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A laboratory study of the erodibilities of four agriculturally productive soils

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To the Graduate Council:

I am submitting herewith a dissertation written by Earl Dean Vories entitled "A laboratory study of the erodibilities of four agriculturally productive soils." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Biosystems Engineering.

Robert D. von Bernuth, Major Professor

We have read this dissertation and recommend its acceptance:

B. L. Bledsoe, C. R. Mote, B. A. Tschantz, L. R. Wilhelm

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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Robert D von Bernuth

Robert D. von Bernuth, Major Professor

We have read this dissertation
and recommend its acceptance:

B. L. Bledsoe

Luther R Wilhelm

Accepted for the Council:

CW Minkel

Vice Provost
and Dean of The Graduate School

A LABORATORY STUDY OF THE ERODIBILITIES OF FOUR AGRICULTURALLY PRODUCTIVE SOILS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Earl Dean Vories
August 1987

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ABSTRACT

Soil erosion by water is a serious problem throughout the world. It has been studied for most of this century, but much remains unknown and misunderstood. A study was conducted at The University of Tennessee to investigate relationships among soil properties and their possible uses as indicators of erodibility. Soil losses from four agriculturally productive East Tennessee soils were investigated under simulated rainfall. The effects of soil moisture, particle size distribution, organic matter, and other soil properties were studied, along with the effect of storm intensity.

The largest difference between expected and observed erodibilities appeared to be due to the effect of a strong structure in a finer-textured (clay loam) soil. Subangular blocky structure was not expected to correspond to low erodibility. However, when the permeability of the underlying soil is sufficient and the aggregates are water stable, most of the water that strikes the surface enters the soil rather than becoming soil-carrying runoff.

The findings of the study indicated that intensity and antecedent moisture do not affect all soils equally. Soil-loss tests used to compute a general erodibility value for a particular soil must include as much of a range of conditions as can be expected for that soil. The resulting value will be a good average, but probably a poor predictor for specific cases. Additional work is needed to be able to accurately predict soil loss from a particular site induced by a specific storm.

TABLE OF CONTENTS

SECTION PAGE

I. INTRODUCTION 1

Historical Perspective 2
Problem Definition 3

II. RESEARCH OBJECTIVES 5

III. REVIEW OF LITERATURE AND THEORY 6

Soil-Loss Factors 6
  Rainfall Characteristics 6
  Soil Characteristics 7
  System Characteristics 10
Predicting Erosion 11
  Universal Soil-Loss Equation 12
    Factor R 13
    Factor K 15
    Factor LS 17
    Factor C 19
    Factor P 19
  Other Approaches 20
  Current Status 21

IV. DIMENSIONAL ANALYSIS 24

Background 24
  Units 24
  Buckingham Pi-Theorem 26
Application To a Study of Erosion 27

V. EXPERIMENTAL PROCEDURES 37

Test Factors 37
Experimental Design 38
Soil Selection 39
Equipment 41
  Soil Pans 41
  Rainfall Simulator 43
  Other Equipment 44
Laboratory Procedures 44
  Soil Physical Properties 44
  Rainfall-Simulator Calibration 45
  Soil-Loss Tests 45
Analysis of Data 50

TABLE OF CONTENTS (Continued)

SECTION PAGE

VI. RESULTS AND DISCUSSION 56

- Simulated Rainfall 56
- Soil Properties 61
- Erosion Study 70
  - Qualitative Factors 75
    - Runoff Volume 75
    - Soil Loss 82
    - Summary 91
  - Quantitative Factors 91

VII. CONCLUSIONS AND RECOMMENDATIONS 108

LIST OF REFERENCES 111

APPENDIXES 119

- APPENDIX 1. EXCERPTS FROM SOIL DESCRIPTIONS................. 120
- APPENDIX 2. DATA FROM SOIL-LOSS STUDY........................ 125

VITA 134

LIST OF TABLES

TABLE PAGE

1. Established soil-erodibility (K) values 16
2. Definitions of pi-terms 34
3. Rainfall-simulator data 43
4. Simulated-rainfall data 57
5. Soil properties 62
6. Results from soil-loss study 71
7. Analysis of variance for runoff volume 77
8. Analysis of variance for soil loss 84
9. Average bulk densities and moisture contents 87
10. Unit-plot A values from ANOVA means 93
11. USLE K values from mean unit-plot A values 95
12. Correlations of soil properties with K values 96
13. Correlations of pi-terms with π_1 98
14. Comparison of observed and predicted USLE K values 101
15. Properties of three soils 102
16. K values for three soils at 2-percent organic matter.... 105
17. K values for a typical loam soil and different organic-matter contents 105
18. USLE K values from measured soil-loss values 107
19. Soil-loss test data 126
20. Test conditions 130

LIST OF FIGURES

FIGURE PAGE

1. USLE soil-erodibility factor (K) nomograph in English units 18
2. Soil pan used in study 42
3. Soil-loss test in progress 49
4. Cumulative relative volume versus drop diameter for 5.2 cm/h intensity 58
5. Cumulative relative volume versus drop diameter for 8.0 cm/h intensity 59
6. Particle size distributions for mineral portions of the four study soils 64
7. Soil textural triangle showing the four study soils 65
8. Saturated hydraulic conductivity versus bulk density for the four study soils 68
9. Intensity by soil interaction for runoff volume 80
10. Soil by moisture condition interaction for runoff volume 81
11. Intensity by soil interaction for soil loss 89
12. Soil by moisture condition interaction for soil loss 90
13. Three possible particle size distributions for a 30-µm d_{50} 104

I. INTRODUCTION

The removal of soil by rain is a serious problem all over the world, and particularly in parts of Tennessee. Not only is the loss important for the site where the soil originated, but other areas are affected as well. The soil eroded from one site will be deposited at another, where it may create new problems. If the eroded area is agricultural land, the soil will likely contain chemicals and nutrients, which could pollute or encourage eutrophication of a lake where the soil eventually settles.

Erosion and related problems cause considerable expense. An area may need to be repaired after soil is eroded. Agricultural land will become less productive as topsoil is lost. The location where the eroded soil is deposited will probably also need renovation. Crops on a flood plain may be destroyed by soil laid over them. Navigable rivers have to be dredged to keep the channels clean. Useful lives of reservoirs may be shortened considerably if more soil is carried into them than was expected in their design.

Exposing a soil surface to the wind and rain unquestionably increases the likelihood of that surface being eroded. However, total elimination of soil surface exposure is often impossible. Construction projects, such as for buildings and highways, require some disturbance of the soil. Farming results in large areas of land being bared, although minimum- and no-till schemes reduce the erosion hazard. If some degree of exposure of the soil surface is unavoidable, then a better understanding of the erosion process and the factors that affect it could lead to minimizing the damages done while that surface is exposed.

Historical Perspective

The erosion problem has been recognized for many years, and much study has been devoted to it. Bennett (1939) presented a history of the erosion problems throughout the world. Meyer (1982) reported that the earliest quantitative erosion-research measurements were begun in 1912, and erosion-plot research was started in 1917. That same year, the U.S.D.A. was advising farmers to terrace land to limit erosion (Ramser, 1917). Bates (1924), Bennett and Chapline (1928), and others played major roles in educating the country about the seriousness of the erosion problem, and beginning in 1930, congressional appropriations were provided to establish soil-erosion experiment stations.

