoff and soil losses. Finally, soil erodibility figures are presented and discussed.

4.3.1. Runoff characteristics

Runoff rate and quantity induced by natural storms have a definite effect on soil detachment and transport, and have been used as a basis for soil-loss modelling (Onstad and Foster, 1975; Williams, 1977). An understanding of the soil-loss simulated-test-storm relationship would thus remain incomplete without a description of the runoff patterns induced by the simulated rainfall. Since total runoff induced by each simulated storm intensity is proportional to the required rainfall energy to initiate runoff and observed runoff rates, it is also desirable to obtain a better understanding of how particular soil properties affect these latter dependent variables.

4.3.1.1. Runoff pattern induced by the test storms

Runoff hydrographs for each of the eight sites tested under the standard test storms are reproduced in Appendix 4. Common characteristics are shared by the observed runoff patterns which can be largely attributed to the test storm characteristics and plot preparation procedures. A typical runoff hydrograph, computed from Sheldon site data, is illustrated in figure 4.3.

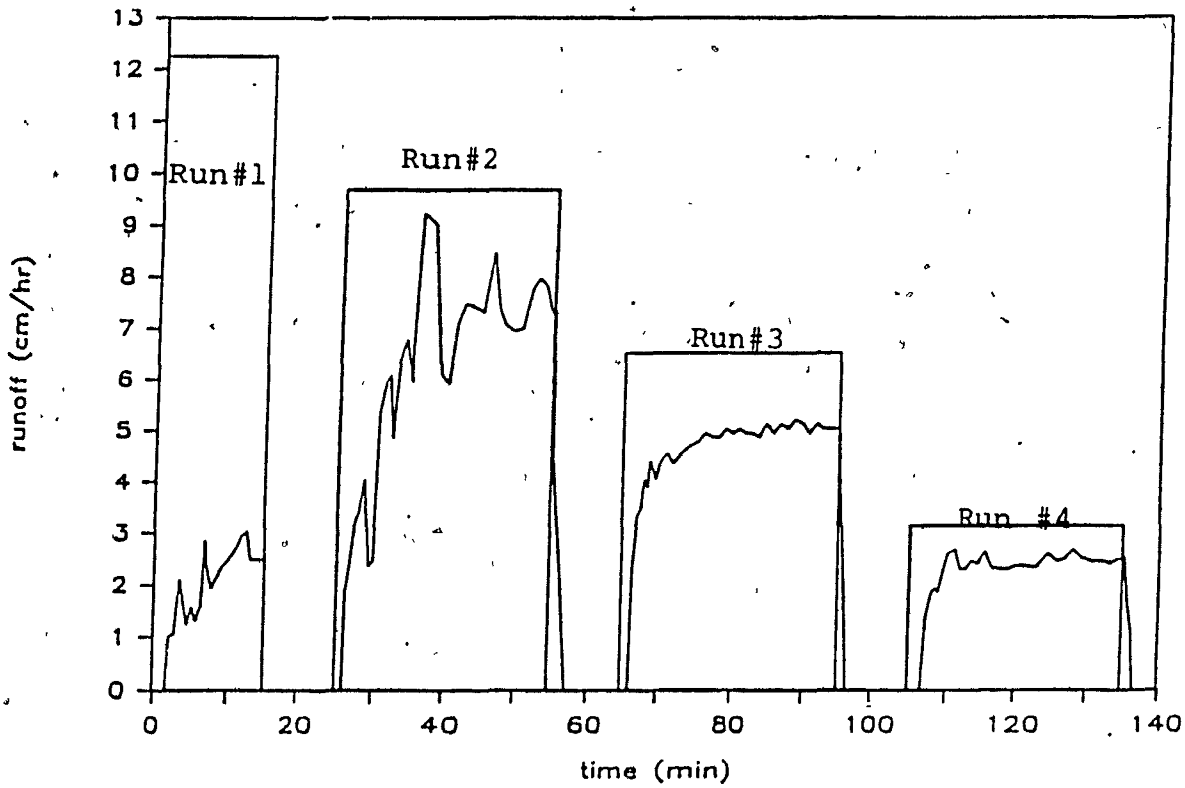


Figure 4.1 Runoff hydrograph computed from Sheldon site data under the standard simulated test storms. (Rainfall intensities for run #1, 2, 3, and 4 are: 127, 97, 66 and 32 mm/hr respectively.)

The relatively loose structure of the top 5 cm of the soil surface, as a result of harrowing of the runoff plot before the test storm, conveys to the tested soils a very high initial infiltrability. However, the intense rainfall used in the first simulated rainfall run provided a supply rate large enough to induce runoff at all sites. It can then be concluded that the infiltration and runoff processes became surface or profile controlled during the first run of the test storm at all sites. Consequently, all sites were subjected to preponding infiltration and surface storage periods of various duration before runoff occurred within the first run. Variation in time to produce runoff can be related to soil surface properties affecting soil infiltrability variation over time and soil surface storage capacity. On all sites, however, a monotonic increase in runoff rate was observed during the first simulated rainfall run. The runoff rates observed, although diverse in magnitude, failed to achieve an equilibrium rate during the first run at all sites, suggesting that the infiltration had not reached a steady state.

Runoff rates near equilibrium were achieved at all sites during the second and third simulated rainfall runs. A gradual decrease in soil infiltrability to approach asymptotically a constant rate (Hillel, 1980) under partial sealing of the soil surface by crust formation, possible migration of pore-blocking particles, swelling of clays, and entrapment of air bubbles can explain in theory the observation of near equilibrium runoff rates in the wet runs. The absence of runoff observed on the fourth run at the Dump and Radar sites indicates that the soil infiltrability exceeded the rainfall delivery rate; thus supply-controlled, non-ponding conditions were assumed. Data for the fourth run from these sites were treated as missing values for the purposes of the statistical analyses.

4.3.1.2. Rainfall energies required to initiate runoff

The variability in rainfall energy required to initiate runoff at the eight sites for each of the consecutive simulated rainfall runs is reported in Table 4.4 Highest variability among soils was observed during the first run, where the Coaticook silty loam (Coaticook site) and the Rideau clay (Highway site) required a rainfall energy of 5.97 and 4.45 MJ/ha, respectively, before yielding any runoff, while the Sheldon sandy loam (Sheldon site) and the Chicot sandy loam (Dump site) yielded runoff, respectively, after only 1.45 and 1.72 MJ/ha. A very marked decrease in rainfall energy required to initiate runoff was observed during the second run. Decreased infiltrability due to higher initial surface matric potential and partial sealing of the soil surface, associated with decreased surface storage capacity due to a decrease in surface roughness and rilling contributed to this sharp decrease in the soils' ability to delay the production of runoff. A general tendency to reduced energy required to initiate runoff was also observed during the two subsequent runs for six of the eight sites studied. The effect of reduced infiltrability and surface storage capacity during these runs may however be masked by the intermittency of the water application which can affect the amount of rainfall energy before runoff occurs (Sloneker et al., 1974).

Table 4.4 Variability in rainfall energy required to initiate runoff at the eight sites studied for the four consecutive simulated rainfall runs

Site	Simulated rainfall run # 1	2	3	4[a]
	Rainfall energy (MJ/ha)			
Arboretum	2.67	0.69	0.70	0.87
Coaticook	5.97	0.85	0.56	0.27
Coleman	2.58	0.50	0.39	0.28
Dump	1.72	0.65	0.84	–
Highway	4.45	0.68	0.64	0.45
Radar	3.97	0.86	0.81	–
Rudy	2.50	0.71	0.37	0.38
Sheldon	1.45	0.54	0.47	0.29
Mean	3.16	0.68	0.60	0.42
Std.Dev.	1.52	0.13	0.18	0.23
Min.	1.45	0.50	0.37	0.27
Max.	5.97	0.86	0.84	0.87

[a]Only six observations were recorded for the fourth run since two soils failed to produce runoff.

Table 4.5 reports the coefficients of simple correlation of the selected soil properties to the energy required to initiate runoff for the four consecutive simulated rainfall runs. Reported in Table 4.6 are the best simple linear regressions significant at the 0.05 level explaining the variability in rainfall energy required to initiate runoff for the first, dry run and the last, very wet run. Data for runs 2 and 3 were excluded from the linear regression study because of relatively low variability of dependent variables. Data for runs 1 and 4, besides presenting a larger variability, are also representative of "extreme case" soil surface conditions.

Table 4.5 Coefficients of simple correlation significant at the 50% level for energy required to initiate runoff as dependent variable

Independent variable	Pearson correlation coefficients and associated probability run #1		run #2		run #3		run #4	
% Organic matter	+0.63	0.096	+0.59	0.125	+0.43	0.284		
% Silt + V.F. Sand/Organic matter	-0.46	0.247	-0.81	0.016*	-0.73	0.039*	-0.68	0.137
% Sand X % Organic matter			+0.40	0.329	+0.78	0.021*	+0.97	0.001**
Clay ratio/% Organic matter			-0.52	0.185	-0.63	0.096	-0.41	0.424
% Clay	+0.31	0.455			-0.51	0.196	-0.37	0.474
% Sand ratio			+0.43	0.284	+0.57	0.378	+0.78	0.066
% (Silt + V.F. Sand)x(Sand - V.F. Sand)	-0.71	0.046*			+0.38	0.355	+0.58	0.227
Water retained at 10 kpa	+0.39	0.345						
Dry bulk density 0-5 cm	-0.69	0.060	-0.67	0.069	-0.54	0.168		
Dry bulk density 20-25 cm	-0.60	0.116	-0.80	0.017*	-0.73	0.040*	-0.56	0.248
Exchangeable Sodium Percentage			-0.53	0.176	-0.49	0.215	-0.68	0.138
$(Slope)^{0.5}$							-0.66	0.150

* Significant at the 0.05 level
** Significant at the 0.01 level

While the soil properties affecting surface roughness would likely play a major role in delaying the occurrence of runoff during the first run by mitigating the beating action of raindrops and offering a large surface storage capacity, their importance was considerably reduced in the last run when infiltrability-related properties largely determined the infiltration/runoff rates in surface-sealed conditions. Energies required to initiate runoff observed at the Coaticook site provided an interesting illustration of this phenomenon. While this site required the highest energy to produce runoff on the dry run (5.97 MJ/ha), it also required the least energy (0.27 MJ/ha) to produce runoff during the very wet run 4. A stable granular soil structure at the soil surface combined with an impeding clayey subsoil are likely responsible for this paradoxical behavior. However, absence of data on evolution of the water-content profile time during the test storm does not permit any conclusion on any soil layering effect for the soils studied. The only information on the initial water content status of the soils was provided by the measurement of the 0-15 cm gravimetric water content, which correlated positively with the energy required to induce runoff on the first run. A positive correlation between initial moisture content and energy to initiate runoff on the first run (r = 0.72) is likely the reflection of the strong correlation observed between organic matter content of the soils and their initial moisture content (r = 0.91, significant at the 0.01 level).

Table 4.6 Best simple linear regressions significant at the 0.05 level for rainfall energy required to initiate runoff as dependent variable for simulated rainfall runs 1 and 4.

Run #	Variable	Parameter estimate	Prob>(T)[1]
1	% (Silt + V.F. Sand) (Sand - V.F. Sand)	-21.99	0.025*
	Organic matter percentage	0.77	0.045*
	Intercept	3.89	
	Model F value: 9.841		
	prob > F: 0.0185		
	R-square: 0.80		
1	% (Silt + V.F. Sand) (Sand - V.F. Sand)	-25.61	0.0021*
	Dry bulk density 20-25 cm	- 7.49	0.0043*
	Intercept	16.01	
	Model F value: 27.694		
	prob > F: 0.0020**		
	R-square: 0.92		
4	% Sand x % O.M.	$3.68 \cdot 10^{-3}$	0.0011**
	Intercept	$2.90 \cdot 10^{-2}$	
	Model F value: 69.045		
	prob > F: 0.0011**		
	R-square: 0.95		

* Significant at the 0.05 level
** Significant at the 0.01 level

[1] Associate probability with the T value.

The effect of soil texture on energy required to produce runoff in the "dry run" is best described by the combined parameter "Silt + very fine sand x Sand - V.F. sand" or "corrected silt x corrected sand" (Wischmeier, 1971). Together with organic matter content or subsoil bulk density, it could explain respectively 80 and 92% of the variation in energy required to induce runoff on the dry run (Table 4.7). The signs of percent clay correlations with energy to initiate runoff were found opposed in dry run versus wet runs. A potential explanation for a positive correlation in the dry run would be an effect of soil texture on initial surface macroroughness of the sites. Initial dry mean weight diameter of the tested surfaces appeared, in fact, positively correlated, although not at a 5% significant level, with percent clay (r=+0.45, prob.=0.16). The correlation of clay percentage would then turn negative, when percent clay would no longer promote infiltrability in the wet runs, but rather be associated to lower soil hydraulic conductivity.

The high level of intercorrelation between organic matter and topsoil and subsoil bulk densities, r(O.M. - Topsoil dens.) -0.93 (significant at the 0.01 level) while r(O.M. - subsoil dens.) = -0.76 (significant at the 0.05 level), prevented a clear identification of their respective effect on energy required to induce runoff. Organic matter appeared consistently positively correlated with the latter dependent variable in the first three runs while both bulk density figures remained negatively correlated. Likewise, the positive correlation between water retention at 10 kPa and energy required to produce runoff is compromised by a correlation significant at the 0.01 level between water retention at 10 kPa and organic matter (r = 0.74).

The ratio of sand to organic-matter percentage explains at a very high level of significance the energy required to induce runoff during the fourth run (Table 4.6). The ability of this combined parameter to explain variation in soil infiltrability is likely the reason for its high correlation with energy required to produce runoff on the very wet run. The sand ratio alone explained over 60% of variability in the latter dependent variable. Percent slope showed 50% significance only in the fourth run indicating a dominance of soil characteristics over slope gradient in governing rainfall energy required to induce runoff among the soils tested.

4.3.1.3. Runoff and seepage rates

The variability in runoff rates among the eight tested sites, as measured at the end of each rainfall simulator run, is reported in Table 4.8. Highest runoff rates were achieved for all soils during the second simulated rainfall run at 97 $mm.h^{-1}$ rainfall intensity, with the exception of the Dump site where the test storm peak runoff rate was observed on the first run at 127 $mm.h^{-1}$ rainfall intensity. Excessively high infiltrability of the tested soils on the first run prevented the attainment of peak runoff rates. Steep hydraulic-head gradients established immediately beneath the soil surface when intense rainfall began on the relatively dry soils favored very high initial infiltration rates, thus minimizing runoff. As rainfall continued during the following simulated rainfall runs, near-surface hydraulic gradients decreased as the "wetting front" moved deeper and ponding was maintained at the soil surface; the infiltration in the wet runs was then more likely controlled by subsurface hydraulic properties.

Table 4.7 Variability in runoff and seepage rates measured at the end of each simulated rainfall run for the eight sites tested.

Site	Simulated rainfall run # (1)		(2)		(3)		(4)[b]	
	Runoff and seepage rates[a] (mm.h^{-1})							
	Runoff	Seepage	Runoff	Seepage	Runoff	Seepage	Runoff	Seepage
Arborétum	61.3	65.7	67.5	29.5	41.4	24.6	12.4	19.6
Coaticook	20.4	106.6	58.6	38.4	46.2	19.8	27.8	4.2
Coleman	26.2	100.8	48.0	49.0	42.8	23.2	20.3	11.7
Dump	54.3	72.7	38.8	58.2	23.6	42.4	-	32.0
Highway	21.3	105.7	21.3	75.7	41.9	24.1	18.6	13.4
Radar	13.1	113.9	19.0	78.0	13.4	52.6	-	32.0
Rudy	31.7	95.3	46.2	50.8	30.6	35.4	13.0	19.0
Sheldon	26.4	100.6	74.4	22.6	50.6	15.4	24.9	7.1
Mean	13.8	113.2	46.7	50.3	36.3	29.7	19.5	12.5
Std.Dev.	17.0		20.1		12.7		6.2	
Min.	13.1	65.7	19.0	22.6	13.4	19.8	12.4	4.2
Max.	61.3	113.9	74.4	78.0	50.6	52.6	27.8	19.6

[a] Seepage rate = precipitation rate - runoff rate

[b] only six observations were recorded for the fourth run since two soils failed to produce runoff.

A comprehension of variation in runoff rates observed during the four consecutive simulator runs is best acheived by comparing the effective "seepage rates" on the tested plots at the end of each run. Seepage rates have been calculated by subtracting from the applied rainfall rate the measured runoff rates (Table 4.7). The term "seepage rate" is used rather than "infiltration rate" to describe the proportion of water applied that was not collected at the lower end of the plot, which is truly representative of the natural soil infiltration rate. Compared to natural conditions, numerous factors lead, in fact, to an overestimation of the amount of water infiltrating into the soil profile in a rainfall simulation-based plot study. The relatively high plot border to plot area ratio (1:1.42) of the test plots contributed assuredly to edge effects on infiltration rates. Intermittency and non-uniformity effects of the applied rainfall enhanced variability in soil-water pressure across the plot surface; minor variability in intended rate of water application cannot be excluded either. Combination of these experimental factors seriously limit the representativity of the seepage rate data as natural infiltration rate.

Observed end-of-run seepage rates show a gradual decrease from the first to fourth run at all sites (Table 4.7). Although runoff data for the fourth run at the Dump and Highway sites were not collected, their potential seepage rates were assumed to be equal to the applied rainfall rate (32 $mm.h^{-1}$). Consistently decreasing seepage rates during the post-ponding period is consistent with near-surface hydraulic gradients decreasing more rapidly than soil hydraulic conductivity increases during rainfall infiltration (Amerman, 1979). Lowest seepage rates achieved in the fourth run approach typical values of steady infiltration rates reported by Hillel (1980).