In 1936 the Forest Service published a handbook for erosion control on the National Forests (U.S.D.A. Forest Service, 1936), and in 1939 the Tennessee Valley Authority published a manual of recommendations for controlling erosion in the Tennessee Valley (Nicholson and Snyder, 1939). Furthermore, the dust-bowl experience of the 1930's convinced the public of the seriousness of erosion. After many years of study, erosion and sedimentation are still recognized as major world problems (Rangeley, 1986).

Problem Definition

The loss of soil is a natural occurrence, and some soil will always be lost, even from virgin prairie or forestland. Problems arise when the rate of soil loss greatly exceeds the rate of renewal. Actions of man, such as farming, deforestation, and construction often contribute much to accelerating erosion.

Soil loss actually involves a combination of two processes: detachment and transport. Detachment, or the freeing of individual soil particles from the soil mass, generally has two causes. The collision between a raindrop and the soil mass will cause some of the soil particles to break away. Water running over the surface of the soil mass will cause a shear stress that can become great enough to free some soil particles.

Transport refers to the process of carrying soil particles away from the site. Some soil will be moved in the splash when a raindrop strikes and part of it rebounds. Much of the transportation takes place in the runoff water leaving the site. Under most conditions, only a fraction of the total detached soil will be transported from the site; however, even a fraction can be quite damaging.

Erosion is generally divided among three types: sheet, rill, and gully. Sheet erosion is the removal of a fairly uniform layer of soil, with no recognizable concentration of flow into specific channels. Rill and gully erosion both involve runoff flowing in visible channels. The distinction usually made is that rills can be completely smoothed by ordinary cultivation, while gullies require special attention. If there is sufficient rainfall, sheet erosion will usually develop into a combination of sheet and rill erosion. If rills are left alone for long enough periods, some will probably develop into gullies.

A better understanding of the factors that affect erosion would permit activities to be planned and scheduled so that damage to the environment is minimized. Disturbing the soil is often unavoidable. However, it may be possible, through better understanding of the erosion processes and better management of activities, to reduce erosion and deposition problems. Research on soil erosion could lead to more effective protection of precious soil resources.

II. RESEARCH OBJECTIVES

The goal of the research presented in this report was to investigate erosion from agriculturally productive soils. The objectives identified for meeting that goal were to:

1) conduct soil-loss tests in a strictly controlled laboratory setting,

2) relate observed soil losses to test conditions and soil properties,

3) relate dimensionless quantities composed of combinations of soil loss and soil properties, and

4) compare findings with those of other researchers.

III. REVIEW OF LITERATURE AND THEORY

Soil-Loss Factors

The mass of soil that leaves an area is affected by many factors that can be lumped into three categories: rainfall characteristics, soil characteristics, and system characteristics. Musgrave (1947) separated the system characteristics into flow or slope characteristics and vegetal cover. Although vegetal cover is quite important, for the purposes of this discussion it will be included as a system characteristic.

Rainfall Characteristics

Rainfall characteristics include properties of the erosive fluid, such as density, viscosity, and surface tension. The properties of the rainfall event, such as individual drop sizes, corresponding impact velocities, and rate and duration of the rainfall are also important. If the area of interest is large enough that rainfall characteristics vary within it, or the rainfall event is actually irrigation, then the uniformity of the application may play an important role.

Since rain water is usually the erosive agent, the fluid properties do not vary much, although temperature affects them somewhat. However, in cases of chemigation, land application of waste water, or irrigation with water containing contaminants, the fluid properties may vary more.

The importance of the rainfall characteristics is obvious. The raindrops detach and transport soil, and the portion of rainfall that runs off the surface also detaches and transports soil. The question of which characteristics are important is less obvious. Researchers have investigated raindrop sizes and velocities, rainfall energy, momentum, and intensity, and other properties and interactions for possible correlations with soil loss.

Park et al. (1983) related the properties of rainfall to splash erosion. However, because of the inability to control natural rainfall, simulated rainfall is generally used in erosion studies. Meyer (1965) discussed the properties of natural rainfall that should be duplicated by a simulator, and several designs have been developed. However, Mech (1965) warned that it is easy to get caught up in developing an effective simulator and lose sight of the original goals (i.e., to study soil loss and ways to reduce it).

Soil Characteristics

Soil characteristics include such properties as particle size distribution, specific gravity, bulk density, infiltration rate, permeability, organic-matter content, moisture content, and degree of structure development. Structure refers to the formation of aggregates from smaller individual particles.

Many soil properties have been investigated for their possible correlations with erosion. Barnett and Rogers (1966) investigated the effects of 34 predictor variables including particle size fractions, bulk density, carbon, moisture properties, suspension percentages, pH, and others along with combinations and transformations using erosion data from 99 plots on 17 different soils at 50 sites. Parameters that were intercorrelated, subjective, or required individual judgment were excluded. They found that eight variables (one term each for slope, depth, and moisture, three for particle size, and two interactions) explained 87 percent of the variation in soil loss for storms composed of four thirty-minute storms separated by ten minutes each. However, their model was based solely upon multiple regression, and they recommended the study of the results with respect to physical laws to improve understanding of the processes.

Soil structure has been shown by several researchers (e.g., Woodburn, 1948; Wischmeier et al., 1971; and Romkens et al., 1977) to significantly affect soil loss. In fact, Luk (1979) found the percentage of water-stable soil aggregates greater than 0.5 mm in diameter to be the most significant soil property for explaining soil loss.

It seems logical that a soil aggregate would behave quite differently than an equal mass of individual particles. However, structure is a quality that is not readily quantified. Soil descriptions refer to size, strength, and shape of aggregates. Wischmeier et al. (1971) reported that strength did not appear to significantly affect erodibility, but one reason suggested was the dependence of the reported value upon the observer's judgment.

Chesters et al. (1957) studied aggregation related to other soil properties. While organic matter is known to affect soil structure, they found the amount of microbial gums, one component of organic matter, to be more highly correlated to aggregation than was total organic carbon (TOC), a common measure of organic-matter content. Romkens et al. (1977) found that the organic carbon coordinated with polyvalent cations and clay was a better predictor of erodibility than TOC, but was highly correlated with TOC.

Trott and Singer (1983) suggested that in addition to the particle size distribution, the particular minerals making up the clay fraction may be important in at least some locations. They found that mineralogical components acted to reduce the erodibility of soils expected to be highly erodible. Romkens et al. (1977) and others also investigated the effects of different mineralogical properties.

Another factor important to erodibility is infiltration, or the rate at which water flows into the soil. Runoff from a rain, crucial to both detachment and transport, will be the difference between the rates of precipitation and infiltration. However, infiltration is quite variable. Many researchers (e.g., Lindstrom and Voorhees, 1980; Steichen, 1984; Thompson and James, 1985; and Mohammed and Kohl, 1986) have reported on how infiltration is affected by factors such as raindrop impact and equipment traffic.

Permeability, which is related to infiltration, refers to the movement of liquids, gases, and roots within the soil. Saturated hydraulic conductivity, the permeability of saturated soil for water, is generally used as the measure of permeability. Permeability is affected by both structure and texture, with structure playing an increasing role in finer-textured soils. Permeability is more stable than infiltration, but less important to runoff. Many soil surfaces crust from raindrop impact, resulting in decreased infiltration and increased runoff. Presence of the surface crust may have a negligible effect on the permeability of the soil as a whole.

System Characteristics

System characteristics include the dimensions and orientation of the surface area, the slope, roughness and degree of exposure of the surface, and the acceleration due to gravity. Geographical location of the site might also be important. One of the most important system characteristics is vegetation, which affects both the roughness and the degree of exposure. Vegetation lessens the impact velocities of the raindrops onto the soil surface by absorbing much of the impact energy. The reduced impact energy produces less detachment by drop impact and less transport by splash. Surface crusting as a result of raindrop impact will also be reduced, allowing the infiltration rate to remain higher.

Furthermore, the vegetation will increase the resistance of the soil surface to the flow of runoff, resulting in lower runoff velocities. Those lower velocities will cause less soil detachment by shear stress and less transportation of the detached soil. The vegetation will also add organic matter to the soil.

The gravity effect is constant. However, some of the other surface characteristics, such as surface roughness and exposure, vary a great deal with time, even within the course of a storm. Vegetation, particularly on cultivated land, varies seasonally.

Predicting Erosion

Since some erosion always occurs, some researchers (e.g., Free, 1960b; Stamey and Smith, 1964; and Smith and Stamey, 1965) concentrated on determining how much erosion could occur before serious yield or siltation problems arose. However, in many instances concerning agriculture or construction, limiting erosion to that acceptable amount was impossible. What was needed was a way to predict how much soil would be lost under given conditions and help with the selection and implementation of corrective or preventive measures.

Meyer (1982) presented a history of erosion research and resulting equations for predicting soil loss. Prediction equations are usually for sheet and rill erosion, with different methods required once gullies have formed.

One of the first equations was suggested by Zingg (1940):

$$X = C\ S^{1.4}\ L^{1.6} \tag{1}$$

where:

X = total soil loss from a land slope of unit width,

C = a constant of variation,

S = degree of land slope, and

L = horizontal length of land slope.

He worked on a Shelby loam soil with simulated rainfall. Other equations, such as those developed by Smith and Whitt (1948) and Van Doren and Bartelli (1956), included more terms than the two recommended by Zingg (1940).

Universal Soil-Loss Equation

Much work was done to combine the plot-research data from different locations to obtain a soil-loss equation which would be universally applicable. Musgrave (1947) presented a "first approximation". Smith and Wischmeier (1957) and Wischmeier et al. (1958) reported on additional work in that area. After analyzing more than 8000 plot-years of erosion-plot data from 37 locations in 21 states, Wischmeier and Smith (1960) presented their Universal Soil-Loss Equation (USLE). That equation has been the subject of much research, with the authors following their original work with two updated versions (Wischmeier and Smith 1965, 1978). Their equation for predicting erosion is the following:

$$A = R\ K\ L\ S\ C\ P \tag{2}$$

where:

A = gross erosion rate per unit area,

R = rainfall and runoff (erosivity) factor,

K = soil-erodibility factor,

L = slope-length factor,

S = slope-steepness factor,

C = cover and management factor, and

P = support-practice factor.

Gross erosion is the amount of soil moved to the bottom of the slope, not necessarily the amount observed at some point farther downstream. The metric units recommended by Wischmeier and Smith (1978) for A were metric tons per hectare (t/ha, where 1 t = 1 000 kilograms (kg) and 1 ha = 10 000 square meters (m^2)). Those units are equivalent to 0.1 kg/m^2 and correspond to the time period for the R factor.

The R factor represents erosivity, or the ability of water to cause erosion. The K factor represents erodibility, or the ability of a unit plot to be eroded by a unit of erosivity when it has been in clean fallow for more than two years and tilled to prevent vegetative growth and surface crusting. The L, S, C, and P factors are ratios relating an individual situation to a unit plot: 22-m long, 9-percent slope, and plowed up and down the slope.

Factor R. The rainfall and runoff factor (R) was presented by Wischmeier (1959) after extensive regression analyses as the best indicator of the capacity of a storm to erode soil. Wischmeier and Smith (1958) reported that EI_{30}, or the product of the rainfall energy (E) and the maximum 30-minute intensity (I_{30}), explained most of the variation in individual-storm erosion. Free (1960a) also observed the highest correlation to splash losses with EI_{30}. An upper limit of 6.35 centimeters per hour (cm/h) placed on I_{30} further improved prediction accuracy (Wischmeier and Smith, 1978). If significant runoff is produced by another source, such as snowmelt, that runoff must also be accounted for in R.

The units for R are units of EI. The recommended metric units for E are t-m/ha, and for I are cm/h, with a factor of 10^{-2} (Wischmeier and Smith, 1978). The resulting units are equivalent to 0.1 kg/h. Rainfall energy can be calculated from the numbers and sizes of the individual raindrops and their corresponding velocities. The energy of a rainfall of varying intensity can be calculated by summing the energies of increments with fairly uniform intensities.

The energy of a uniform-intensity increment of natural rainfall can be estimated with an equation presented by Wischmeier and Smith (1978):

$$e = 210 + 89 \log(i) \tag{3}$$

where:

e = kinetic energy of the rainfall during the increment (t-m/ha-cm),

i = rainfall intensity (constant) during the increment (cm/h), and

log = logarithm, base 10.

The median-drop size does not increase with intensity above 7.6 cm/h, so an upper limit of 7.6 is placed on i (Wischmeier and Smith, 1978).

The total rainfall energy (E) would be determined:

$$E = \sum_{j=1}^{k} e_j V_j \qquad (4)$$

where:

V = the depth of rain in the increment (cm), and
k = the total number of uniform-intensity increments within the period of interest.

The period of interest may be a particular individual storm, or some longer time period. Long-term averages computed from historical records were especially effective predictors. Annual averages can be obtained from isoerodent maps published in many sources (e.g., Wischmeier and Smith, 1978; Foster, 1982).

Factor K. The erodibility factor for a soil represents an average for many antecedent moisture conditions and storm sizes. The recommended metric units (Wischmeier and Smith, 1978) are t/ha per unit of EI, which is equivalent to h/m^2.

Values of K for many soils are tabulated according to soil type. Olson and Wischmeier (1963) presented a table of K values for 20 soil types to serve as "benchmark" values for estimating the erodibility of other soils. Table 1 contains some established K values reported by Wischmeier et al. (1971) (the values were converted from English units to the metric units used elsewhere in this report).