Coefficients of simple correlation significant at 50% relating sampled soil properties to end-of-run runoff rates are reported in Table 4.8. Best simple linear regression significant at the 0.05 level explaining the variability in final runoff rates for runs one, three and four are reported in Table 4.9. For the dry run, the combined textural parameter "corrected silt x corrected sand" explains alone 80% of the variability in runoff. Since the runoff rates measured at the end of the first run were markedly on an upward trend, their amplitude remains largely time-dependent and associated with energy required to initiate runoff (r = -0.52). The last two dependent variables thus share the same textural variable as the best predictive parameter on the dry run. Negatively correlated clay content and initial aggregate mean weight diameter are likely associated with the effect of surface roughness on surface storage capacity during the dry run.

Table 4.8 Coefficients of simple correlation significant at the 50% level for end-of-run runoff rates as dependent variable

Independent variable	Pearson correlation coefficients and associated probability: Run #1		Run #2		Run #3		Run #4	
% Clay	-0.43	0.283			+0.57	0.142		
% (Sand - V.F. Sand)			-0.35	0.402	-0.83	0.010*	-0.89	0.018*
% (Silt + V.F. Sand)			+0.62	0.104	+0.68	0.065	+0.92	0.008**
% (Silt + V.F. Sand)x(100-% Clay)[1]			+0.66	0.075	+0.47	0.244	+0.78	0.065
% (Silt + V.F. Sand)x(Sand - V.F Sand)	+0.81	0.014*			-0.39	0.334	-0.58	0.225
Mean Weight Diameter	-0.34	0.414						
Dry bulk density 20-25 cm			+0.37	0.428	+0.39	0.333		
$(Slope)^{0.5}$	-0.70	0.052	-0.62	0.098	-0.53	0.178		

[1] M parameter (Wischmeier and Smith, 1978)

* Significant at the 0.05 level
** Significant at the 0.01 level

Table 4.9 Best simple linear regressions significant at the .05 level for end-of-run runoff rates as dependent variable for the four consecutive rainfall runs.

Run #	Variable	Parameter Estimate	Prob > (T)[1]
1	% (Silt + V.F. Sand) (Sand - V.F. Sand)	$3.11 \cdot 10^{-2}$	0.014*
	Intercept	-10.19	
	Model F value: 11.598		
	prob > F: 0.0144*		
	R-square: 0.66		
3	% (Sand - V.F. Sand)	0.54	0.010*
	Intercept	57.59	
	Model F value: 13.475		
	prob > F: 0.0104*		
	R-square: 0.69		
4	% (Silt + V.F. Sand)	1.34	
	Intercept	$4.35 \cdot 10^{-1}$	0.008**
	Model F value: 23.693		
	prob > F: 0.0082**		
	R-square: 0.86		
4	% (Sand - V.F. Sand)	$3.57 \cdot 10^{-1}$	0.018*
	Intercept	31.14	
	Model F value: 15.029		
	prob > F: 0.0179*		
	R-square: 0.80		

* Significant at the .05 level
** Significant at the .01 level

(1) Associated probability with the T value.

Textural parameters dominate the table of correlation coefficients for the wet simulator runs (Table 4.8). Sand fraction excluding the very fine sand and the silt fraction including the very fine sand appear respectively negatively and positively correlated with runoff rate in simulator runs two, three and four. The "corrected sand" fraction explained 69 and 80% of the variation in runoff rates respectively in runs three and four, while the "corrected silt" fraction accounts for 86% in the fourth run. Subsoil bulk density was noted positively correlated with runoff rates in runs two and three, but failed to improve the probability level associated to the textural predictive parameters. The textural parameter "M" (% silt + very fine sand x 100- % clay) described by Wischmeier et al. (1971), achieved fair positive correlation (not presented) with runoff rates in the wet simulator runs.

The observed negative correlation between slope gradient and runoff rates in the three first runs is assumed accidental in nature. Actually this correlation does not bear any physical meaning, since soil infiltrability is inversely proportional to slope gradient for constant soil conditions (Hillel, 1980); nevertheless, it indicates the dominance of intrinsic soil properties over slope gradient in accounting for variations in runoff rates.

4.3.2. Sediment concentrations in runoff and soil losses

In simple terms, the soil loss observed within a given rainfall event is the product of the induced runoff and its mean sediment concentration. Although not independent of each other and largely controlled by a similar set of soil and test storm properties, it becomes useful to interpret separately these two dependent variables in order to further our understanding of the erosion process. By isolating the variability in sediment concentration in runoff, it is possible to focus on the properties affecting the soil detachability and transportability components (Ellison, 1947; Meyer and Wischmeier, 1969) of soil's erodibility.

4.3.2.1. Sediment concentration

Variability in measured sediment concentration in runoff at the end of each simulated rainfall run is reported in Table 4.10. Figure 4.2 illustrates the evolution of sediment concentration in runoff at the Sheldon site through the four consecutive simulated rainfall runs; evolution of sediment concentration levels for all other sites is reported in Appendix 3.

Highest sediment concentrations were measured on the first run at all sites except for the Arboretum site. Highest soil detachability by rainfall and runoff, conferred by the initially loose, freshly harrowed soil, favored a wide availability of detached soil for transport and is likely a major factor in achieving peak sediment concentrations in the first run. A more intense soil detachment by rainfall was also favored by higher rainfall intensity in the first run, assuming that soil detachment by rainfall is roughly proportional to the square of the rainfall intensity (Meyer and Wischmeier, 1969).

Table 4.10 Variability in sediment concentration in runoff at the eight sites studied for the four consecutive simulated rainfall runs.

Site	Sediment concentration in runoff ($g.L^{-1}$)			
	Simulated rainfall run #			
	(1)	(2)	(3)	(4)[a]
Arboretum	27.15	28.15	11.87	4.17
Coaticook	8.01	6.91	4.01	2.35
Coleman	35.21	36.95	24.91	7.26
Dump	47.15	43.78	33.44	–
Highway	119.10	91.41	39.86	13.90
Radar	165.65	131.17	127.72	–
Rudy	63.99	59.81	47.72	12.22
Sheldon	37.37	24.01	13.26	6.30
Mean	62.95	52.77	37.85	7.70
Std.Dev.	53.02	40.63	39.26	4.51
Min.	8.01	6.91	4.01	2.35
Max.	165.65	131.17	127.72	13.90

[a] Only six observations were recorded for the fourth run since two soils failed to produce runoff.

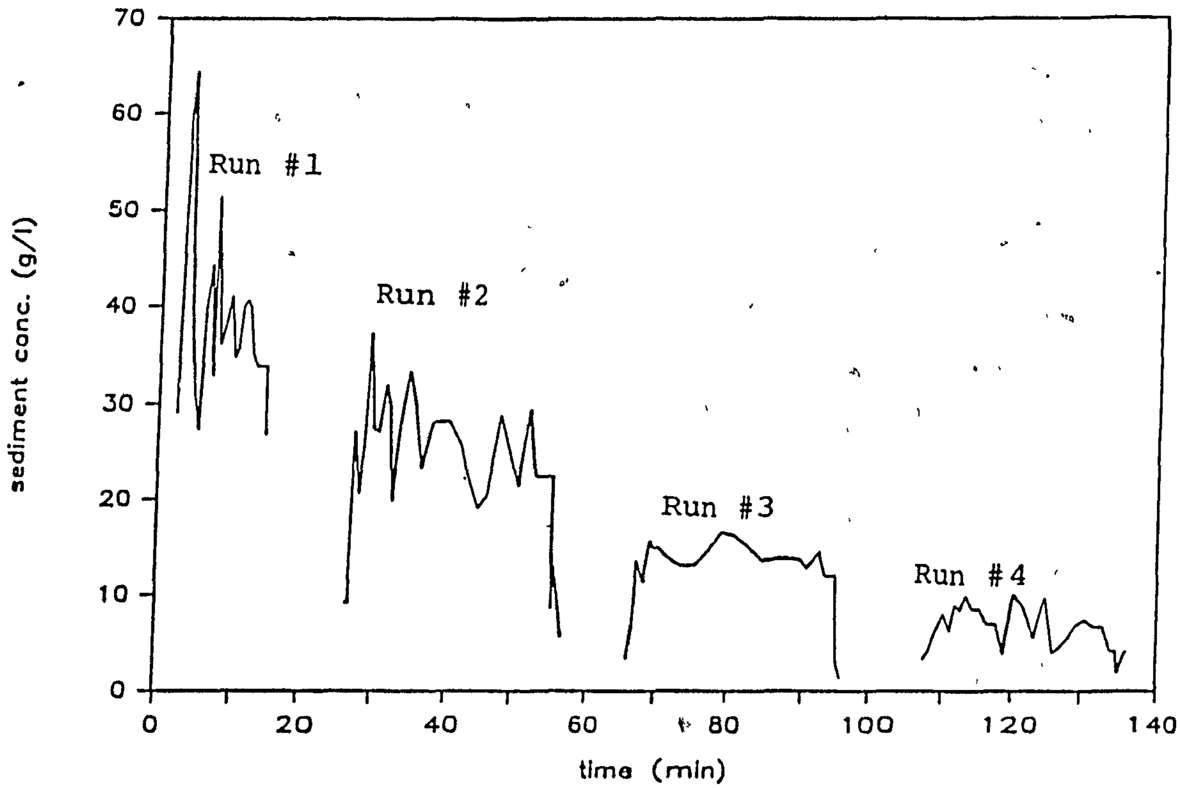


Figure 4.2 Evolution of sediment concentration in runoff at Sheldon site through the four consecutive simulated rainfall runs. (Rainfall intensities for run #1, 2, 3, and 4 are: 127, 96, 66 and 32mm/hr respectively.)

Subsequent simulated rainfall runs yielded consistently decreasing sediment concentration in runoff. Besides reduced detachability of the soils as the test storms progressed and continuous erosion of the more easily detached and transported soil, decreasing rainfall intensity and runoff rates likely contributed to diminishing sediment concentration in runoff. The direct proportionality of rainfall intensity to transport capacity of rainfall (Ekérn, 1953) and rainfall detachment (Ellison, 1944) added to the direct proportionality between runoff rates and transport/detachment capacity of runoff (Meyer, 1965) support in theory the observed trend in decreasing sediment concentrations.

The range in sediment concentrations reported in table 4.10 is fairly comparable with interill erosion data collected by Meyer and Harmon

(1984) on 0.9 m^2 runoff plots. Mean sediment concentrations observed by Meyer and Harmon (1984) varied from 16 to 145 $g.L^{-1}$ on a dry simulated rainfall run and from 21 to 93 g/l on a subsequent wet run at the same 77 mm/h rainfall intensity. A theoretical explanation for the observation of similar sediment concentration range on a 0.5- m slope length (Meyer and Harmon, 19824 and the 7.5 m slope length of the present study may be found partially in Meyer and Wischmeier's (1969) mathematical simulation of soil erosion processes, which demonstrated that below a slope length of 7 m and a slope gradient of 12%, sediment load equaled the transport capacity of rainfall and runoff. Following this interpretation, the available detached soil could have exceeded the transport capacity of the test storm in both the Meyer and Harmon (1984) and the present experiment, thus sediment concentration and soil loss data could possibly be "transport" controlled rather than "detachment" controlled. Although the present study provides no grounds to conclude on the relative importance of the erosion phases taking place, the relatively high range and low variability in sediment concentration observed in the first three runs on Coleman, Dump, Radar, and Rudy sites, while the rainfall intensity decreased by 50%, likely support Meyer and Wischmeier's (1969) mathematical interpretation, at least for these sites.

Variability among soils for each simulated rainfall run clearly reflect the effect of slope gradient on soil detachability and transport capacity of rainfall and runoff. The steepest sites were subjected to highest sediment concentrations in runoff in all rainfall runs; the Radar and Highway sites experienced peak end-of-run concentrations of 166 and 199 g/l, respectively, in the first run. As shown in table 4.11, tabulating coefficients of simple correlation significant at 50% level between site properties and sediment concentrations, slope appears highly correlated with end-of-run sediment concentration in runoff during all runs. The square-root of the slope gradient alone significantly explained at the .01 level 71% of the variation in sediment concentration in the first run while significantly accounting for 64% and 69% of the variation, at the 0.05 level, in runs #2 and 3 respectively.

Percent water stable aggregates larger than 1.0 mm showed consistent negative correlations with sediment concentration in runoff in all simulated rainfall runs (Table 4.11). Its association with slope gradient as a predictive parameter for sediment concentration in runoff yielded the best independent variables combination for the simulated rainfall runs 1, 2, and 4. Table 4.12 reports the simple linear regression figures. The significance of aggregation stability in explaining concentration in runoff stresses the importance of the aggregation characteristics in affecting particle detachment and transport by rainfall and surface flow among the tested soils; similar conclusions using rainfall simulation were reached by Young and Mutchler (1977) on Minnesota soils, by Luk (1979) in Southern Alberta and El-Swaify and Dangler (1976) in Hawaii from soil loss data. A fairly high correlation between water stable aggregates and mean weight diameter ($r = +0.60$) restricts however the interpretation of the initial aggregate size distribution's correlation with sediment concentration in runoff. The sand ratio-slope gradient predictive parameters combination, best accounting for variability in sediment concentration in run 3, also indirectly includes the effect of water stable aggregates, the latter variable being negatively correlated at 60% with sand ratio.

Table 4.11 **Coefficients of simple correlation significant at 50% for sediment concentration in runoff as dependent variable**

Independent variable	Pearson correlation coefficients and associated probability run #1		run #2		run #3		run #4	
Organic matter	-0.30	0.478	-0.34	0.410	-0.34	0.416	-0.55	0.257
Fine + Very fine sand	+0.35	0.389	+0.40	0.323	+0.45	0.267		
Very coarse + Coarse sand	-0.35	0.395	-0.35	0.398				
Clay ratio							+0.73	0.099
Silt ratio	-0.62	0.096	-0.70	0.054	-0.60	0.119	-0.65	0.164
Sand ratio	+0.66	0.075	+0.71	0.052	+0.86	0.006**		
Mean weight diameter	-0.47	0.245	-0.51	0.194	-0.52	0.190		
W.S. aggregates >1.0 mm	-0.52	0.191	-0.61	0.110	-0.51	0.192	-0.47	0.344
Cation exchange capacity	-0.41	0.312	-0.44	0.270	-0.46	0.251	-0.47	0.343
Exchangeable sodium percentage							+0.61	0.201
Pyro. exchangeable Fe + Al							-0.54	0.270
Water retained at 10 cbar	-0.74	0.036						
$(Slope)^{0.5}$	+0.84	0.009**	+0.80	0.017*	+0.83	0.012*	+0.65	0.166

* Significant at the 0.05 level
** Significant at the 0.01 level

Table 4.12 Best simple linear regressions significant at the .05 level for sediment concentration in runoff as dependent variable for the four consecutive rainfall runs.

Run #	Variable	Parameter estimate	Prob > (T)[1]
1	$(\%\ Slope)^{0.5}$	36.50	0.002**
	Water stable aggregates >1.0 mm	-1.61	0.017*
	Intercept	-9.32	
	Model F value: 27.474		
	prob > F: 0.0020**		
	R-square: 0.92		
2	$(\%\ Slope)^{0.5}$	26.32	0.001**
	Water stable aggregates >1.0 mm	-1.50	0.003**
	Intercept	0.84	
	Model F value: 43.390		
	prob > F: 0.0007**		
	R-square: 0.95		
3	$(\%\ Slope)^{0.5}$	17.49	0.009**
	Sand ratio	23.32	0.005**
	Intercept	-38.79	
	Model F value: 40.653		
	prob > F: 0.0008**		
	R-square: 0.94		
4	$(\%\ Slope)^{0.5}$	4.40	0.0176*
	Water stable aggregates >1.0 mm	-0.20	0.0275*
	Intercept	1.08	
	Model F value: 14.991		
	prob > F: 0.0274*		
	R-square: 0.91		

* Significant at the .05 level
** Significant at the .01 level

[1] Associate probability with the T value.

The consistent negative correlations of organic matter and cation exchange capacity (C.E.C.) with sediment concentration during all runs cannot be isolated from each other due to high intercorrelation of these independent variables (r = 0.89), significant at the .01 level. The influence of organic matter content on sediment concentration can likely be related to its well-documented promotion of aggregate stability by minimizing stresses caused by wetting and rain drop impact (Imeson and Jungerius, 1976); a positive correlation of 32% was evaluated between percent water stable aggregates and organic matter content of the tested soils. The C.E.C., very weakly correlated with clay percentage (r=+0.17) and moderately correlated with percent water stable aggregates (r=+0.40) and sediment concentration during all runs (41 <r <47) may possibly reflect an effect of the mineralogical properties of the soils. High C.E.C. montmorillonite soils have been associated with better aggregation and lower susceptibility to erosion on the aggregated Upper American Midwest soils (Young and Mutchler, 1977). Meyer and Harmon (1984) also strongly correlated negatively interill erosion rates with C.E.C.; the latter, however, was in turn highly correlated with clay and organic matter percentages. Unfortunately, the absence of mineralogical data on the soils tested under the present study prevent any conclusions regarding a potential effect of mineralogical properties on sediment load.