Table 1. Established soil-erodibility (K) values.(1)

Soil Type	Location	Established K Value (h/m^2)(2)
Austin clay	Temple, TX	0.37
Caribou gravelly loam	Presque Is., ME	0.36
Cecil silt loam	Statesville, NC	0.36
Fayette silt loam	LaCrosse, WI	0.49
Keene silt loam	Zanesville, OH	0.62
Lexington silt loam	Holly Springs, MS	0.58
Loring silt loam	Holly Springs, MS	0.66
Mansic clay loam	Hays, KS	0.41
Marshall silty clay loam	Clarinda, IA	0.43
Mexico silt loam	McCredie, MO	0.41
Shelby loam	Bethany, MO	0.53
Tifton loamy sand	Tifton, GA	0.13
Zaneis fine sandy loam	Guthrie, OK	0.28

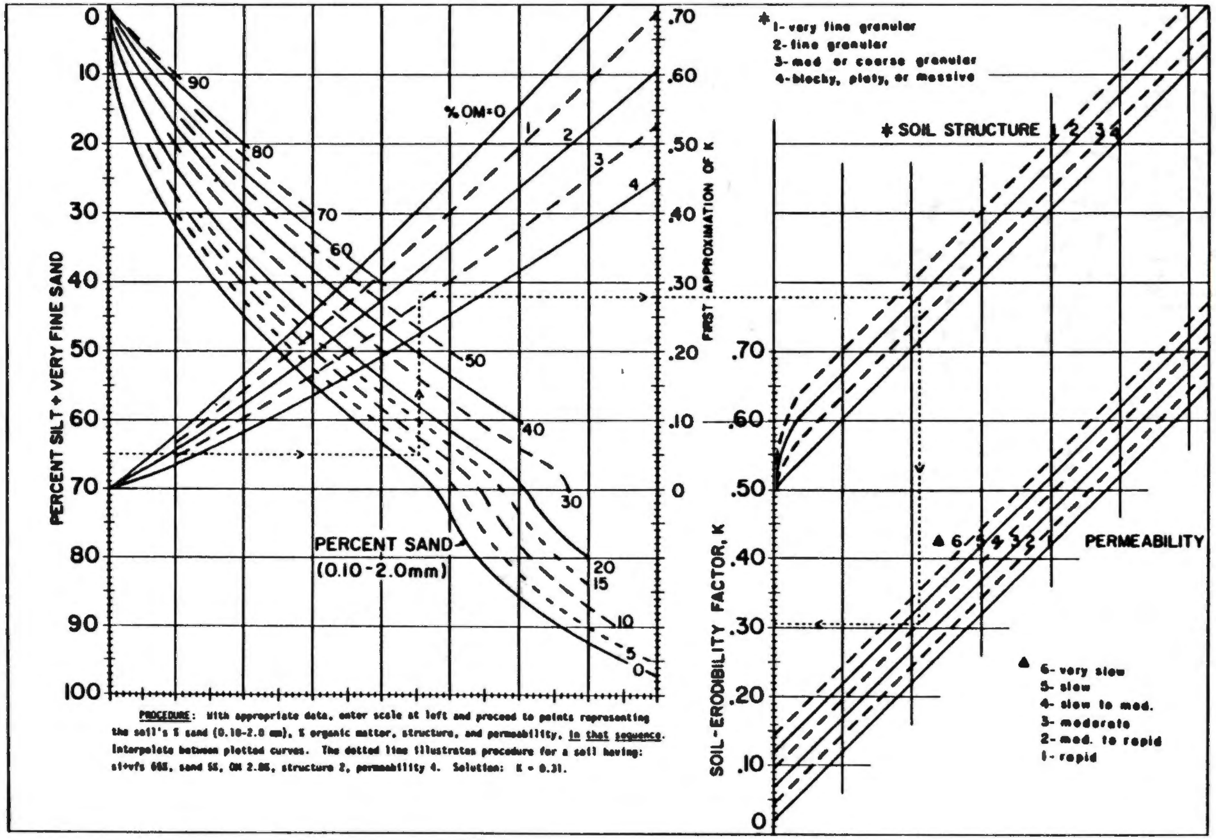
(1) Converted to metric units from: Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Cons. 26(5):189-193.

(2) Units are equivalent to the metric units recommended by: Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S.D.A. Agr. Handbook No. 537. U.S. Gov. Printing Off. Washington, D.C. 47pp.

Wischmeier and Mannering (1969) developed an equation for K, but with 24 terms it was not readily applicable. Wischmeier et al. (1971) presented a nomograph to determine K from the soil-particle size distribution, organic-matter content, structure, and permeability. The nomograph, shown in Figure 1 (the K values in Figure 1 are in English units, and must be multiplied by 1.29 to convert to the metric units used elsewhere in this report), is especially useful for disturbed soils such as those at construction sites.

Roth et al. (1974) reported that the nomograph could not be improved for surface soils by considering other mineralogical and chemical parameters. However, studies of high-clay subsoils have shown the nomograph to be a poor predictor of erodibility for those soils. Roth et al. (1974) developed an equation and nomograph for high-clay subsoils, that included the concentrations of amorphous hydrous oxides of iron, aluminum, and silicon. They reported that those oxides serve as soil stabilizers in subsoils, while organic matter is the major stabilizer in surface soils.

Factor LS. Zingg (1940) suggested that slope steepness and length could be considered independently. However, in the USLE they are not. Because of the interaction between slope length and steepness, often an LS factor is presented, rather than the two terms separately. The factors are ratios to relate a particular condition to the unit plot (22-m long at 9-percent slope).



<u>PROCEDURE</u>: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, <u>in that sequence</u>. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Figure 1. USLE soil-erodibility factor (K) nomograph in English units.(1)

(1) The K values from the nomograph must be multiplied by 1.29 for the metric units used elsewhere in this report (h/m^2). From: Wischmeier, W. H., and D. D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S.D.A. Agr. Handbook No. 537. U.S. Gov. Printing Off. Washington, D.C. p.11.

The equation for the slope-length factor (L) was presented by Wischmeier and Smith (1978):

$$L = (\lambda/22)^m \qquad (5)$$

where:

λ = slope length, and

m = an exponent, dependent upon slope steepness.

An equation for the slope-steepness factor (S) was presented by Schwab et al. (1966):

$$S = \frac{0.43 + 0.30s + 0.043s^2}{6.613} \qquad (6)$$

where:

s = field slope in percent.

Methods to account for irregular slopes were reported by Foster and Wischmeier (1974) and Wischmeier and Smith (1978).

Factor C. The cover and management factor (C), discussed by Wischmeier (1960), is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow. Many representative C values were included by Wischmeier and Smith (1965, 1978).

Factor P. The support-practice factor is the ratio of soil loss with a support practice such as contouring to that with straight-row farming up and down the slope. Representative P values were included by Wischmeier and Smith (1965, 1978).

Other Approaches

Some researchers have taken different approaches. For example, Bubenzer and Jones (1971) and Mazurak and Mosher (1968, 1970) chose to study the splash-detachment process separately, but Kinnell (1974) and Farrell et al. (1974) reported problems with the splash-cup technique commonly used. Park et al. (1982) did a dimensional analysis of the splash-erosion process. Such a theoretical approach involves more terms and is more complicated than many people would accept. However, sometimes a more accurate prediction would be worth the added complexity, particularly in research. Furthermore, a dimensional-analysis approach is preferable to some of the purely statistical models proposed because of its theoretical base.

Meyer and Wischmeier (1969) developed a computer model to consider four separate components of soil loss: detachment by rainfall, detachment by runoff, transport by rainfall, and transport by runoff. The four components were combined to estimate the soil lost. A similar approach was employed by Rowlison and Martin (1971).

Rose et al. (1983) presented a mathematical model that considered the rates of rainfall detachment, sediment deposition, and sediment entrainment to predict sediment discharge from a plane. The model employs four soil-dependent parameters, two cover factors (one for rainfall and one for runoff), slope, and time-varying rates of precipitation and runoff. Runoff can be predicted from precipitation if infiltration characteristics are known.

Komura (1976) predicted slope erosion from slope, slope length, runoff (a function of rainfall intensity), mean sediment size, and coefficients for bare-soil area and erodibility. He used the Kalinske bed-load function as the equation of motion for sediment transport.

Foster et al. (1977) and others separated erosion into rill and interrill components, suggesting that the erosion processes are significantly different for the two components. They concluded that a resulting prediction equation would improve soil loss estimates for single-storm events and specific time periods. Experimental studies by Mosley (1974), Meyer and Harmon (1984), and others have been devised to observe the two components separately.

Current Status

The USLE is the most widely accepted predictor of gross erosion. It generally gives a reasonable estimate of erosion and is useful for planning farming and construction activities. Furthermore, much work has been devoted to modifying or improving the equation to make it more useful. For example, much information was included in U.S.D.A. Agriculture Handbook No. 282 (Wischmeier and Smith, 1965) that was not presented in the earlier report on the equation (Wischmeier and Smith, 1960). Likewise, much more was included in U.S.D.A. Agriculture Handbook No. 537 (Wischmeier and Smith, 1978) than was in the earlier Handbook No. 282.

Foster et al. (1977) pointed out that for any other equation to be as useful (hence as frequently and widely used) as the USLE, it would have to retain much of the USLE's simplicity. Complicated mathematical models may predict erosion quite well, but never gain widespread acceptance. A model like CREAMS (Knisel, 1980), which is much more detailed than the USLE and concerns more than just soil loss, can be used when more specific information is required (Foster, 1982). SEDIMOT II (Univ. of Kentucky, date unknown), another watershed modeling program can also be used to estimate soil losses.

Wischmeier (1976) reported on some of the limits to using the USLE and how those limits are sometimes neglected, resulting in inaccurate predictions for soil loss. One particular area of misuse and misunderstanding is the soil-erodibility factor. Laflen (1982) reported that calculated K values were quite similar regardless of the calculation procedure (e.g., equation, nomograph). He further stated that on the basis of his study it was difficult to agree with others that the quality of the estimate for a soil-erodibility value was "good", unless that was relative to the other variables in the USLE.

Erodibility (K) values found in the literature are intended as long term averages, covering a variety of initial moisture contents, surface conditions (even though fallow and tilled, the degree of surface crusting will vary), seasons, and years. Methods discussed previously relate the erosivity (R) to a single storm or particular time period, but no similar method exists for a more case-specific K value. Very often, particularly in research, the time scale of interest is small (often one season). Wischmeier and Smith (1978) suggested how to conduct erosion research to get reasonable K values. However, often the results obtained are not averaged over enough conditions to represent "true" K values. Furthermore, more accurate predictions are often desired than the average values can provide.

IV. DIMENSIONAL ANALYSIS

Background

Measurements of physical properties may be qualitative or quantitative. Qualitative measures are inexact, usually valid only in context, and based upon judgment. A cup of coffee may be called "cold" and a glass of milk called "hot", even though both are at room temperature.

One way around the ambiguities associated with qualitative measurements is to quantify the measurements, or give them numerical values. However, a quantitative measurement is meaningless without units. If a temperature is reported as 90 degrees, it makes considerable difference whether the units are degrees Kelvin, Celsius, or some other temperature unit.

Units

A system of units is usually employed, whereby a set of reference or base units are selected and other units are derived from them. In this report, the Systeme International d' Unites (SI) will be used, along with some non-SI units (hour (h), degrees C (°C)) and multiples of units (metric ton (t), hectare (ha)) as recommended in ASAE Engineering Practice: ASAE EP285.6 (A.S.A.E., 1984). The base units include meter (m), second (s), and kilogram (kg). Derived units include newtons (N, kg-m/s^2), joules (J, N-m), and pascals (Pa, N/m^2).

Often it is preferable to deal with reference dimensions, rather than specific units. The millimeter and kilometer both refer to the reference dimension length, even though the quantities they represent are quite different in magnitude. A system of reference dimensions (e.g., MLT: mass (M), length (L), and time (T)) can be used to describe physical quantities without regard to their magnitudes or units of measure. Other quantities can be defined in terms of the reference dimensions. A quantity of area in the MLT system would have dimensions of L^2; work, the product of a force and distance, would have dimensions of ML^2T^{-2}; and so on. Additional reference dimensions, such as temperature, may be necessary to define more complicated quantities, such as specific heat capacity.

Although an infinite number of reference dimensions are possible, it is often desirable to use the smallest-possible linearly independent set. In other words, length or area could be a reference dimension, but since either can be expressed in terms of the other, they are not linearly independent. A smallest-possible set of linearly independent reference dimensions would not contain both.

Individual physical quantities can be combined by multiplication and division to form dimensionless products (DP's). Although the resulting combination has no dimensions, the DP may still have units. For example, the change in elevation (m) over a 100-m horizontal distance yields the dimensionless slope, but the units are m/100-m or percent.

Some DP's indicate certain qualities of a situation. The DP formed by dividing the product of velocity and characteristic length by dynamic viscosity is referred to as the Reynolds number, and is commonly used in hydraulics to indicate turbulence of flow. Another DP, formed by dividing velocity by the square root of the product of acceleration due to gravity and characteristic length is referred to as the Froude number, and is used in open-channel hydraulics to indicate the relationship between a particular flow condition and critical flow. Numerous other examples of commonly used and indicative DP's can be found.

Buckingham Pi-Theorem

According to the Buckingham pi-theorem, as reported by Isaacson and Isaacson (1975), a dimensionally homogeneous equation (i.e., all terms combined by addition or subtraction have the same dimensions) relating n quantities defined in terms of r independent reference dimensions may be reduced to a relationship among n - r independent dimensionless products (pi-terms or π's). In other words, a dimensionally homogeneous equation among four quantities defined in terms of two independent reference dimensions could be expressed as a relationship between two (4 - 2) DP's.

The pi-theorem might be a useless mathematical exercise if the form of the original equation were already known. However, if the exact form were not known, an equation relating two new variables could be investigated experimentally, rather than the original equation relating four variables. If the relationship between the two DP's were determined, then that equation could be written in terms of the original four terms. In addition to having fewer variables in the new equation (the number of variables was reduced from n to n - r, but all n original terms still appeared in the new equation), the magnitudes of some of the DP's may yield information about the situation without the equation being solved.

Application To a Study of Erosion

The USLE is the standard for predicting erosion losses due to rainstorms. Its simplicity makes it useful to a wide range of engineers and soil scientists, and it is commonly employed for soil-loss predictions on agricultural land and construction and mining sites. However, there are shortcomings related to it, especially with respect to the soil-erodibility factor (K).

If an accurate method were available to predict erodibility for a specific set of conditions and properties, then probabilistic methods could be used to estimate longer-term averages. Wischmeier and Smith (1978) suggested observing soil loss at different antecedent moisture contents and weighting the results based upon the likelihood of that antecedent moisture content occurring. A similar approach could be taken with any other variable in the prediction of K. If such an approach were available, better estimates of erosion from single-storm events and specific time periods could be made.