The soil texture influence on sediment concentration in runoff was best described by the variation in sand and silt ratios among the tested sites during the first three simulated rainfall runs. However, the observed trends in correlation of these textural parameters with sediment concentration measured in runoff are opposed to the nomographic model of soil erodibility (Wischmeier et al.,1971). The nomograph reflects a general increasing trend in erodibility with greater silt content and lower sand content. The influence of soil aggregation, however, was not apparent from Wischmeier et al.'s (1971) data on medium-textured Midwest soils and neither was included in the nomograph. Young and Mutchler (1977) demonstrated the need to consider aggregation characteristics in using textural predictive parameters for well-aggregated soils in Minnesota and could significantly explain 75% of variation in soil erodibility with aggregate index and percentage of montmorillonite alone. In the present study, the aggregated nature of the high-silt soils is clear. The two soils studied in the Eastern Townships, the Coaticook and Sheldon series, were both characterized by the highest silt percentages of the soils studied (respectively 59.5 and 48%) and also by the highest percentage of water-stable aggregates larger than 1.0 mm (respectively 42 and 46%). Both series were also characterized by clay contents over 20% and the Coaticook series showed highest organic matter content (4.87%) of the soils studied, two properties generally promoting aggregate formation and stabilization respectively (Emerson, 1959). The resultant high correlation between silt content and water stable aggregates observed among the soils studied (r = 0.92, significant at the .01 level) thus conveys on the silt fraction a negative correlation with sediment concentration in runoff. Sand content, appearing positively correlated with sediment concentration in runoff, may reflect the effect of sand on aggregate stability (r = -0.60 between sand ratio and water stable aggregates %). In his study of erosion by wash and splash on Southern Alberta soils, where soil aggregation was the most significant variable explaining soil loss, Luk (1979) also observed positive correlation of sand content with the soil loss variables examined over a wide range of soil environments. When looking specifically at cultivated Prairie soils, Luk (1979) observed however a significant positive correlation between clay content and soil loss as a result of the unaggregated nature of the clay colloids. Likewise, the positive correlation between clay content and sediment concentration in runoff observed in the fourth simulated rainfall run of the present study, may reflect the maximal disruption of surface aggregation attained by the tested soils in the fourth run. Lower transport capacity of runoff for coarser than clay sediments, related to lower rainfall erosivity than the preceeding simulator runs, could also favor a positive correlation between clay content and sediment concentration in runoff during the fourth run.

4.3.2.2. Soil losses

Cumulative soil loss evolution over time for the tested soils under the standard test storm are presented in Appendix 4. Figure 4.3 illustrate the data for the Sheldon site. Table 4.14 summarizes the variability in soil loss observed on the eight sites by presenting individual run subtotals. The highest soil losses were measured during run 2 on all soils. Highest rainfall erosivity, applied in run 2 combined to reduce infiltrability and surface storage capacity due to surface sealing, and rilling contributed to the achieving peak soil losses. However, the soils studied demonstrated a fair variability in soil losses with respect to run sequence. Highest soil losses observed for the first run at the Arboretum (2.57 t/ha) and Dump (3.07 t/ha) sites are likely linked to the runoff rates and energy required to induce runoff observed at these sites, respectively the highest and lowest observed among the sites (Table 4.2 and 4.5). Relatively high soil losses observed at the Sheldon (1.76 t/ha) and Rudy sites (1.82 t/ha) are also likely runoff-related as they ranked next in terms of observed runoff rates and rainfall energy required to induce runoff. A significant coefficient of simple linear correlation at the 0.05 level between runoff rate and soil loss dependent variables observed in the first run (Table 4.14), statistically reflects the importance of runoff intensity in affecting soil loss during the dry run. In the wet runs, the variability in soil losses among the sites is distinct from the dry run. Runoff intensity does not appear any more as the dominant parameter in explaining soil loss variability among the sites. The Highway and Radar sites were respectively subjected to highest soil losses during runs 2 and 3, and the overall trend in soil losses observed among the eight sites appeared predominantly associated with sediment detachability and transportability, as suggested by a negative correlation with runoff rates and consistently increasing correlation of soil losses with sediment concentration in runoff (Table 4.14) through subsequent wet runs; during the very wet run 4, sediment concentration in runoff appeared significantly correlated at the 0.05 level with soil loss (r = + 0.85).

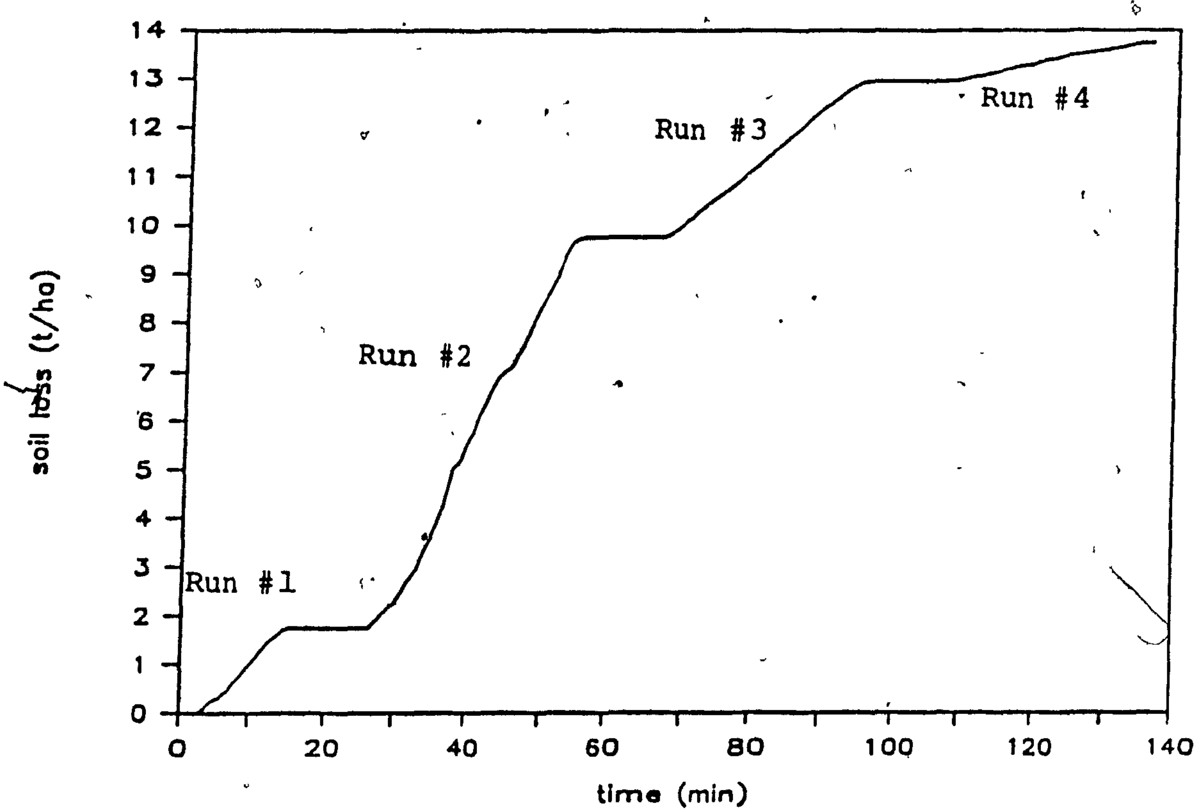


Figure 4.3 Evolution of cumulative soil loss at Sheldon site through the four consecutive simulated rainfall runs. (Rainfall intensities for run #1, 2, 3, and 4 are: 127, 97, 66 and 32 mm/hr respectively.)

Table 4.13 Variability in soil loss at the eight sites studied for the four consecutive simulated rainfall runs.

Site	Soil loss (t/ha)[a]				
	(1)	(2)	(3)	(4)	Total
	- Simulated rainfall run # -				
Arboretum	2.57	9.36	1.88	0.20	14.01
Coaticook	0.13	1.38	0.90	0.27	2.68
Coleman	1.05	7.34	3.99	0.66	13.04
Dump	3.07	9.02	3.68	-	15.77
Highway	2.18	27.16	7.60	0.85	37.79
Radar	1.40	9.90	6.36	-	17.66
Rudy	1.82	10.96	4.60	0.96	18.34
Sheldon	1.76	8.01	3.19	0.79	13.75
Mean	1.75	10.39	4.03	0.62	
Std.Dev.	0.91	7.38	2.20	0.32	
Min.	0.13	1.38	0.90	0.20	
Max.	3.07	27.16	7.60	0.96	

[a] Only six observations were recorded for the fourth run since two soils failed to produce runoff.

Table 4.14 Coefficients of simple correlation between soil loss and the other observed dependent variables for the individual simulated rainfall runs.

Variable	Pearson correlation coefficients with soil loss dependent variables run #1	run #2	run #3	run #4
End-of-run runoff rate	+0.72*	-0.58	-0.44	-0.14
Rainfall energy required to induce runoff	+0.64	-0.11	+0.15	-0.48
Sediment concentration in runoff	+0.14	+0.56	+0.67	+0.85*

* Significant at the 0.05 level

The correlation and regression analyses of the measured physico-chemical soil properties with soil loss reflects a combination of the previous analysis performed on runoff and sediment concentration (Table 4.15 and 4.16). As with runoff rates the correlation of "corrected silt x corrected sand" and aggregate mean weight diameter with soil loss showed 50% significance during the dry run only, reflecting the dominant effect of runoff intensity on the dry run soil loss. The correlation analysis of soil loss data for the dry run also highlighted independent variables previously associated with sediment concentration in runoff, namely: water stable aggregates, C.E.C., silt ratio, and water retention at 10 kPa. No combination of independent variables explained at the 0.05 level of significance the variation in soil loss during the dry run.

Table 4.15 Coefficients of simple correlation significant at the 50% level for soil loss as dependent variable

Independent variable	Pearson Correlation Coefficients & Associated Probability run #1		run #2		run #3		run #4	
% Organic matter					-0.51	0.199	-0.75	0.082
Clay ratio			+0.76	0.030*	+0.51	0.202	+0.52	0.287
Silt ratio	-0.54	0.168	-0.53	0.175	-0.68	0.061	-0.41	0.423
% (Silt + V.F. sand)x(sand - V.F. sand)	+0.65	0.079						
Mean weight diameter	-0.48	0.230						
% W.S. aggregates > 1.0 mm	-0.46	0.248	-0.44	0.272	-0.53	0.180		
% W.S. aggregates > 1.0 mm x % O.M.	-0.58	0.128	-0.49	0.22	-0.62	0.099	-0.41	0.413
Clay ratio/% W.S. aggregates > 1.0 mm	+0.40	0.330	+0.39	0.338			+0.76	0.082
Water retention at 10 kPa	-0.74	0.036*	-0.79	0.019*	-0.78	0.023*	-0.70	0.121
Cation exchange capacity	-0.45	0.258			-0.52	0.184	-0.66	0.157
Exchangeable sodium percentage			+0.34	0.405	+0.56	0.149	+0.77	0.075
Pyro. extractable Fe + Al	-0.33	0.418	-0.61	0.105	-0.44	0.270	-0.36	0.484
$(Slope)^{0.5}$					+0.72	0.043*	+0.87	0.024*
LS factor					+0.57	0.136	+0.78	0.067

* Significant at the 0.05 level

Table 4.16 Best simple linear regressions significant at the .05 level for soil loss as dependent variable for the four consecutive simulated rainfall runs.

Run #	Variable	Parameter Estimate	Prob > (T)[1]
2	Clay ratio/W.S. Aggregates > 1.0 mm	3.24	0.005**
	$(Slope)^{0.5}$	1.26	0.328
	Intercept	$1.77 \cdot 10^{-1}$	
	Model F valve: 12.225		
	prob > F: 0.0119*		
	R-square: 0.83		
3	Clay ratio	$4.37 \cdot 10^{2}$	0.008**
	W.S. Aggregates > 1.0 mm	$-7.11 \cdot 10^{2}$	0.007**
	$(Slope)^{0.5}$	1.22	0.002**
	Intercept	$6.30 \cdot 10^{-1}$	
	Model F valve: 35.118		
	prob > F: 0.0025**		
	R-square: 0.96		
4	Water retained at 10 cbar	$-1.70 \cdot 10^{-2}$	0.0682
	$(Slope)^{0.5}$	$2.71 \cdot 10^{-1}$	0.0157*
	Intercept	$3.95 \cdot 10^{-1}$	
	Model F valve: 20.823		
	prob > F: 0.0174*		
	R-square: 0.93		
4	W.S. Aggregates > 1.0 mm x % O.M.	$-1.68 \cdot 10^{-3}$	0.118
	$(Slope)^{0.5}$	$3.03 \cdot 10^{-1}$	0.017*
	Intercept	$3.05 \cdot 10^{-2}$	
	Model F valve: 14.482		
	prob > F: 0.0288		
	R-square: 0.91		
4	% Organic Matter	$-1.09 \cdot 10^{-1}$	0.139
	$(Slope)^{0.5}$	$2.32 \cdot 10^{-1}$	0.055
	Intercept	$3.46 \cdot 10^{-1}$	
	Model F valve: 12.981		
	prob > F: 0.0333*		
	R-square: 0.90		

* Significant at the .05 level
** Significant at the .01 level

(1) Associate probability with the T value.

For the wet runs, soil loss correlated best with independent variables already identified as being closely associated with sediment concentration in the previous section. Percent organic matter and cation exchange capacity remained negatively correlated with soil loss at a 50% level of significance in runs three and four while percent water stable aggregates negatively correlated with soil loss in wet runs two and three. Clay ratio, exchangeable sodium percentage, pyrophosphate extractable iron and aluminum and water retention at 10 kPa are all linearly correlated at a 50% level of significance with soil loss for the three wet runs. Consistent indications of correlation with soil loss for these independent variables in all wet runs likely bears the same physical meaning regarding soil detachability and transportability, pointed out in the previous section. The significance of water retention at 10 kPa in explaining soil loss cannot be interpreted physically because of its high level of correlation with organic matter (+0.74) and water stable aggregates (+0.83), both significant at the 0.05 level.

Table 4.17 summarizes the best simple linear regressions, significant at the 0.05 level, for soil loss as the dependent variable for the three wet runs. As for the regression study on sediment concentration in runoff, the slope gradient is included in all significant regressions. Percent water stable aggregates is also part of a significant regression for the three wet runs; combined with clay ratio in explaining soil loss for run two, it contributes as an individual parameter to the best regressions for runs three and four. Clay ratio, a significant contributor in runs 2 and 3 regressions, and with association to aggregation in explaining soil loss, emphasizes that the relation of soil loss to percent clay depends to a considerable extent on the aggregation status of the soils studied. Organic matter is only part of a regression explaining soil loss on run 4, although its regression parameter estimate is not significant at the 0.05 level.

4.3.3. Soil erodibility indices

The soil erodibility factor of the USLE for each of the eight soils tested was determined directly from soil-loss data. The slopes of the computed least-quares regression lines of soil loss on storm combination EI values, but corrected to a standard unit plot condition, were considered as the value of the factor K for the tested soils (Wischmeier and Mannering, 1969; Wischmeier, 1972). Table 4.17 summarizes the regression data for the eight sites and the two storm combinations, previously described as "dry" and "wet" combinations in section 4.2.4.2. Appendix 4 illustrates graphically regression data for all sites. Sample data for the Sheldon site are reproduced in Figure 4.4.

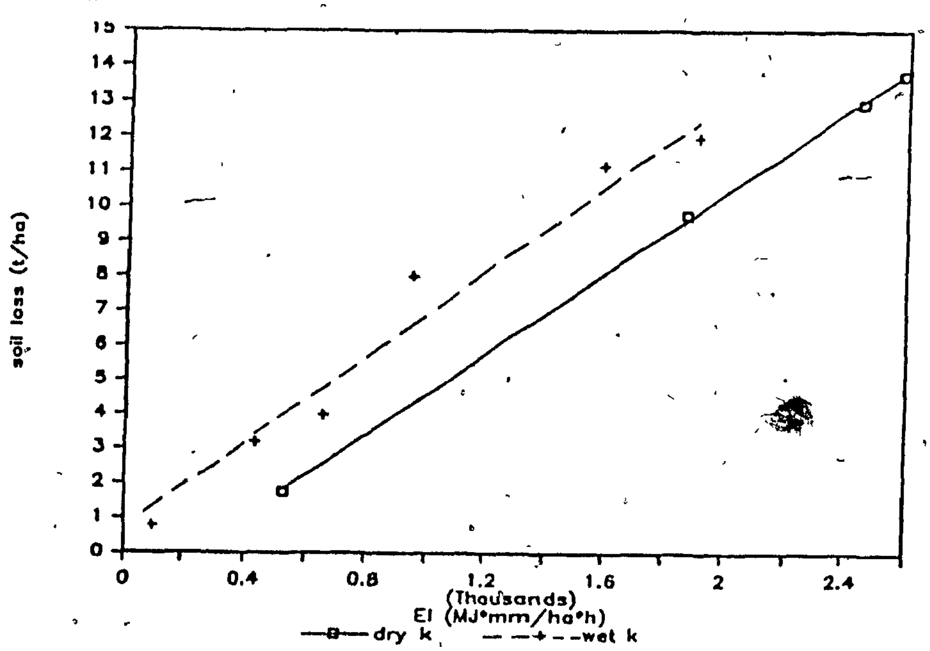


Figure 4.4 Soil loss versus rainfall erosivity for dry and wet runs combinations of simulated rainfall runs at Sheldon site.

Simple linear regression of soil loss data over rainfall erosivity yielded first degree equations (linear model $Y = B_0 + B_1 X$) significant at the 0.05 level for all sites and storm combinations, except for the wet storm combination at the Radar and Dump sites. The absence of runoff during the fourth run for these sites left only three observations available for the regression of soil loss data over storm EI, thus providing excessively high critical F values for the statistical analysis. Graphical illustration of soil loss and storm EI data for these sites (Appendix 4) demonstrate, however, that the observed individual storm erosion losses are proportional to the rainfall parameter EI.

Table 4.17 Simple linear regressions of soil losses on storm erosivities for both storm combinations and associated statistics.