Assigning dimensions to an empirical equation is not always a straightforward operation. For example, Chow (1959) discussed some of the different ideas concerning the dimensions of the roughness coefficient (n) in the Manning equation. Some proposed that the constant term in that equation is a dimensional constant, allowing the dimensions to equate when a dimensionless roughness coefficient is assumed. Others suggested the presence of a gravitational acceleration term, even though one is not normally included in the equation.

For the USLE, the K factors were determined from the ratios of observed A values and corresponding R factors. Units were assigned to K based upon the units of the other two terms. An argument could be made for considering R to have only the dimension 1/time (T^{-1}), to account for the time period of interest. With such an approach, A would have dimensions of mass/length^{2}time ($ML^{-2}T^{-1}$) and K would have dimensions of mass/length^2 (ML^{-2}). R would relate a base soil-loss amount to a specific time period and the erosivity corresponding to that time period, in the same way that the other factors relate specific conditions to a unit plot. A dimensional constant would be assumed to account for the dimensions of EI_{30} (or some other erosivity indicator) so that R would not contain any erosivity dimensions.

With such an approach, R would represent a true erosivity and EI_{30} would be one method of estimating that erosivity. Foster (1982) discussed some studies that addressed other erosivity factors. However, for the purposes of this study, dimensions were assigned to K based on the metric units of A and EI_{30} recommended by Wischmeier and Smith (1978).

If the soil-erodibility factor could be considered independent of the other terms in the USLE (i.e., R, L, S, C, P) then it might be explained by the following relationship:

$$K = f(d,s,D,B,W,p,o,g) \qquad (7)$$

where:

K = USLE soil-erodibility factor,

f = an unknown function,

d = a representative soil-particle diameter,

s = a particle-size variation term,

D = a particle-density term,

B = bulk density,

W = initial water content,

p = saturated hydraulic conductivity,

o = organic-matter content term, and

g = acceleration due to gravity.

Those terms describe many of the soil characteristics discussed previously and are readily determined. If a sufficiently descriptive relationship cannot be found with those terms, more terms can be investigated in subsequent studies. However, it is desirable to use the smallest number of terms possible to facilitate both laboratory testing and the use of the resulting equation.

The units of the energy term recommended by Wischmeier and Smith (1978) are based on mass rather than force (i.e., metric ton-meters rather than kilojoules), and the soil-loss term includes mass (metric tons) rather than weight. Therefore, when their units are employed, the erodibility factor has dimensions of time/length^2 (TL^{-2}). Foster (1982) discussed using SI units based on force in the energy term. If the units of R were based on force and the soil loss was still mass, then the dimensions of K would be time^3/length^3 (T^3L^{-3}).

Since soil is composed of many particles of various sizes, the d and s terms would represent the distribution of sizes of individual particles in a particular soil. Two possibilities for d would be a mass-mean or 50-percent-finer diameter (d_{50}) and a geometric-mean diameter (d_g). The d_{50} is the diameter for which 50 percent of the soil mass consists of particles with smaller diameters (and similarly for d_{84} and d_{16}).

With a log-normal particle size distribution (PSD), d_{50} and d_g are the same. However, a geometric-mean diameter, approximated by the square root of the product of d_{84} and d_{16}, is often used in sedimentation work even when the PSD is not log normal (Vanoni, 1975). Regardless of which diameter is selected for d, it will have the dimension of length (L).

One possibility for s would be a geometric standard deviation (s_g), approximated by the square root of the ratio of d_{84} and d_{16}. That approximated geometric standard deviation is also commonly used in sedimentation work when the PSD is not log normal (Vanoni, 1975). Another possibility would be M, presented by Wischmeier et al. (1971) as the product of percent sand and silt (particle sizes from 2 to 2 000 micrometers (μm)) and percent very fine sand and silt (particle sizes from 2 to 100 μm). They reported that the M factor alone accounted for 85 percent of the variance in observed K values in their study. Both the geometric standard deviation and M are dimensionless.

The particle density (D) refers to the mass per unit volume of only the soil material. Any air and water are not considered. Particle density may be determined for the whole soil, including organic matter, or for only the mineral portion after any organic matter has been oxidized. Often a specific gravity (G), or the ratio of particle density to the density of water (1 000 kg/m^3), is reported instead of the particle density. For the purposes of dimensional analysis, using the specific gravity would seem to introduce another variable (the density of water). However, since a constant value is used for the density of water, rather than one that varies with temperature or water purity, it acts as a dimensional constant and not a variable. The dimensions of particle density are mass/length^3 (ML^{-3}), and specific gravity is dimensionless.

The bulk density (B) refers both to the density of the particles and their packing. It is the mass of dry soil material per unit volume of soil, air, and water. The dimensions of bulk density are mass/length^3 (ML^{-3}).

The water content (W) is the mass of water per unit volume of soil, air, and water. Since the mass of the air is negligible, the sum of water content and bulk density is the total mass per unit volume, also known as the wet density. The dimensions of water content are mass/length^3 (ML^{-3}).

Saturated hydraulic conductivity, a measure of permeability, is affected somewhat by bulk density. It is also affected by temperature, so it is usually reported at 20 °C. Infiltration would be a more descriptive value, but its higher variability makes it less desirable for a prediction equation. Some of the properties affecting infiltration are included as other terms (e.g., particle size, organic matter, moisture content). The dimensions of saturated hydraulic conductivity are length/time (LT^{-1}).

For the organic-matter content term, probably the most common measure is TOC. When organic matter is reported, it is often calculated by measuring TOC and assuming that the organic matter is 58-percent carbon (Jackson, 1958). Some studies have indicated that certain components of organic matter might be better predictors of erodibility than the total, but there is no one accepted measure. TOC was the organic-matter term employed in this investigation. TOC is reported as a fraction or percentage and is dimensionless.

In cohesive soils the effect of gravity on holding soil before detachment may be minor. However, it definitely affects other processes involved, such as splash and particle settling in the runoff. The acceleration due to gravity has dimensions of length/time^2 (LT^{-2}).

The nine variables in Equation (7) are somewhat interrelated. For example, saturated hydraulic conductivity is affected by bulk density, and Rawls (1983) estimated bulk density from organic matter and the particle size analysis. However, bulk density is not dependent upon organic matter, only correlated with it under common agricultural conditions.

Equation (7) is not a list of all possible factors. Structure was not included, even though it has been shown to affect erodibility. Since it is more commonly thought of as a quality than a physical quantity it was not included. In the future, however, it might be necessary to include a scaled structure similar to that used by Wischmeier, et al. (1971), the percentage of water-stable aggregates greater than 0.5 mm in diameter suggested by Luk (1979), or some other term.

The depth of the soil was also not included. For the purposes of this study, the soil is assumed homogeneous to a depth sufficient for depth not to influence the erodibility. The minimum necessary depth probably varies according to the other properties, but it was not investigated in this study.