Site	Run Comb.	B_1 ($\cdot 10^{-3}$)	B_0 (Intercept)	F value	Model Pr>F	Model R^2	C.V.
Arboretum	Dry	4.73	1.52	27.9	0.0340	0.93	16.23
	Wet	7.00	-0.53	27.2	0.0064	0.87	34.37
Coaticook	Dry	1.04	-0.30	799.9	0.0012	>0.99	4.18
	Wet	1.23	0.27	320.9	0.0001	0.99	7.46
Coleman	Dry	4.95	-0.78	251.8	0.0039	>0.99	6.87
	Wet	6.31	0.73	178.1	0.0002	0.99	11.01
Dump	Dry	6.00	0.80	257.3	0.0396	>0.99	5.58
	Wet	7.74	0.79	32.8	0.1101	0.97	13.03
Highway	Dry	14.73	-1.69	43.8	0.0221	0.96	16.08
	Wet	21.00	-0.64	40.8	0.0031	0.91	26.68
Radar	Dry	7.52	-1.08	386.0	0.0324	>0.99	5.43
	Wet	8.64	2.26	108.0	0.0611	0.99	6.27
Rudy	Dry	6.79	1.59	143.5	0.0069	0.99	7.44
	Wet	9.00	0.61	118.3	0.0004	0.97	14.14
Sheldon	Dry	4.90	0.15	140.6	0.0070	0.99	8.31
	Wet	6.49	0.43	115.1	0.0004	0.97	14.35

Differences in observed values of B_0 and B_1 between dry and wet storm combinations are related to differences in antecedent moisture and surface conditions. Consistently higher B_1 values, or slope of the regression lines, were observed for the wet storm combinations. This indicates that soil erodibility, as related to sustained infiltration rates and a soil's ability to resist particle detachment and transport, was influenced by soil surface conditions. The observed trend for higher B_1 estimates in the wet storm combinations is compatible with the concept of K variability over varying surface conditions during the year, illustrated and observed on natural plots by Mutchler and Carter (1983) and Kirby (1985).

The magnitude of B_0 in regression equations for erodibility studies has been primarily related to initial infiltration rate and surface retention (Wischmeier and Mannering, 1969). Within the present study the fairly high positive correlation between B_0 and runoff rates measured at the end of the dry run ($r = +0.69$; Prob: 0.060) illustrates this conceptual relation. However, the magnitude in B_0 observed here appeared much larger than the range reported by Wischmeier and Mannering (1969) in their rainulator study. While the absolute values of the negative intercept were in the general range of 10 times the slope B_1 in the latter study, B_0 values appeared 30 to 300 times larger than B_1 within the present study. The physical meaning of this difference in B_0 amplitude is difficult to evaluate, since different methodologies were used for data treatment in Wischmeier and Mannering (1969) and the present study. While Wischmeier and Mannering (1969) used statistically "adjusted" data for antecedent surface conditions in their regression study of soil loss on simulated storm EI, no prior data adjustment was used in the present study. The amplitude of the B_0 estimates evaluated within the present study stresses, however, the importance of time-dependent variables, such as antecedent moisture and surface condition, in affecting soil losses on the basis of EI for specific storms.

Soil erodibility factors for the tested sites, as evaluated by linear regression and corrected for slope length and gradient factors of the USLE, are tabulated in Table 4.19. Estimations using the K nomograph (Wischmeier et al., 1971), based on profile and sample physico-chemical characteristics are also reproduced in Table 4.19. For most soils, there is a considerable difference between the measured K value and the nomographic estimation. With the exception of the Arboretum and Highway sites, the nomograph value is larger than the field measurement at all sites for both simulated storm combinations. Failure of the nomograph to reflect the field measured K can possibly be interpreted by a dominant influence of aggregation in explaining soil loss (Table 4.16), while soil aggregation stability was absent from Wischmeier et al. (1971) erodibility model. The inclusion in the study of soils high in silt but demonstrating stable aggregation (Coaticook and Sheldon series), emphasized the importance of structural characteristics over soil particle-size distribution. In fact, both Coaticook and Sheldon soil series were rated as the most erodible by the nomograph (K = 0.035 and 0.034 t.h/MJ.mm respectively after correction for LS), but demonstrated very weak erodibility under the simulated rainfall (K < 0.007 t.h/ha.mm after correction for LS).

Table 4.18 K values as evaluated by linear regression of runoff plot data and as predicted by the nomograph

Site	K from field data[1] Dry comb. (t.h/ha.mm)	Wet comb.	K from nomograph[2]
Arboretum	0.053	0.078	0.017
Coaticook	0.004	0.005	0.035
Coolman	0.014	0.018	0.029
Dump	0.016	0.020	0.028
Highway	0.017	0.025	0.025
Radar	0.002	0.003	0.008
Rudy	0.014	0.018	0.020
Sheldon	0.005	0.007	0.034

(1) Four linear regression of dry storm combination (i.e.: run #1, 1+2, 1+2+3, 1+2+3+4) and wet storm combination (i.e.: run 2, 3, 4, 2+3, 2+3+4, 3+4).

(2) From Wischmeier et'al. (1971) and measured and described profile and physico-chemical characteristics of the sites.

The slope adjustment factor LS could also have contributed to the lack of agreement between nomograph and field estimates of K. As stressed by Laflen (1979), plots on identical soils at different slopes can have different K values under rainfall simulation because of the slope adjustment. The relatively short slope length used within the present study (7.5 m) was much smaller than the unit-plot specification (22.1 m) and could possibly bias the slope adjustment of K values. The use of plots with slope gradient out of the "secure range" of the USLE (Radar: 26%, Arboretum: 1.2%) also possibly contributed to biased K estimates (Wischmeier and Smith, 1978). In fact, the use of slope gradients raised to the half-power, as an independent variable, likely appeared as a better predictor of soil loss than the USLE LS factor for the tested sites (Table 4.15 and 4.16).

When studying the correlation and regression of the LS-corrected K field estimates with the selected set of independent variables, no single combination of selected independent variables could significantly explain K variability for both storm combinations. Failure of simple linear regression and correlation techniques, in significantly explaining the variation in measured K values, is largely imputable to the low number of observations used in the analysis. Previous statistical equations for significantly predicting soil loss per EI needed from 5 to 9 independent variables (Wischmeier et al., 1971; Barnett and Rogers, 1966); and up to 99 plots trials (Barnett and Rodgers, 1966). Since failure to conform to unit plot conditions of slope length and gradient within the present study also possibly introduced some bias in corrected K values, the indications given by the correlation analysis on intrinsic soil properties, as they affected the erodibility, should be considered with reserve. Table 4.19 reports the coefficients of simple correlation significant at the 50% level for LS-corrected K from the two storm combinations as dependent variables. The highest correlation was obtained for the 0-5/5-10 cm ratio of soil bulk density as sampled after the simulated storm event. When regarded as an index of structural stability through the simulated rainfall event, this bulk density ratio would likely express the importance of aggregation stability in reducing soil erodibility within the present study. The physical meaning of the correlation between soil K values and percent water stable aggregates, percent pyrophosphate extractable iron and aluminium, and soil texture-related independent variables likely agrees with the previous correlation and regression analysis of runoff and soil loss variables. Fine to very fine sand fraction appears positively correlated with measured K values (r = +0.51), while the coarser sand fraction correlates negatively. The negative correlation of the silt fraction with measured K values (r = -0.33) follows the indications given by the statistical analysis of sediment concentration in runoff and soil loss dependent variables. The positive correlation of the combined independent variables, using Wischmeier et al. (1971) corrected silt and sand fractions, illustrates, however, that the relation of erodibility to a given particle size percentage depends on the remainder of the soil mass. Although high-silt soils demonstrated low K values (likely inherited from aggregation characteristics), when combined with sand fraction as multiplier, the corrected silt fraction (Wischmeier et al., 1971) appeared positively correlated with measured K values. Pyrophosphate extractable levels of iron and aluminum, negatively correlated with measured K values, indicate the potential for organo-metallic complexes to have affected negatively the erodibility of the tested soils and is consistent with its negative correlation with soil loss dependent variable at all simulated rainfall runs (Table 4.15). Better correlation with K values for the last independent variable than for total organic carbon may suggest an active role of iron and aluminum ions in structure stabilization of the tested soils.

Table 4.19 Coefficients of simple correlation, significant at the 50% level, for measured soil erodibility factor for both storm combinations and corrected for LS, as dependent variable.

Independent variable	Pearson correlation coefficients and associate probability: Dry storm comb.		Wet storm comb.	
% Fine to Very Fine Sand	+0.51	0.200	+0.51	0.193
% Very Coarse to Medium Sand	-0.38	0.358	-0.39	0.343
Silt ratio	-0.33	0.424	-0.32	0.435
%(Silt+V.F. Sand)x(Sand-V.F. Sand)	+0.43	0.288	+0.41	0.314
Mean Weight Diameter	-0.28	0.499	-0.28	0.496
% W.S. Aggregates > 1.0 mm	-0.46	0.249	-0.45	0.262
Ratio Bulk Density 0-5 cm/5-10 cm	+0.59	0.121	+0.59	0.127
Pyro. Extr. Fe+Al.	-0.44	0.272	-0.44	0.280

4.4. Conclusions

The use of a variable-intensity rainfall simulator on outdoor runoff plots made possible the collection of runoff and sediment concentration data from various soils under a standard simulated rainfall event. The data collected provided a basis for direct comparsion of a soil's response to consecutive simulated rainstorms in terms of runoff production and timing, sediment concentration, soil loss, and soil erodibility factor.

The highest variability in rainfall energy required to initiate runoff was observed during the dry run among the soils tested. Under saturated conditions, a soil's relative ability to delay runoff production differed widely from those observed on initial dry-surface conditions. A textural predictive parameter (silt+v.f.sand x sand-v.f.sand), used with either organic matter percentage or bulk density parameters, significantly explained respectively 80 and 92% of the variation in energy required to initiate runoff during the dry run. The product of sand by organic matter percentages, used as a predictive parameter in the fourth run, significantly explained 97% of the variation in rainfall energy required to initiate runoff.

Calculated seepage rates were characterized by a gradual decrease from the first to fourth run at all sites, which appears consistent with decreasing hydraulic gradients and intensifying soil surface sealing. Since sustained seepage rates were not reached during the dry run, their amplitude remained closely associated with rainfall energy required to initiate runoff. The combined textural parameter (silt+v.f.sand x sand-v.f.sand) significantly explained 66% of the variation in runoff rates in the dry run. During the wet runs, negative and positive significant correlations of measured runoff rates were observed, respectively, with soil particles coarser than very fine sand and combined (silt+v.f. sand) fractions. Likewise, the textural parameter "M" from Wischmeier et al. (1971) achieved fair, although not significant, positive correlation with runoff rates in the wet runs. Slope gradient was not positively correlated with runoff rates among the sites tested.

A diminishing trend in sediment concentrations in runoff was observed from the first to the fourth run at all sites. The observed trend appears consistent with reduced detachibility of the soil, continuous erosion of the more easily detached soil, and decreased transport and detachment capacities of rainfall and runoff, as the test storm progressed with decreasing rainfall intensities. Relatively high levels and low variability of sediment concentrations among the first three runs at individual sites likely indicates that soil losses observed were "transport" controlled rather than "detachment" controlled.

The slope gradient parameter (% slope$^{0.5}$) appeared positively correlated at a significant level with sediment concentration in runoff during the first three runs, likely as an effect of transport and detachment capacity of the runoff. Percent water-stable aggregates larger than 1.0 mm showed consistent negative correlation with sediment concentrations during all runs. When used with slope gradient as a predictive parameter, aggregate stability contributed in explaining, at a significant level, the variability of either sediment concentration or soil loss, or both, during all runs.

Measured soil losses in the dry run appeared more likely related to runoff production than to intrinsic soil detachibility and transportability. In wet runs, where sustained runoff rates were reached, the latter soil properties were more influential on soil loss. A statistical reflection of this is the significant negative correlation observed between soil loss and rainfall energy to produce runoff in the dry run, while soil loss correlated positively, at a significant level, with sediment concentration during the fourth run.

No predictive linear regression equation could account significantly for the soil loss variation in the dry run. Clay ratio, stability of aggregates and slope gradient significantly accounted for 83 and 98%, respectively, of the variation in soil loss in runs two and three. Either stability of aggregates or organic matter content could significantly account for, respectively, 90 and 91% of the soil loss variation in run four, when regressed with slope gradient.

The observed trends in simple correlations of textural properties of the soils studied with soil loss, although not significant, are opposed to Wischmeier et al.'s (1971) nomograph. A strong significant correlation between aggregation stability and silt percentage in the soils studied favored the divergency. The significant regressions explaining soil loss in the wet runs stress, however, that the direct relation of soil loss to clay percentage depends considerably on the aggregation status of the soils studied.

The simple linear regression of soil loss data over rainfall erosivity yielded first degree equations at all sites, confirming the feasibility of determining K values by linear regression using variable-intensity rainfall simulation. Consistently higher values of B_1 estimates (slope of regression line) were observed for "wet" storm combinations as compared to "dry" storm combinations at all sites, indicating that soil erodibilities were influenced by soil surface conditions.

Exception made of Arboretum and Highway sites, measured k values, as corrected for LS factors of the USLE, were smaller than nomographic estimations (Wischmeier et al., 1971). Lack of agreement between the measured and nomographic K reside possibly in the dominant influence of aggragation in explaining soil loss variability within the present study. Measured K variability, as corrected for LS factors, could not be accounted for significantly by the given set of independant variables. Failure to conform to unit plot conditions and use of plots with slope gradient out of the secure predictive range of the USLE possibly introduced some bias in measured, LS corrected K values.

5. GENERAL CONCLUSIONS

The conception, construction and operation of a stationary, varible-intensity rainfall simulator was made possible by using a nozzle with a free passage diameter equal to orifice size. The intermittency of spray application was successfully accomplished by three-way solenoid valves. Drop-size distribution, impact velocity and energy of the simulated rainfall were near those of natural rainfall. The rainfall simulator apparatus proved to be a useful and efficient tool for research as well as for demonstration purposes.

Soil losses and runoff measured using the apparatus under initially dry surface conditions were found correlated with a different set of soil properties than those that correlated with wet-run data. Rates of soil loss with cumulative rainfall erosivity were found smaller for dry-run combinations than for wet-run combinations. These effects of soil surface characteristics on runoff, soil loss, and soil erodibility particularly stress the dynamic nature of soil loss and highlight the variable character of soil erodibility.

If the soils studied were shown to vary widely in their rates of soil loss per unit of rainfall erosivity, they demonstrated also a wide variability in rainfall energy required to initiate runoff. A practical implication of the study is thus the importance of considering rainfall energy required to initiate runoff in soil loss prediction modelling, a factor that may account for a significant part of the seasonal variability in soil erodibility.

Finally, aggregation stability demonstrated a definite ability in predicting sediment concentration in runoff and soil loss among the soils studied. Since definite lack of agreement was observed between measured and nomographic (Wischmeier et al., 1971) K values, the study raised the question on the need to incorporate aggregation stability characteristics for adequate soil erodibility predictions in southern Quebec, a dimension absent from the nomographic model.

LITERATURE CITED

Adams, J. E., Kirkham, D. and P. P. Neilsen. 1957. A portable rainfall simulator infiltrometer and physical measurements of soil in place. Soil Sci. Soc. Am. Proc. 21: 473-477.

Agricultural Institute of Canada. 1980. Soil Erosion on Agricultural land in Canada. Agrologist Fall 1980: 23-28.

Agriculture Canada. 1984. Analytical methods 1984. Land Resource Research Institute. Research Branch, Research Program Service. Ottawa.

Amerman, G. R., Hillel, D. I. and A. E. Peterson. 1970. A sprinkling infiltrometer. Soil Sci. Soc. Am. Proc. 34: 830-832.

Ateshian, J. K. H. 1974. Estimation of rainfall erosion index. J. Irr. Drain. Div. ASCE. 100 (IR3): pp. 293-307.

Barnes, O. F. and G. Costell. 1957. A mobile infiltrometer. Agron. J. 49: 105-107.

Barnett, A. D. and J. S. Rogers. 1966. Soil physical properties related to runoff and erosion from artificial rainfall. Trans. ASAE 9: 123-125, 128.

Barnett, A. D., J. R. Carreker, F. Abruva and A. E. Dooley. 1971. Erodibility of selected tropical soils. Trans. ASAE 15: 1112-1114.

Barnett, A. D., J. S. Rogers, J. H. Halladay and A. E. Dooley. 1965. Soil erodibility factors for selected soils in Georgia and South Carolina. Trans. ASAE 8: 393-395.

Bertrand, A. R. and J. F. Parr. 1961. Design and operation of the Purdue sprinkling infiltrometer. Purdue Univ. Res. Bull. No. 723. Lafayette, Ind.

Blackburn, W. H., Meeuwig, R. O. and C. M. Skau. 1974. A mobile infiltrometer for use on rangeland. J. Range Manag. 27: 322-323.

Brakensiek, P. O., Rawls, W. J. and W. R. Hamon. 1979. Application of an infiltrometer system for describing infiltration into soils. Trans. ASAE 22: 320-323.

Brooks, F. L. 1976. Use of the universal soil loss equation in Hawaii. In Soil Erosion: Prediction and Control. Soil Conservation Society of America, pp. 29-30.

Browning, G. M., Parish, C. L. and J. A. Glass. 1947. A method for determining the ues and limitations of rotation and conservation practices in control of soil erosion in Iowa. J. Am. Soc. Agron. 39: 65-73.

Bubenzer, G. D. 1979. Rainfall characteristics important for simulation. In Proc. Rainfall Simulation Workshop Tucson Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; 22-34.