According to the Buckingham pi-theorem, as reported by Isaacson and Isaacson (1975), Equation (7) relating nine quantities (K, d, s, D, B, W, p, o, g), defined in terms of three independent reference dimensions (mass, length, and time) may be reduced to a relationship among six independent dimensionless products. By the process of inspection, the six DP's, or π's may be assigned as shown in Table 2. Whichever term is used for diameter (d_{50} or d_g) will be the same in π_1 and π_6. The term s in π_2 may represent either s_g or M.

The interaction between saturated hydraulic conductivity (p) and diameter (d) in π_1 may indirectly address infiltration. A high conductivity with a small diameter might correspond to strong structure, whereas weaker structure could be found with a larger d without affecting p. The stronger structure would probably be more resistant to surface crusting. Since saturated hydraulic conductivity can vary considerably within a field, it may be necessary to

Table 2. Definitions of pi-terms.

Pi-Term(1)	Definition(2)
π_1	Kpd
π_2	s_g
π_2	M
π_3	$\frac{D}{B}$
π_3	G
π_4	$\frac{W}{B}$
π_5	o
π_6	$\frac{p^2}{gd}$

(1) Two possibilities are shown for π_2 and π_3.

(2) Symbols used in text.

reconsider using p as a parameter in the dependent pi-term when applied to nonhomogeneous soils outside the laboratory.

Using force-based units for R, resulting in different dimensions for K as discussed previously would cause the DP for π_1 to be Kpdg. Because g is a constant in this application, it would not affect the procedure. Only the form π_1 = Kpd will be referred to in this study. The DP for π_4 (W/B) is the mass of water per unit mass of dry soil, or moisture content on a dry-mass basis. The DP included as π_6 ($p^2/g\text{-}d$) is similar to the square of the Froude number presented earlier.

The new equation would be the following:

$$\pi_1 = f_2(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6) \tag{8}$$

where:

f_2 = an unknown function, different from f in Equation (7).

The form of f_2 depends partly upon which terms are selected for diameter, variability, and particle density. Writing Equation (8) in terms of the original quantities of Equation (7), it becomes the following:

$$Kpd = f_3(s, G, \frac{W}{B}, o, \frac{p^2}{gd}) \tag{9}$$

or:

$$Kpd = f_4(s, \frac{D}{B}, \frac{W}{B}, o, \frac{p^2}{gd}) \qquad (10)$$

depending upon which particle-density term is used (specific gravity or density). The functions f_3 and f_4 represent two possible forms of f_2.

The form of f_2, a function among the six pi-terms in Equation (8), can be investigated through laboratory experiments and eventually related to f, the function among nine variables in Equation (7).

V. EXPERIMENTAL PROCEDURES

To achieve the objectives previously presented, a study was conducted at the Agricultural Engineering Laboratory, of The University of Tennessee, Knoxville.

Test Factors

The nomograph presented by Wischmeier et al. (1971) and included in Figure 1, page 18, did not account for antecedent moisture or interactions with the other USLE factors (R, L, S, C, P). However, Wischmeier and Smith (1978) discussed the need to perform tests at a variety of antecedent moisture contents and with a variety of storms so that the resulting K values would be averages.

To gain insight into any effects of the R factor or antecedent moisture on a soil's erodibility, two levels of each were included in the study. The levels of R were represented by two storm intensities, with target values of 5 and 8 cm/h. Moisture conditions, representing preparation procedures rather than target moisture contents, were used to test for moisture effects. Since every soil has different moisture properties, it was more practical to follow a common procedure on all soils than to aim for the same moisture content. The two qualitative moisture-condition levels were dry and prewetted (soaked with water before the surface was prepared).

A soil-surface width of 1.0 m was selected. It was expected to be wide enough for any effects of the sides of the soil containers to be negligible. A slope length of 2.0 m was chosen. The length was felt to be sufficient for some rills to form, but still small enough to allow the tests to be prepared and conducted by one person. A uniform depth of 30 cm was selected, with the expectation that it was sufficient for depth not to be a factor. Because of other restrictions placed on the study, the number of soils included was limited to four.

Experimental Design

The experimental design selected for the investigation was a balanced incomplete block. With the incomplete-block design a preliminary portion of the study could be conducted with only two soils, and then two more soils could be added for the completion of the study. Such an approach was useful for obtaining information with limited time, equipment, and space. By employing the balanced incomplete-block design, each soil appeared in two blocks, but each block was a different pairing of two of the four soils.

Each block consisted of a split-plot experiment with rainfall intensity as the whole-plot effect. The split plot was a randomized factorial, with the two levels of moisture condition and two of the soils. The first block contained four subsamples. Subsamples in subsequent blocks were to be decided upon after the completion of the first block, based partially upon the variability among subsamples observed in the first block.

An advantage of the selected design was that much of the information gained from the experiments dealt with the split plot.

Less was learned about intensity, but intensity was already known to have a major effect. Interactions among intensity, soil, and moisture appeared in the split plot. The least information was learned about the block effect and its interactions, but they were expected to be of minor importance.

Soil Selection

The number of soils that could be included in the study was limited to four, but it was desirable to cover as much of a range of erodibility as possible using available nearby soils. Furthermore, a fairly even spacing throughout that range was desired. Dr. David Lietzke(1) (1986, personal communication) suggested the soils to use, based upon his experiences with soils in the area.

Only agriculturally productive soils were considered for the study. Since it would be necessary to remove topsoil from a fairly large area, the search was restricted to the various farms of the Knoxville Agricultural Experiment Station. The fields investigated for suitable soils were all used to grow corn for silage.

After a suitable soil was located, approximately 15 cm were scraped off the top of an approximately 25-m^2 area and hauled to the Agricultural Engineering Laboratory. The soils were piled outside and covered with plastic.

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(1) Dr. Lietzke was formerly an Associate Professor with the Plant and Soil Science Department, The University of Tennessee, Knoxville, TN.

The first two soils were found on the Knoxville Agricultural Experiment Station Dairy Farm. One was located very near the Tennessee River in an area mapped as Staser fine sandy loam (U.S.D.A. Soil Cons. Serv., 1955). The other soil was from a natural terrace located slightly upslope from the Tennessee River in an area mapped as Ooltewah silt loam (U.S.D.A. Soil Cons. Serv., 1955). Appendix 1 contains portions of soil descriptions obtained from Ricky Lambert(1) and Tony Jenkins(2) (1986, personal communication) for soil pits located near the sites from which the two soils were obtained. The soils were obtained in May, 1986, just before the fields were planted.

Soils for the continuation of the study were located at the Knoxville Agricultural Experiment Station Blount County Farm. One soil was located very near the Little River in an area mapped as Staser fine sandy loam (U.S.D.A. Soil Cons. Serv., 1959). Its physical appearance was different from the other Staser fine sandy loam, even though they were mapped the same. The fourth soil was from a sloping field in an area mapped as Decatur silty clay loam, eroded sloping phase (U.S.D.A. Soil Cons. Serv., 1959). Appendix 1 contains portions of soil descriptions obtained from Tony Jenkins (1986, personal communication) for soil pits located near the sites from which the two soils were obtained. The soils were obtained in early

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(2) Mr. Jenkins is a student employee of the Plant and Soil Science Department, The University of Tennessee, Knoxville, TN.

October, 1986, after corn had been harvested, but before any cultivation had taken place.