Bubenzer, G. D. and B. A. Jones. 1971. Drop size and impact velocity effects on the detachment of soil under rainfall simulation. Trans. ASAE 14: 625-628.

Bubenzer, G. D. and L. D. Meyer. 1965. Simulation of rainfall and soils for laboratory research. Trans. ASAE 8: 73-75.

Bubenzer, G. D., L. D. Meyer and E. J. Monke. 1966. Effect of particle roughness on soil erosion by surface runoff. Trans. ASAE 9:562-564.

Carter, C. E., Greer, J. D., Braud, H. J. and J. M. Floyd. 1974. Raindrop characteristics in the south central United States. Trans. ASAE 17: 1033-1037.

Christiansen, J. E. 1942. Irrigation by sprinklers. Univ. of California Agric. Exp. Sta. Bull. 670.

Chow, V. T. and T. E. Harbaugh. 1965. Simulation of rainfall and soils for laboratory research. Trans. ASAE 8:73, 75.

Cook, H. L. 1936. The nature and controlling variables of the water erosion process. Soil Sci. Soc. Am. Proc. 1: 60-64.

Dangler, E. W., S.A. El-Swaify, L. R. Ahuja and A. D. Barnett. 1976. Erodibility of selected Hawaii soils by rainfall simulation. U.S. Dep. Agric., Agric. Res. Serv. ARS-W-35.

Desphande, T. L., Greenland, D. J. and J. P. Quirk. 1968. Changes in soil properties associated with the removal of iron and aluminum oxides. J. Soil Sci. 19:108-110.

Eckern, P. C. 1953. Problems of raindrop impact erosion. Agric. Eng. 34: 23-25.

Ellison, W. D. 1944. Studies of raindrop erosion. Agric. Eng. 5: 131-138, 181-182.

Ellison, W. D. 1947. Soil erosion studies I and II. Agric. Eng. 28: 442-444, 450.

Ellison, W.D. and W. H. Pomerance. 1944. A rainfall applicator. Agric. Eng. 25: 220.

El-Swaify, S. A. and A. W. Dangler. 1976. Erodibilities of selected tropical soils in relation to structural and hydrologic parameters. In Soil Erosion: Prediction and Control. Soil Conserv. Soc. Am., Ankeny, Iowa. pp. 105-114.

Emerson, W. W. 1959. The structure of soil crumbs. J. Soil Sci. 10: 235.

Evans, R. and G. Kalkanis. 1976. Use of the universal soil loss equation in California. In Soil Erosion: Prediction and Control. Soil Conserv. Soc. Amer., Ankeny, Iowa. pp. 31-40.

Foster, G. R., Eppert, F. P., and L. D. Meyer. 1979. In Proc. Rainfall Simulation Workshop Tucson Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; pp. 45-59.

Foster, G. R. and L. D. Meyer. 1975. Mathematical simulation of upland erosion using fundamental erosion mechanics. In Present and Prospective Technology for Predicting Sediment Yields and Sources. U.S. Dept. Agric., Agr. Res. Serv., ARS-S-40, pp. 190-207.

Foster, G. R., L. D. Meyer and C. A. Onstad. 1977a. An erosion equation derived from basic erosion principles. Trans. ASAE 20: 678-682.

Foster, G. R., L. D. Meyer and C. A. Onstad. 1977b. A runoff erosivity factor and variable slope length exponents for soil loss estimates. Trans. ASAE 20: 683-687.

Foster, G. R. and W. H. Wischmeier. 1974. Evaluating irregular slopes for soil loss prediction. Trans. ASAE 17: 305-309.

Free, G. R. 1960. Erosion characteristics of rainfall. Agric. Eng. 41: 447-449, 455.

Gunn, R. and G. D. Kinzer. 1949. Terminal velocity of water droplets in stagnant air. J. Meteoral. 6: 243-248.

Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York.

Holland, M. E. 1969. Design and testing of a rainfall system. Col. State Exp. Sta. CER 69-70 MEH 21. Ft. Collins.

Hudson, N. W. 1963. Raindrop size distribution in high intensity storms. Rhodesian J. Agric. Res. 1: 6-11.

Imeson, A. C. and P. D. Jungerius. 1976. Aggregate stability and colluviation in the Luxembourg Ardennes; an experimental and geomorphological study. Earth Surface Processes 1: 259-271.

Kemper, W. D. and E. J. Koch. 1966. Aggregate stability of soils from western U.S. and Canada. Tech. Bull. 1355, Agric. Res. Serv., U.S. Dep. Agric., Wash. D.C.

Kirby, P. C. 1985. The seasonal variation of soil erosion and soil erodibility in Southern Quebec. Unpl. MSc Thesis. Renewable Resources Dep., Macdonald College. McGill Univ., Canada.

Laflen, J. M. 1979. Interpretation of rainfall simulation data. In Proc. Rainfall Simulation Workshop Tucson, Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; 101-107.

Laflen, J. M. and H. P. Johnson. 1976. Soil and water loss from impoundment terrace systems. 3rd Federal Inter-Agency Sedimentation Conference Proceedings 2: 20-41.

Laws, J. O. 1941. Measurements of the fall-velocities of waterdrops and raindrops. Trans. Am. Geophys. Union. 22: 709-721.

Laws, J. O. and D. A. Parsons. 1943. The relation of raindrop size to intensity. Trans. Am. Geophys. Union. 24: 452-459.

Luk, S. H. 1979. Effect of soil properties on erosion by wash and splash. Earth Surface Processes 4: 241-255.

Lusby, G. C. 1977. Determination of runoff and sediment by rainfall simulation. In Erosion: Research Techniques, Erodibility and Sediment Delivery. Geo. Abstracts Ltd., Norwich, England.

McCool, D. K., Papendick, R. L. and F. L. Brooks. 1976. The universal soil loss equation adapted to the Pacific Northwest. 3rd Federal Inter-Agency Sedimentation Conference Proceedings 2: 135-147.

McCool, D. K., Wischmeier, W. H. and L. C. Johnson. 1982. Adapting the universal soil loss equation to the Pacific Northwest. Trans. ASAE 25: 928-934.

McGregor, K. C. and C. K. Mutchler. 1976. Status of the R factor in northern Mississipi. In Soil Erosion: Prediction and Control. Soil Conserv. Soc. Am., Ankeny, Iowa. pp. 135-141.

Meyer, L. D. 1960. Use of the rainulator for runoff plot research. Soil Sci. Soc. Am. Proc. 24: 319-322.

Meyer, L. D. 1965. Simulation of rainfall for soil erosion research. Trans. ASAE 8: 63-65.

Meyer L. D. 1979. Methods in attaining desirable characteristics in rainfall simulation. In Proc. Rainfall Simulation Workshop Tucson, Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; 35-44.

Meyer, L. D. 1981. How rainfall intensity affect interrill erosion. Trans. ASAE 24: 1472-1475.

Meyer, L. D., G. R. Foster and M. J. M. Romkens. 1975. Source of soil eroded by water from upland slopes. Sediment Prediction Workshop Proceedings, Oxford, Miss. ARS-S-40: 177-189.

Meyer, L. D. and W. C. Harmon. 1979. Multiple intensity rainfall simulator for soil erosion research on row sideslopes. Trans. ASAE 22: 100-103.

Meyer, L. D. and W. C. Harmon. 1984. Susceptibility of agricultural soils to interrill erosion. Soil Sci. Soc. Am. J. 48: 1152-1155.

Meyer, L. D. and D. L. McCune. 1958. Rainfall simulator for runoff plots. Agric. Eng. 39: 544-548.

Meyer, L. D. and M. A. Ports. 1976. Prediction and control of urban erosion and sedimentation. In National Symposium on Urban Hydrology, Hydraulics and Sedimentation Proceedings, University of Kentucky, Lexington, Bull. 111: 323-331.

Meyer, L. D. and W. H. Wischmeier. 1969. Mathematical simulation of the process of soil erosion by water. Trans. ASAE 12: 754-757, 781.

Meyer, L. D. and W. H. Wischmeier. 1974. Evaluating irregular slopes for soil loss prediction. Trans. ASAE 17: 305-309.

Mihara, Y. 1951. Raindrops and soil erosion. Nat. Inst. Agric. Sci. Bull. A1: 1-51.

Morin, J., Goldberg, D. and I. Seginer. 1967. A rainfall simulator with a rotating disk. Trans. ASAE 10: 74-77.

Murphree, C. E. and C. K. Mutchler. 1981. Verification of the slope factor in the USLE for low slopes. J. Soil Water Conserv. 38: 300-302.

Musgrave, G. W. 1947. The quantitative evaluation of factors in water erosion, a first approximation. J. Soil and Water Conserv. 4:99-102.

Mutchler, C. K. and C. E. Carter. 1983. Soil erodibility variation during the year. Trans. ASAE 26: 1,102-1,104, 108.

Mutchler, C. K. and J. D. Greer. 1980. Effect of slope length on erosion from low slopes. Trans. ASAE 23: 866-869, 876.

Mutchler, C. K., and K. C. McGregor. 1979. In Proc Rainfall Simulation Workshop Tucson Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; pp. 8-16.

Mutchler, C. K., Murphree, C. E. and K. C. McGregor. 1982. Subfactor method for computing C factors for continuous cotton. Trans ASAE 25: 327-332.

Olson, T. C. and W. H. Wischmeier, 1963. Soil erodibility evaluations for soils on the runoff and erosion stations. Soil Sci. Soc. Am. Proc. 27: 590-592.

Onstad, C. A. and G. R. Foster. 1975. Erosion modeling on a watershed. Trans. ASAE 18: 288-292.

Pall, R., Dickinson, W. T., Green, D. and R. McGirr. 1982. Impacts of soil characteristics on soil erodibility. In Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield Proceedings, Exeter Symposium. IAHS Publ. no. 137.

Parsons, D. A. 1943. Discussion on the application and measurement of artificial rainfall as type FA and type F infiltrometer. Trans. Am. Geophys. Union. 29: 485-487.

Pesant, A. 1985. Lennoxville experimental farm, Agriculture Canada. Pers. Comm.

Quansah, C. 1981. The effect of soil type, slope, rain intensity and their interactions on splash detachment and transport. J. Soil Sci. 32: 215-224.

Rawitz, E., Margolin, M. and D. I. Hillel. 1972. An improved variable-intensity sprinkling infiltrometer. Soil Sci. Soc. Am. Proc. 36: 533-535.

Renard, K. G., and J. R. Simanton. 1975. Discussion of "Estimation of rainfall erosion index" by J. K. H. Ateshian, J. Irr. Drain. Div. ASCE. 101 (IR3): 242-244.

Rogers, J. S., Johnson, L. C., Jones, D. M. A. and B. A. Jones. 1967. Sources of error in calculating the kinetic energy of rainfall. J. Soil Water Conserv. 22: 140-142.

Römkens, M. J. M. 1979. Interpretation of rainfall simulation data. In Proc Rainfall Simulation Workshop Tucson Arizona: U.S. Dep. Agric., Sci. Educ. Adm., Agric. Review Manual ARM-W-10; pp. 97-100.

Römkens, M. J. M., Gleen, F. L. and D. W. Nelson. 1975. A laboratory rainfall simulator for infiltration and soil detachment studies. Soil Sci. Soc. Am. Proc. 39: 158-160.

Römkens, M. J. M., Nelson, D. W. and C. B. Roth. 1975. Soil erosion on selected high clay subsoils. J. Soil Water Conserv. 30: 173-176.

Römkens, M. J. M., C. B. Roth and D. W. Nelson. 1977. Erodibility of selected clay subsoils in relation to physical and chemical properties. Soil Sci. Soc. Am. J. 41: 954-960.

Saini, et al. 1966. The influence of some physical and chemical properties on soil aggregation and response to vama. Can. J. Soil Sci. 46: 155.

Savat, J. and J. Poesen. 1981. Detachment and transportation of loose sediments by raindrop splash Part II: Detachability and transportability measurements. Catena 8: 19-41.

Schuepp, P. H. 1984. Macdonald College of McGill Univ. Pers. Comm.

Science Council of Canada. 1986. La dégradation des sols au Canada: un mal en progression. Science Council of Canada, Ottawa.

Segal, B. 1979. High-intensity rainfall statistics for Canada. Comm. Res. Centre. Report No. 1329-E. Comm. Dep. Canada.

Seimens, J. C. and W.R. Oschwald. 1978. Corn-soybeans tillage systems: erosion control, effects on crop production, costs. Trans. ASAE 21: 117-132.

Shriner, D. S., Abner, C. H. and L. K. Mann. 1977. Rainfall simulation for environmental application. Oak Ridge National Lab. Env. Sci. Div. Publ. No. 1067.

Sloneker, L. L. and W. C. Moldenhauer. 1974. Effect of varying the on-off time of rainfall simulator nozzles on surface sealing and intake rate. Soil. Sci. Soc. Am. Proc. 38: 157-159.

Sloneker, L. L., Olson, T. C. and W. C. Moldenhauer. 1974. Soil water pressure during intermittent-simulated rain application measured with a new rapid-response tensiometric technique. Soil Sci. Soc. Am. Proc. 38: 985-987.

Smith, D. D. 1941. Interpretation of soil conservation data for field use. Agric. Eng. 22: 173-175.

Smith, D. D. and D. M. Whitt. 1948. Evaluating soil losses from field areas. Agric. Eng. 29: 394-396.

Stol, P. T. 1971. On the decomposition of the extreme value distribution of daily rainfall depths and the derivation of probabilities of compound events. J. Hydrol. 14: 181-196.

Swanson. L. P. 1965. Rotating boom rainfall simulator. Trans. ASAE 8: 71-72.

Towner, G. D. and E. C. Childs. 1972. The mechanical strength of unsaturated porous granular material. J. Soil Sci. 23: 481-498.

U. S. Department of Agriculture. 1941. Yearbook of agriculture, climate and man. U. S. Govt. Printing Office, Washington, D.C.

U. S. Department of Agriculture. 1951. Soil survey manual. Agric. Handbook. No. 18. U. S. Govt. Printing Office, Washington, D.C.

U. S. Department of Agriculture. 1968. A method for estimating volumes and rate of runoff in small watersheds. Soil Conserv. Serv. SCS-TP-149.

U. S. Department of Agriculture. 1973. A method for estimating volumes and rate of runoff in small watersheds. Soil Conserv. Serv. SCS-TP-149 (revised edition).

Van Heerden, W. M. 1964. Splash erosion as affected by the angle of incidence of raindrop impact. Unpublished PhD thesis. Purdue University, West Lafayette, Indiana.

Williams, J. R. 1975. Sediment yield prediction with Universal Equation using runoff energy factor. In Present and Prospectine Technology for predicting sediment yield and sources. U.S. Dep. Agric., Agric. Res. Serv., ARS-S-40, pp. 244-252.

Wilm, H. G. 1953. The application and measurement of artificial rainfall on types FA and F infiltrometers. Trans. Am. Geophys. Union. 24: 480-484.

Wischmeier, W. H. 1955. Punched cards record runoff and soil-loss data. Agric. Eng. 36: 644-666.

Wischmeier, W. H. 1959. A rainfall erosion index for a universal soil loss equation. Soil Sci. Soc. Am. Proc. 23:246-249.

Wischmeier, W. H. 1960. Cropping-management factor evaluations for a universal soil loss equation. Soil Sci. Soc. Am. Proc. 24:322-326.

Wischmeier, W. H. 1972. Upslope erosion analysis. In Environmental Impacts on Rivers. Water Resources Publ. Fort Collins, Colo.

Wischmeier, W. H. 1973. Conservation tillage to control water erosion. National Conservation Tillage Conference Proceedings, Soil Conservation Society of America, pp. 133-141.

Wischmeier, W. H. 1975. Evaluating the soil loss equation's cover and management factor for undisturbed areas. In Sediment Yield Workshop Proceedings, Oxford, Miss. U.S. Dep. of Agric., ARS-S-40.

Wischmeier, W. H. 1976. Use and misuse of the universal soil loss equation. J. Soil Water Conserv. 31:5-9.

Wischmeier, W. H. and D. D. Smith. 1958. Rainfall energy and its relationship to soil loss. Trans. Am. Geophys. Union. 39:285-291.

Wischmeier, W. H. and D. D. Smith. 1960. A universal soil-loss estimating equation to guide conservation farm planning. Trans. 7th Int. Congr. Soil Sci. 1:418-425.

Wischmeier, W. H. and D. D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains. USDA Agric. Handbook No. 282, 47 pages.

Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses - a guide to conservation planning. USDA Agric. Handbook No. 537, 58 pages.

Wischmeier, W. H. and J. V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33: 131-137.

Wischmeier, W. H., C. B. Johnson and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv. 26: 189-192.

Young, R. A. and C. K. Mutchler. 1977. Erodibility of some Minnesota soils. J. Soil Water Conserv. 32: 180-182.

Yoder, R. E. 1936. A direct method of aggregation analysis of soils and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28: 337-351.

Zingg, A. W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Eng. 21: 59-64.

Zuzel, J. F., Allmaras, R. R. and R. Greenwalt. 1982. Runoff and soil erosion on frozen soils in northeastern Oregon. J. Soil Water Conserv. 37: 351-354.

APPENDIX 1

Spray characteristics of the nozzles selected for preliminary testing

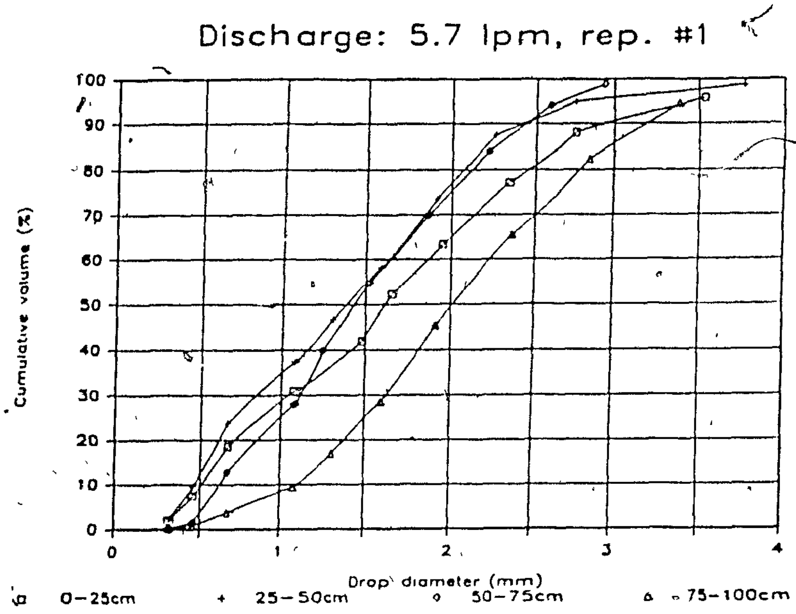
Appendix 1: Spray characteristics of the nozzles selected for preliminary testing.

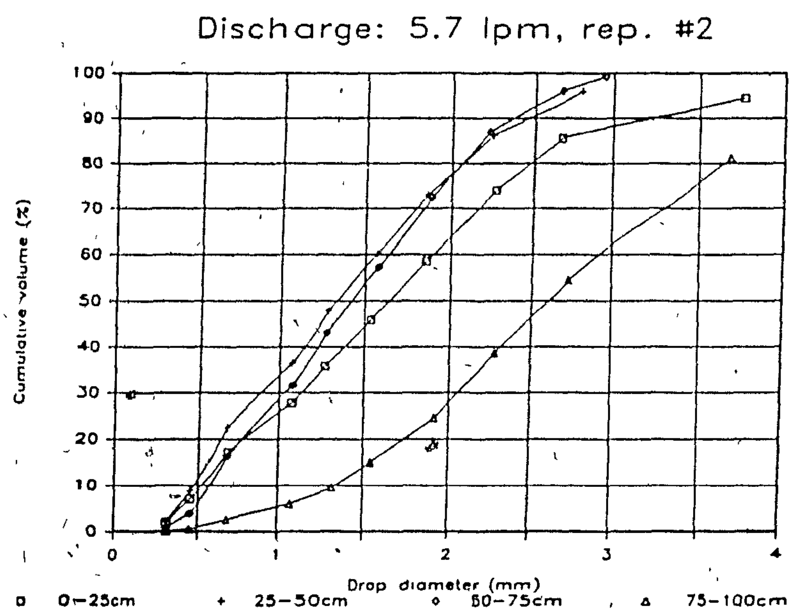
Nozzle Model	Operating Pressure (kPa)	Fall Height (cm)	Coeff. Uniformity (%)	Rainfall Intensity (mm/h)	Drop-size Distribution D_{10}	D_{50} (mm)	D_{90}
Bete 3/8 WL4120	42	185	70.6	34.7	0.76	1.82	3.55
Bete 3/8 WL4120	77	185	72.4	32.8	0.57	1.26	2.50
Bete 3/8 WL4120	98	185	74.4	35.1	0.51	1.13	2.08
Bete 1/4 WL1.5120	42	215	86.0	9.5	not evaluated		
Bete 1/4 WL1.5120	94	215	76.4	12.7	not evaluated		
Bete 3/8 M187M	63	215	59.9	54.5	0.76	1.88	3.81
Bete 1/2 WL120	77	185	<50%	---	not evaluated		
Bete 3/8 MP125	77	185	<50%	---	not evaluated		
Sp. Syst. 24W	45	215	62.7	40.8	0.81	1.80	3.21
Sp. Syst. 17W	42	215	77.2	32.8	1.10	1.66	3.01
Sp. Syst. 20W	40	215	56.8	34.2	0.95	2.09	3.33
Bete 3/8 MP156M	56	215	62.0	71.3	1.03	2.06	3.47
Bete 3/8 MP156M	70	215	73.1	76.6	0.84	1.85	3.13
Bete 3/8 MP156M	63	215	71.0	73.0	0.74	1.90	3.32

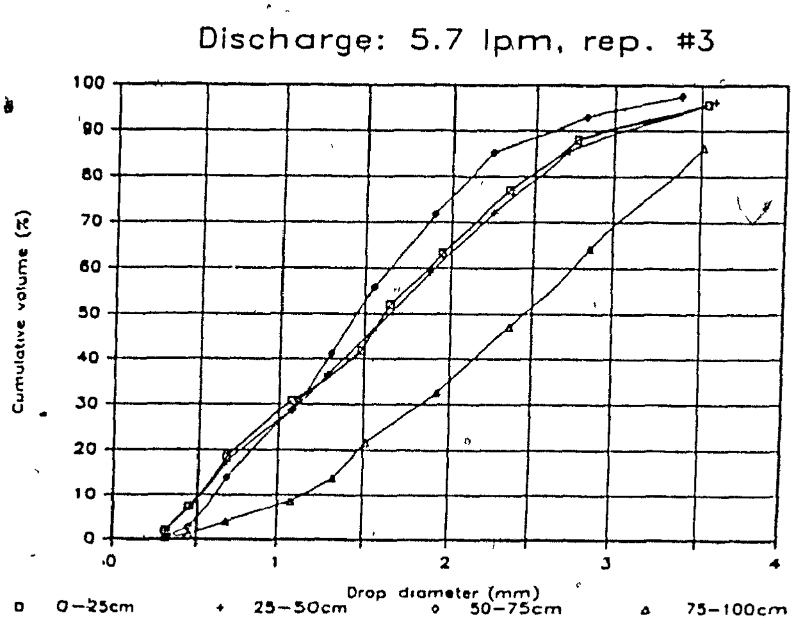
N.B. All tested nozzles have free passage diameters equal to 50% of orifice sizes, except for the Bete MP models, which have free passage diameters equal to orifice sizes.

APPENDIX 2

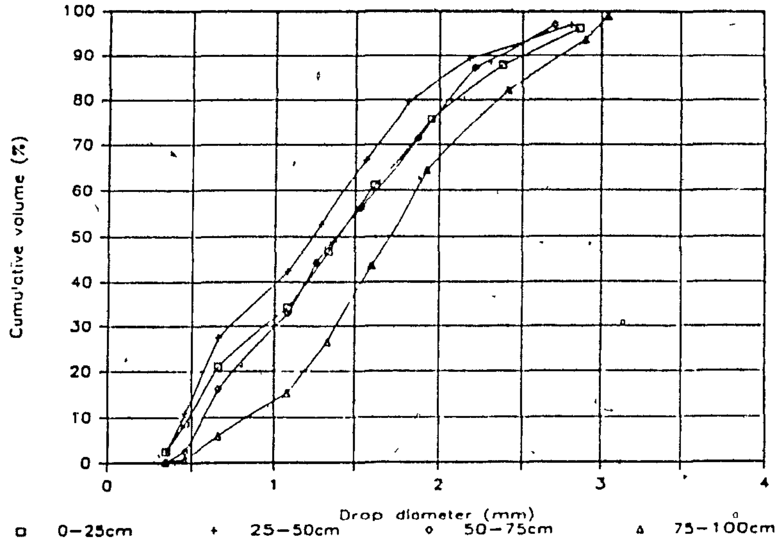
Drop-size distribution spatial variability of Bete Fog nozzle MP156M at varying discharge rates


Discharge: 5.7 lpm, rep. #1
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm

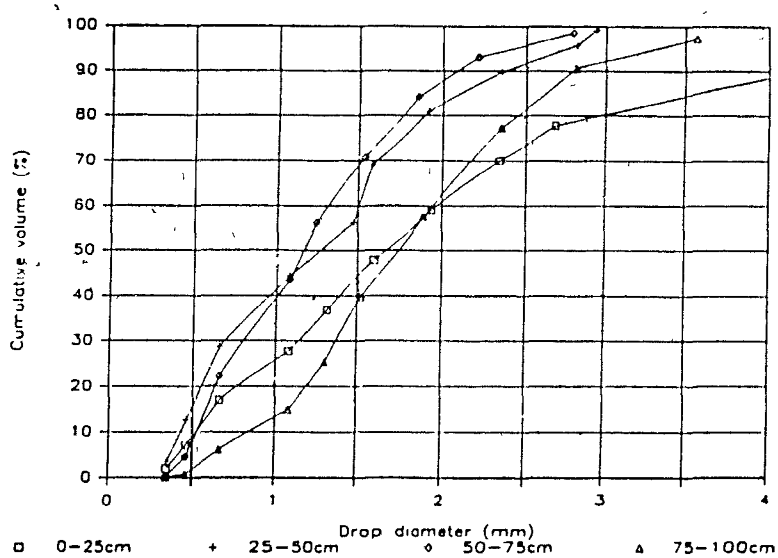

Discharge: 5.7 lpm, rep. #2
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm


Discharge: 5.7 lpm, rep. #3
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm

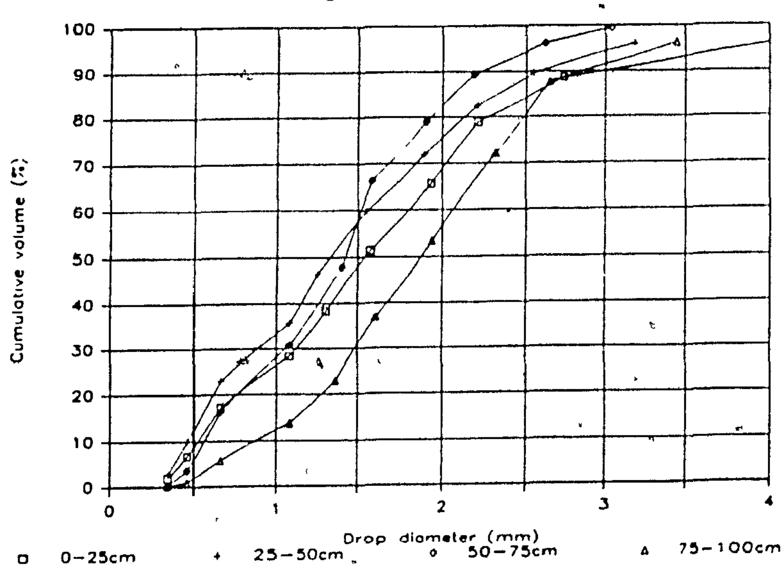
Discharge: 6.3 lpm, rep. #1



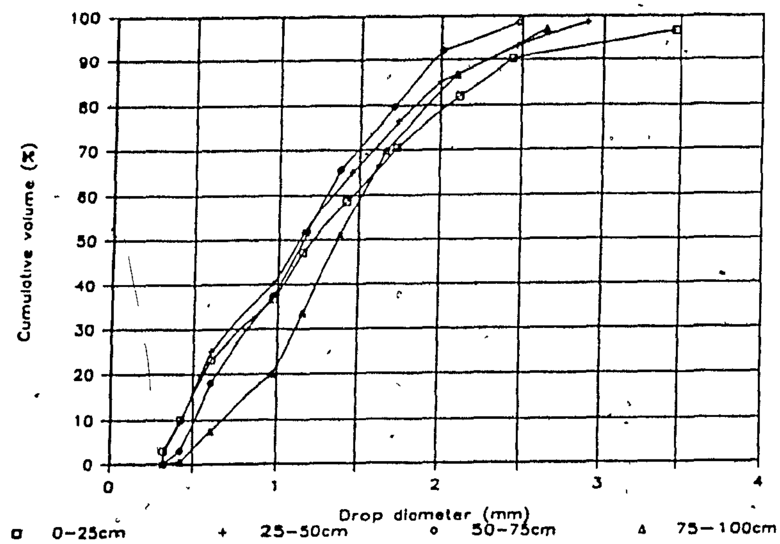
Discharge: 6.3 lpm, rep. #2



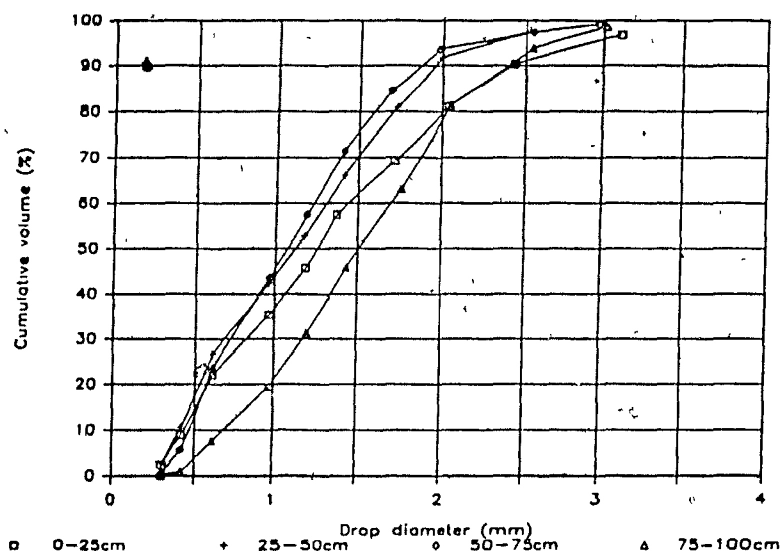
Discharge: 6.3 lpm, rep. #3



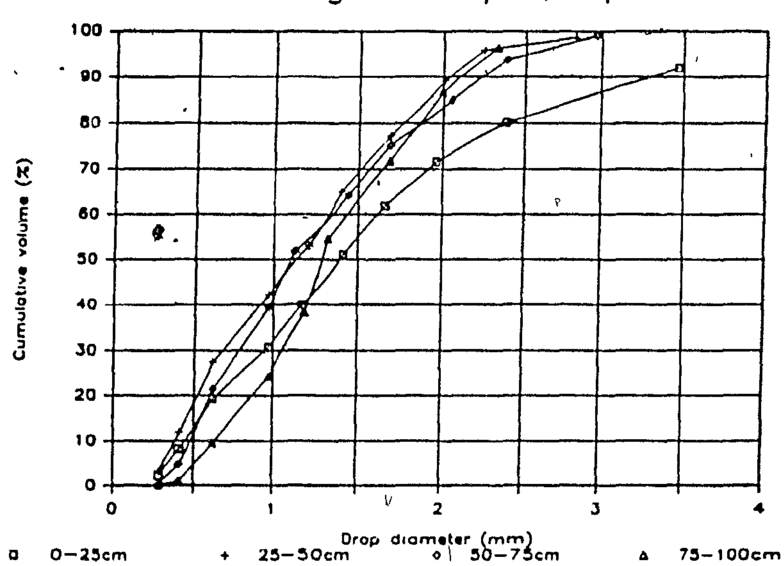
Discharge: 6.9 lpm, rep. #1



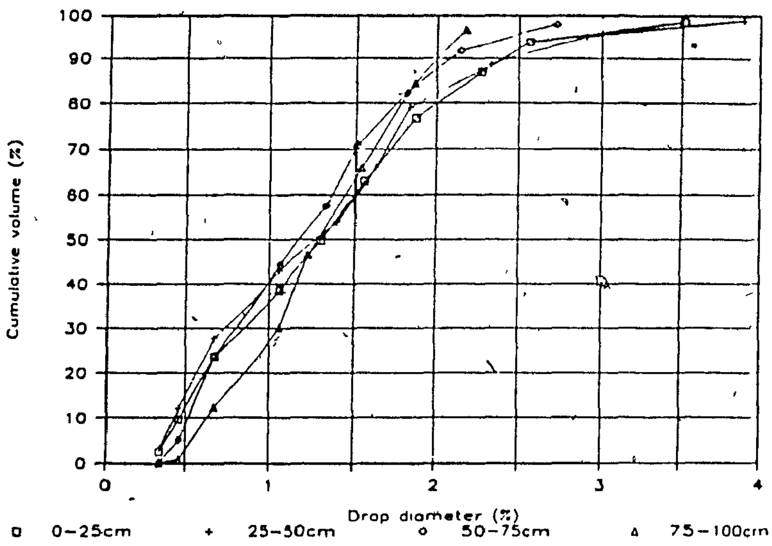
Discharge: 6.9 lpm, rep. #2



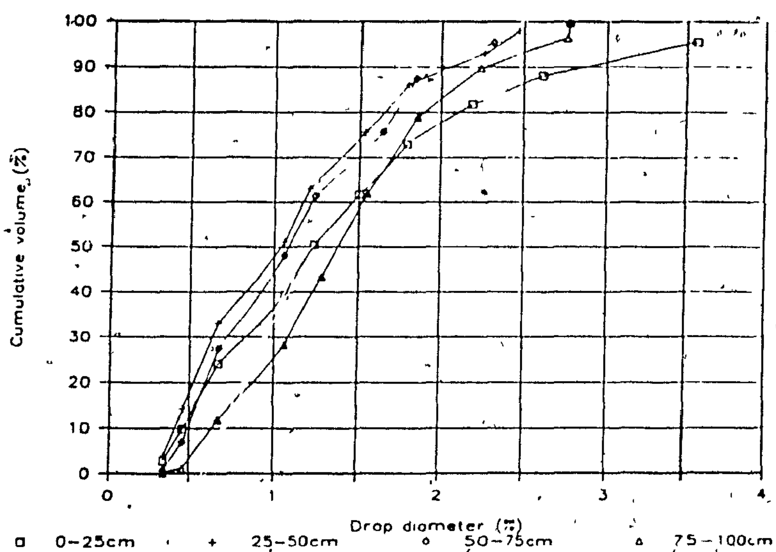
Discharge: 6.9 lpm, rep. #3



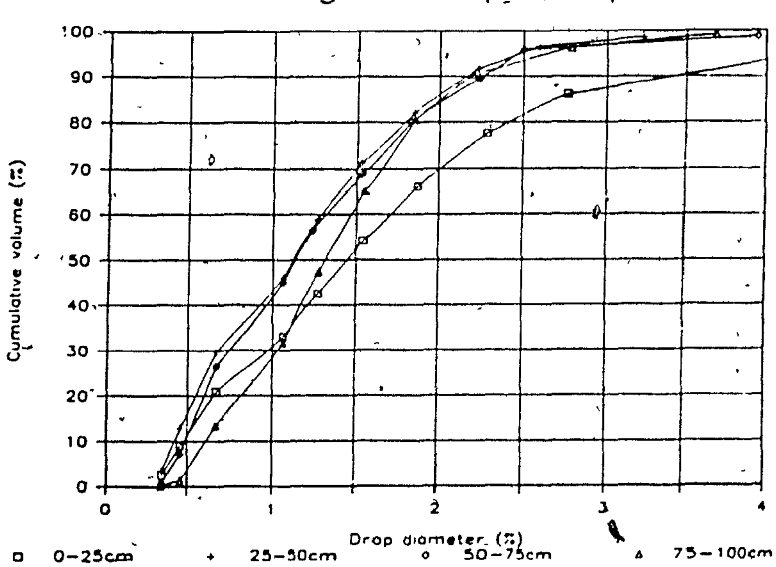
Discharge: 7.5 lpm, rep. #1

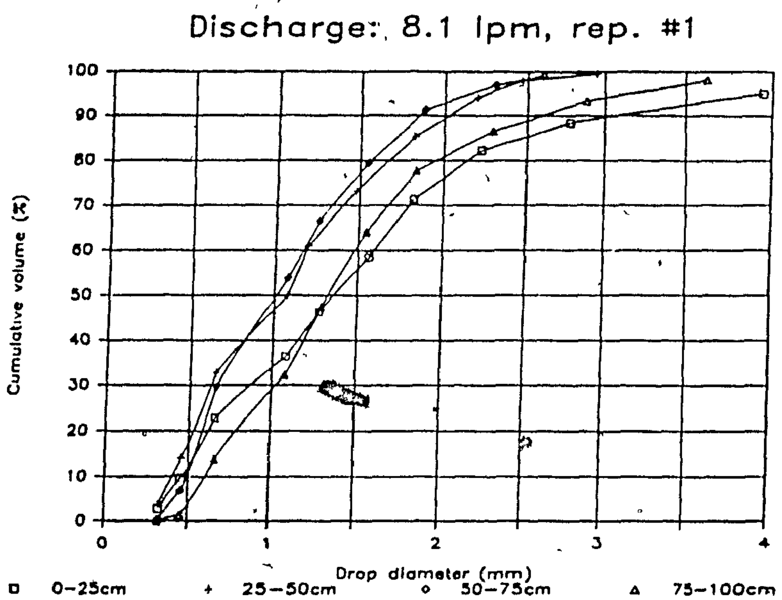


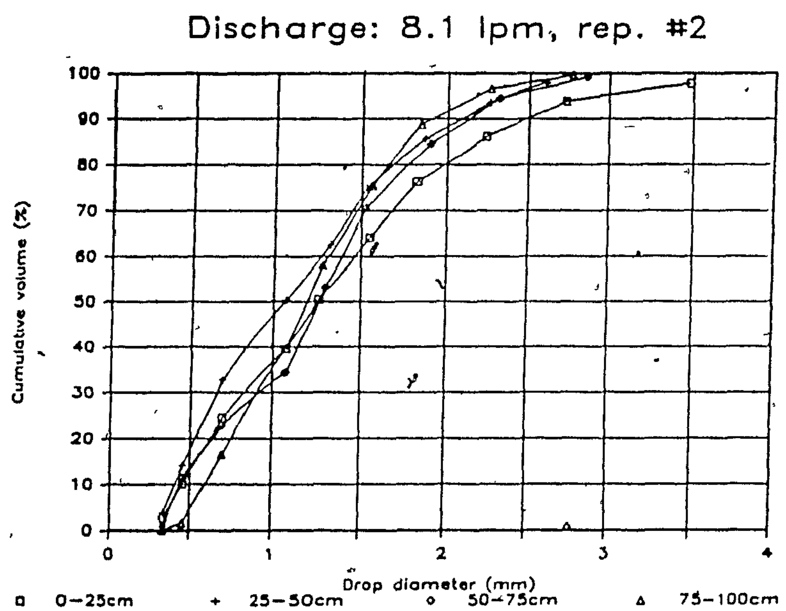
Discharge: 7.5 lpm, rep. #2

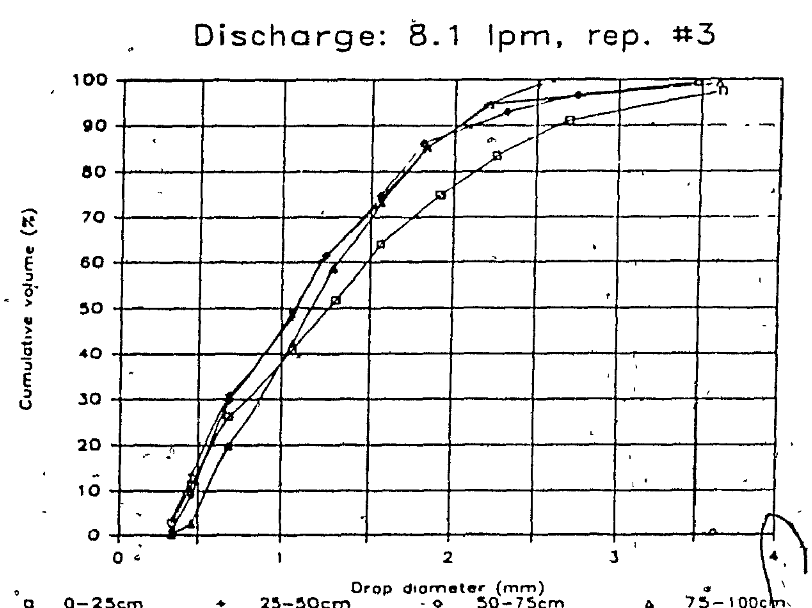


Discharge: 7.5 lpm, rep. #3




Discharge: 8.1 lpm, rep. #1
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm


Discharge: 8.1 lpm, rep. #2
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm


Discharge: 8.1 lpm, rep. #3
Cumulative volume (%)
Drop diameter (mm)
0–25cm
25–50cm
50–75cm
75–100cm

APPENDIX 3

Tipping bucket calibrations at the eight experimental sites

Appendix 3: Tipping bucket calibration at the eight experimental sites.

Site	Regression parameter Estimate(1)	F value	Prob>F	R^2
Arboretum	1.392	768.0	<0.0001	>0.99
Coaticook	1.690	645.7	<0.0001	>0.99
Coleman	1.100	1424.3	<0.0001	>0.99
Dump	1.024	649.4	<0.0001	>0.99
Highway	1.128	664.6	<0.0001	>0.99
Radar	1.290	571.6	0.0002	>0.99
Rudy	1.135	1680.3	<0.0001	>0.99
Sheldon	1.778	2688.8	<0.0001	>0.99

(1) Statistical model: LPM = B_1 X PTPM

where: LPM is the discharge rate in $l.min^{-1}$

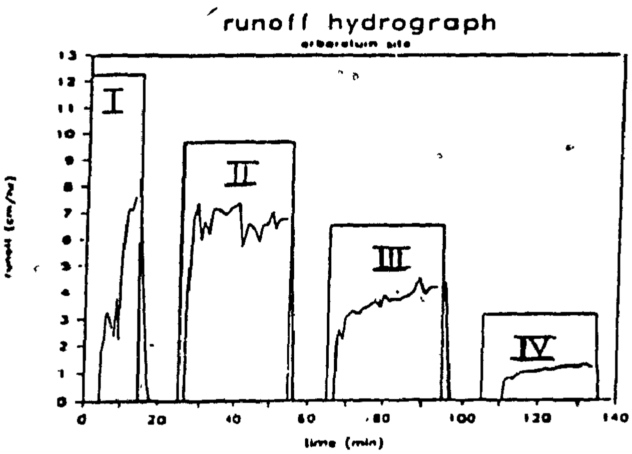
PTPM is the pairs of tips per minute

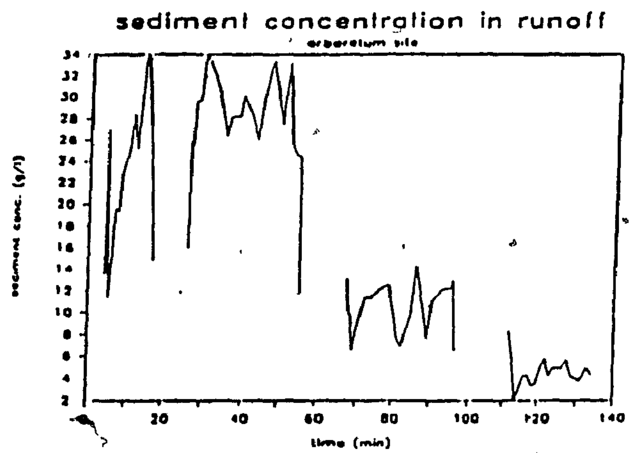
B_1 is the estimate of the regression parameter

APPENDIX 4

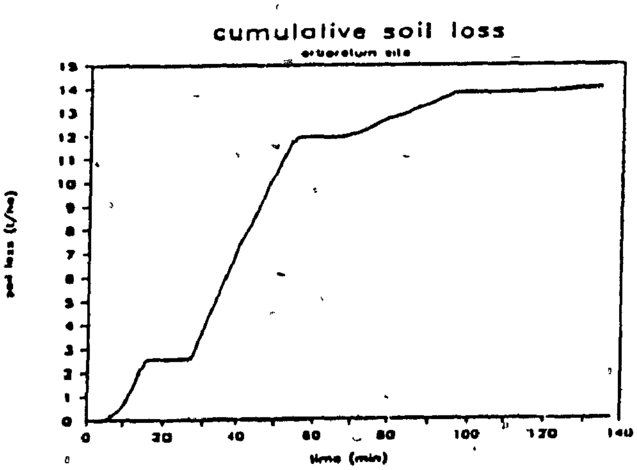
Runoff, sediment concentration in runoff and cumulative soil loss evolutions in time, and soil losses in relation to simulated rainfall erosivities at the eight experimental sites

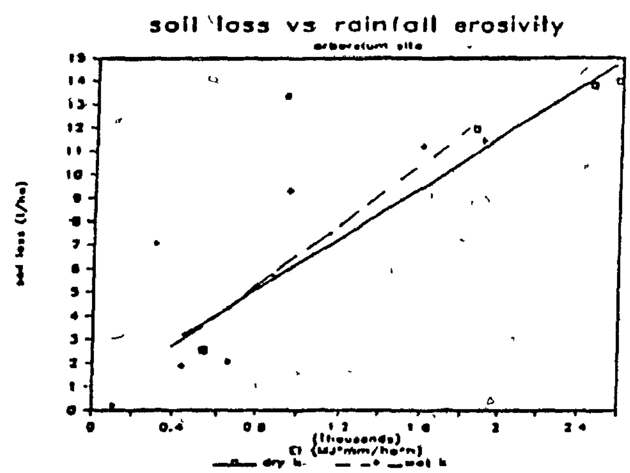
ARBORETUM SITE DATA



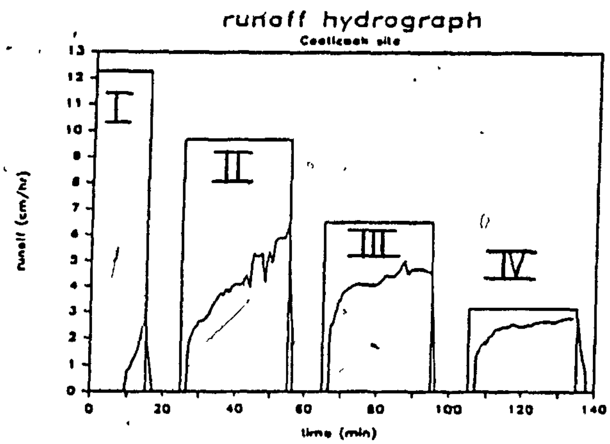


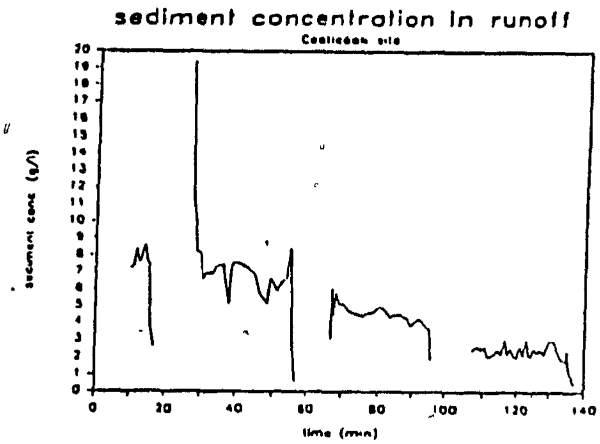
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



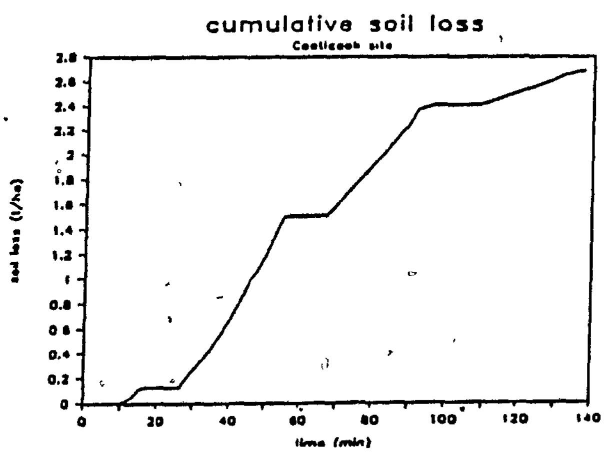


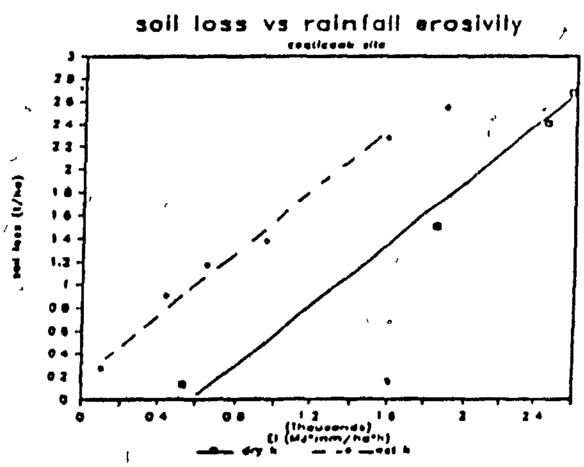
COATICOOK SITE DATA



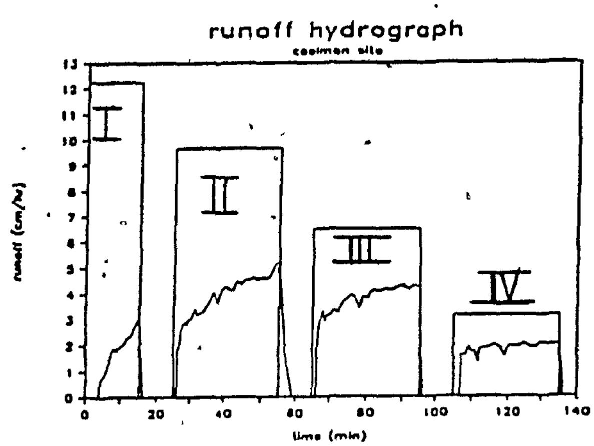


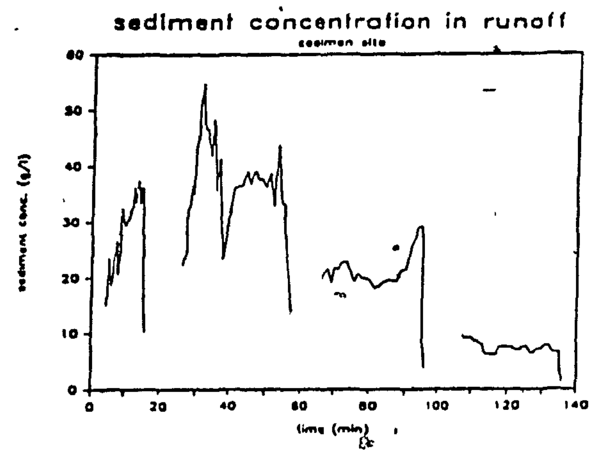
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



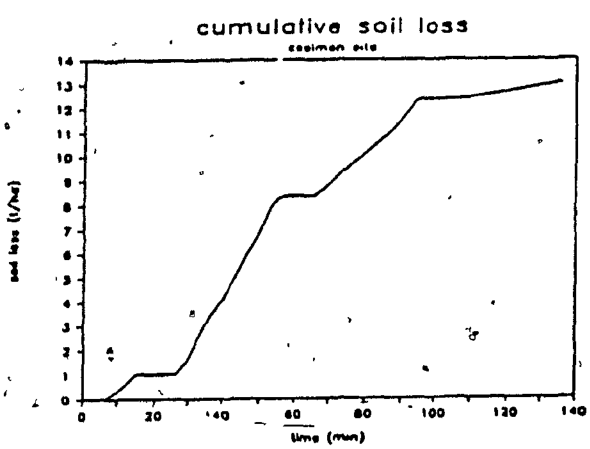


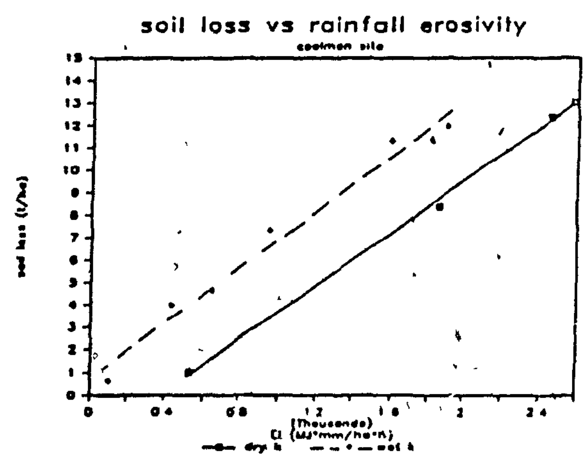
COLEMAN SITE DATA



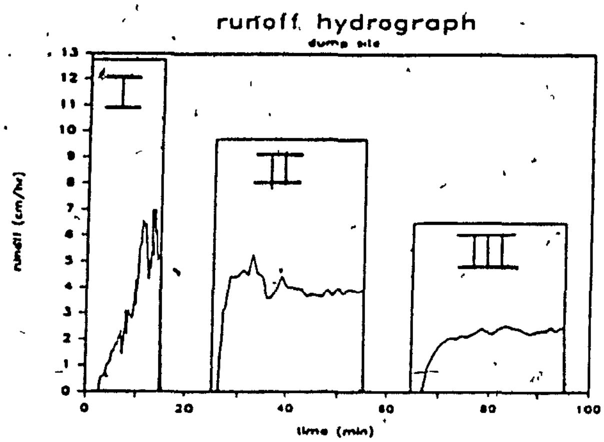


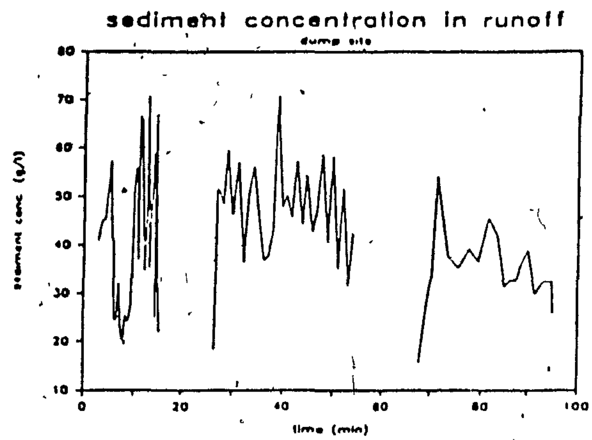
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



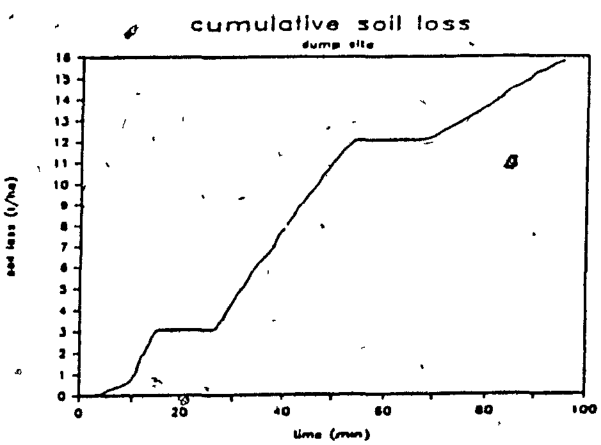


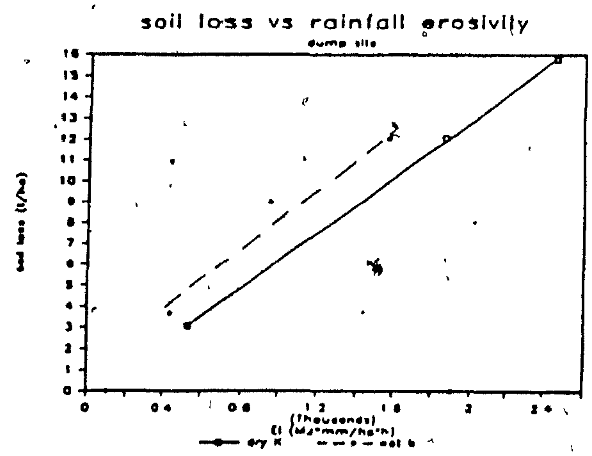
DUMP SITE DATA



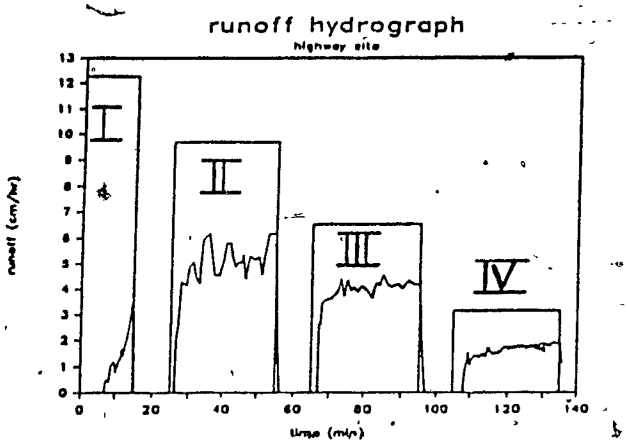


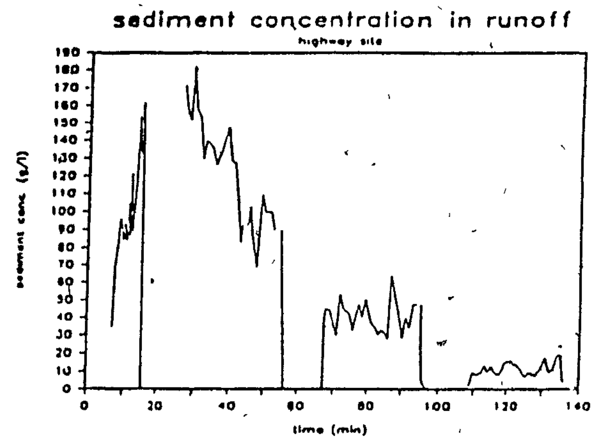
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



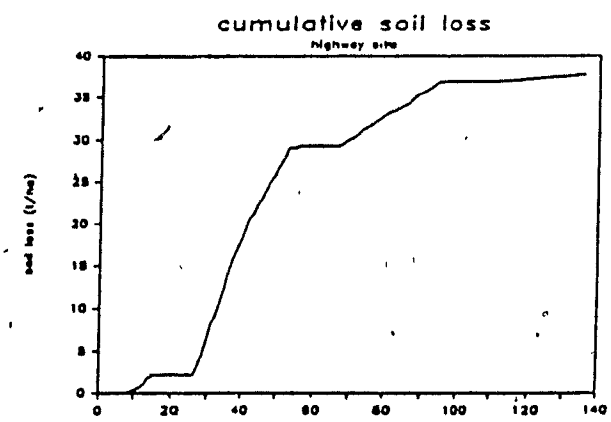


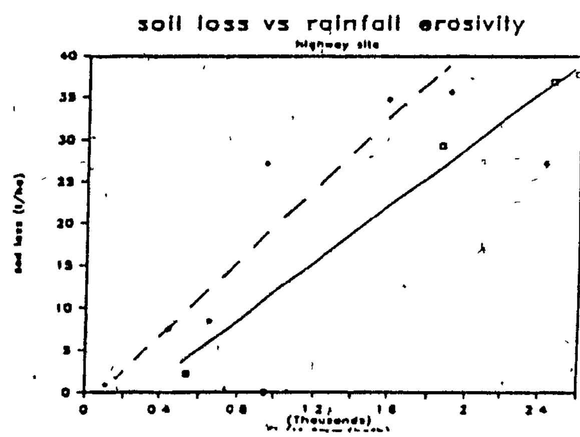
HIGHWAY SITE DATA



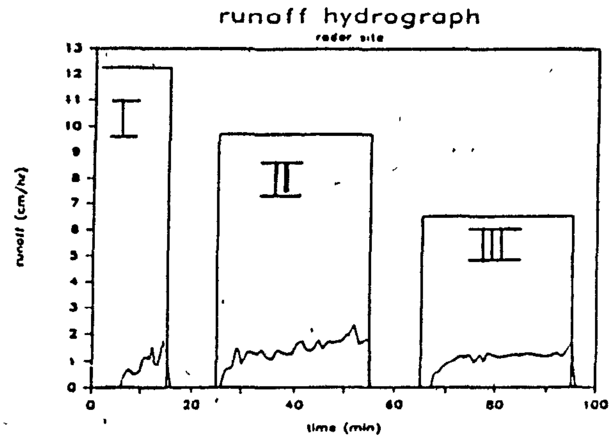


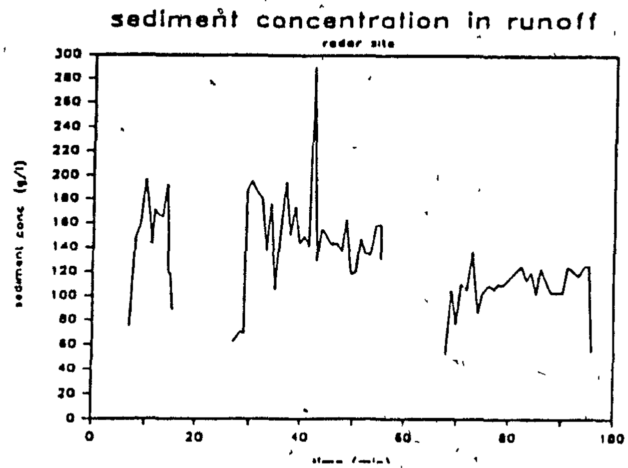
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



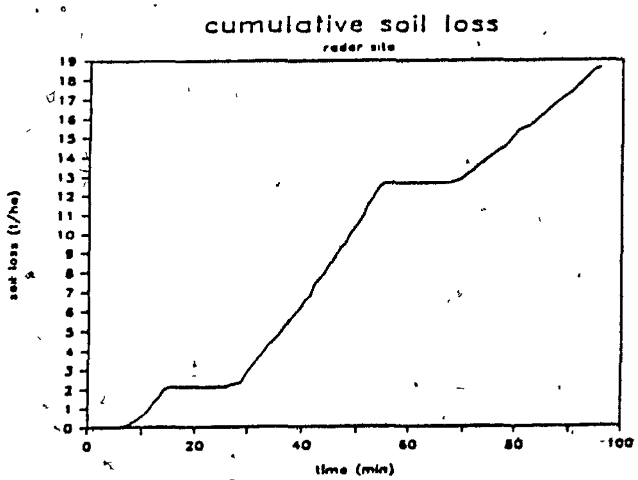


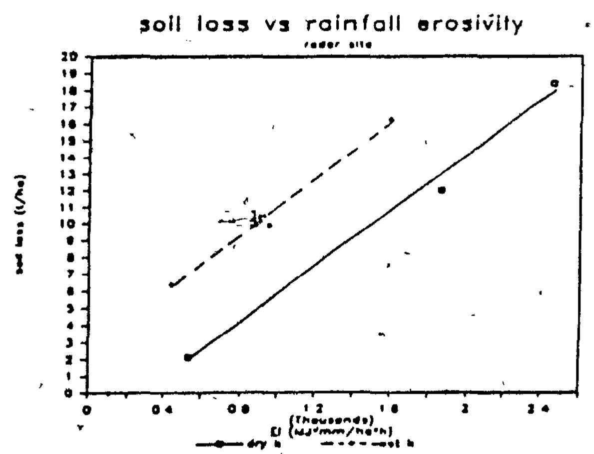
RADAR SITE DATA



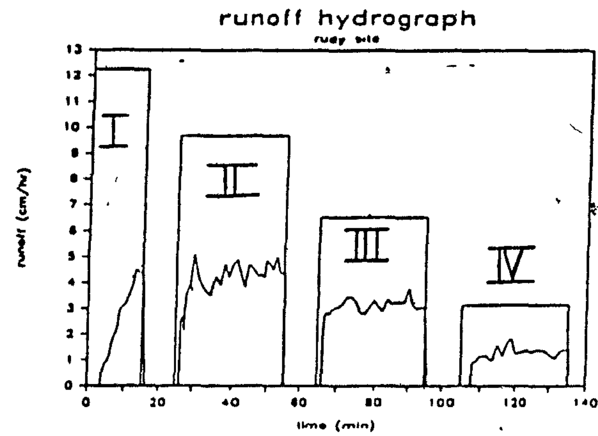


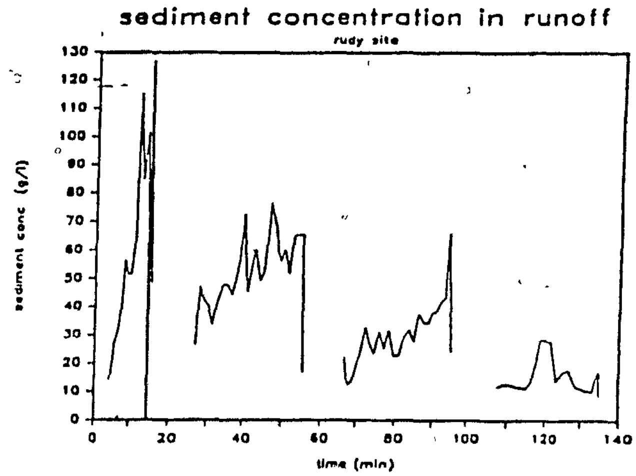
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.



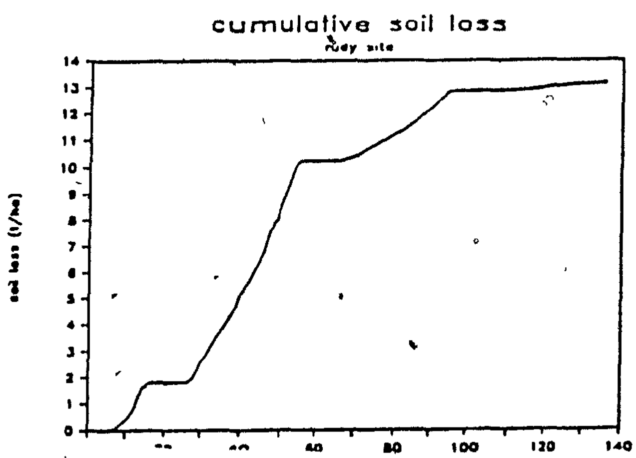


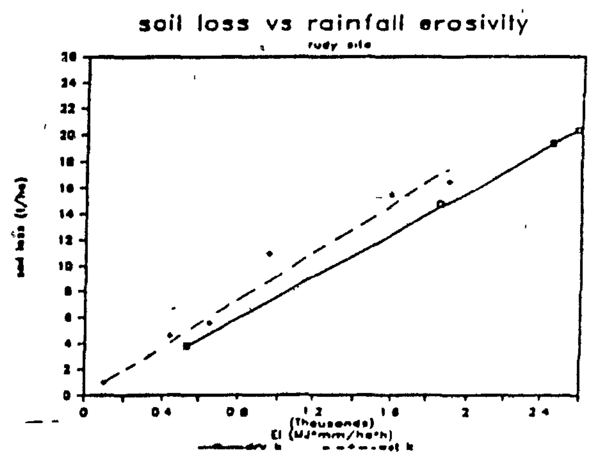
RUDY SITE DATA



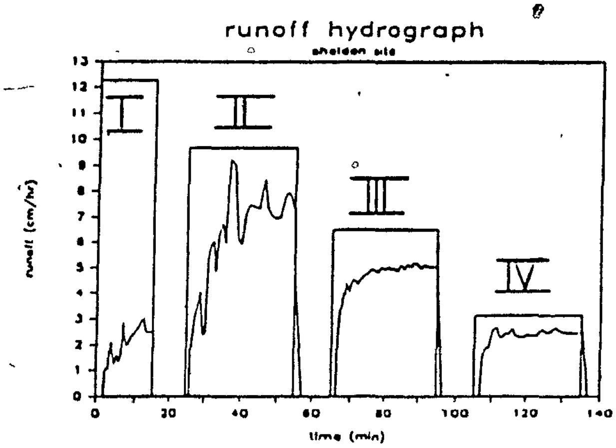


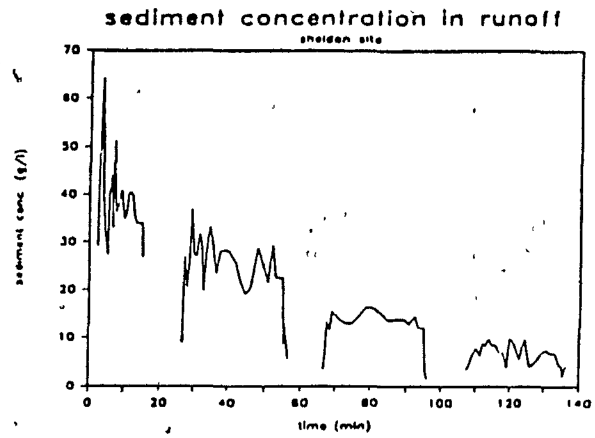
(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.





SHELDON SITE DATA





(I): Run #1, 15 min duration, 127 mm/hr.
(II): Run #2, 30 min duration, 97 mm/hr.
(III): Run #3, 30 min duration, 66 mm/hr.
(IV): Run #4, 30 min duration, 32 mm/hr.