Additional information concerning all four of the soils is included in subsequent portions of this report.

Equipment

Soil Pans

Soil pans were constructed to contain the soil during a test with a minimum of hindrance to the soil-carrying runoff. The pans had to be strong enough to contain the 0.6 m^3 of saturated soil, and portable enough to move to and from the outdoor soil piles and inside the laboratory.

The design decided upon was a preservative-treated plywood bottom, sides, and ends in an angle-iron frame. A sheet-metal lip was placed over the top of the downstream end. A slotted pvc pipe hung below the lip and served as a runoff trough. A series of 100 equally spaced 6-mm diameter holes were drilled in the plywood bottom. Each hole was stuffed with cotton, to allow water to drip out while preventing any soil from being lost. An aluminum screen was stapled to the underside of the pan to hold the cotton in place.

The pan assembly was mounted on four 10-cm diameter steel casters and placed at a 9-percent slope (the slope of the unit plot for the USLE). Two similar pans were constructed and there was assumed to be no difference between them. Figure 2 shows one of the soil pans.

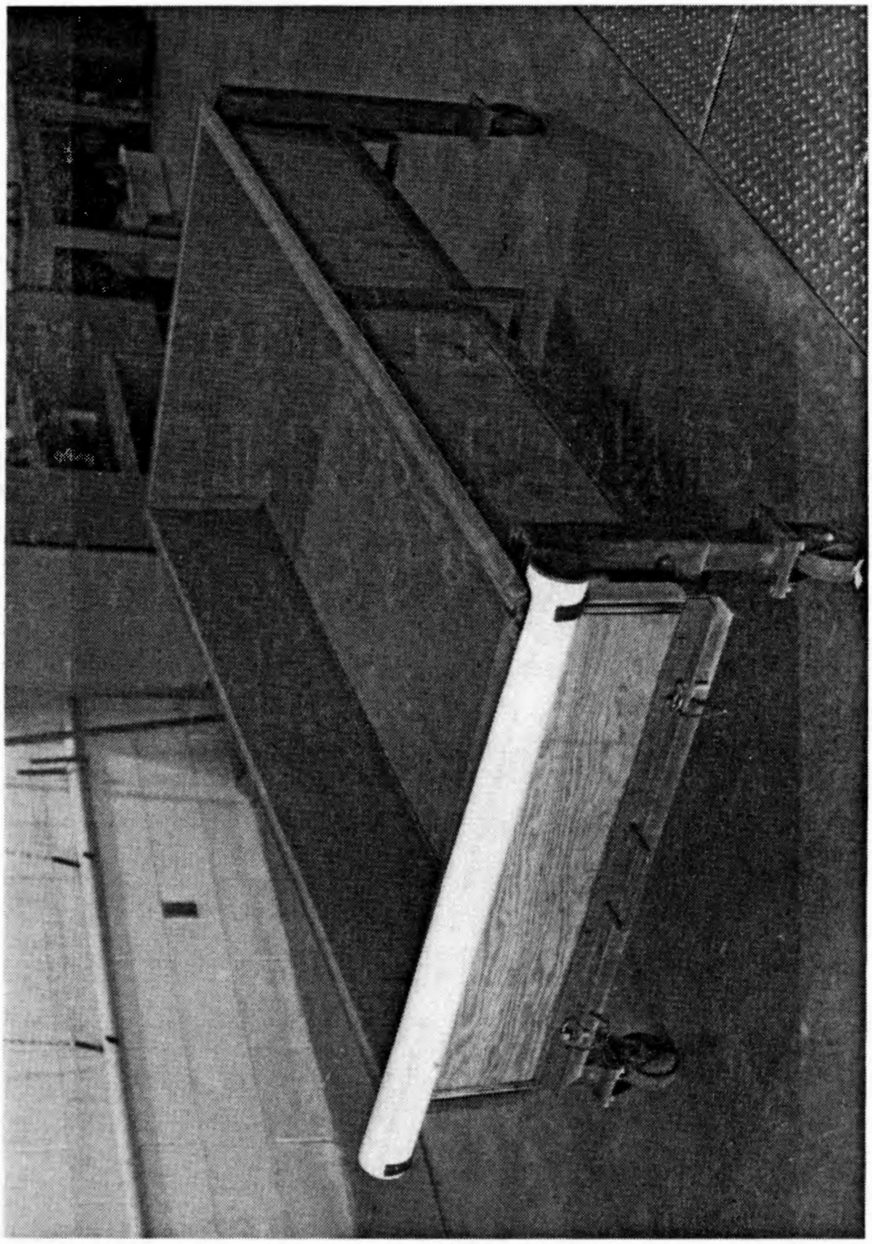

Figure 2. Soil pan used in study.

Rainfall Simulator

A rainfall simulator was constructed, similar to the one used by Shelton et al. (1985). Low pressure air was introduced into the water stream just upstream from a Spraying Systems FullJet square-pattern hydraulic nozzle. The simulator had to produce drops of a variety of sizes at two different intensities while maintaining Christiansen's coefficient of uniformity (C_u) (Christiansen, 1942) greater than 80 percent (the value of 80 percent was arbitrarily selected as a lower bound of acceptable uniformity).

Two identical nozzles were used, with a spacing in the soil pan's 2.0-m direction of 2.3 m (neither nozzle was directly over the soil surface), and a spacing in the soil pan's 1.0-m direction of 0.4 m. Intensity was changed by changing the nozzles and the water and air pressures, as indicated in Table 3. The simulator was mounted to the laboratory ceiling approximately 2 m above the average surface of a filled soil pan.

Table 3. Rainfall-simulator data.

Target Intensity (cm/h)	Spraying Systems FullJet Nozzle Number	Water Pressure (kPa)	
		Without Air	With Air
5	3/8HH20WSQ	24	33
8	1/2HH30WSQ	31	38

Other Equipment

Other equipment used in the study included a Fisher Scientific Digital Hygrometer-Thermometer for measuring air temperatures and relative humidities, a mercury-in-glass thermometer graduated in 1-°C increments for measuring water temperatures, a platform scale graduated in 0.2-pound (0.1-kg) increments to weigh the runoff collected, and a Troxler Model 3411-B Moisture-Density Gauge to measure moisture contents and bulk densities of the soils. A Particle Measuring Systems Inc. Ground Based Precipitation Probe Model GBPP-100, and the necessary hardware and software to interface with an IBM PC (Wilkerson et al., 1985; Dr. R. D. von Bernuth(1), 1986, personal communication) were used to measure the sizes of the drops generated by the rainfall simulator and estimate their velocities.

Laboratory Procedures

Soil Physical Properties

The TOC and soil-particle size analyses were conducted in The University of Tennessee Plant and Soil Science Department Soil Mineralogy Laboratory (Tony Jenkins and Debbie Phillips(2), 1986, 1987, personal communication). Soil samples for the tests were collected about midway through the study. The TOC was measured with a

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(1) Dr. von Bernuth is an Associate Professor with the Agricultural Engineering Department, The University of Tennessee, Knoxville, TN.

(2) Ms. Phillips is a Graduate Research Assistant with the Plant and Soil Science Department, The University of Tennessee, Knoxville, TN.

LECO Carbon Determinator CR12. The particle size distribution was determined by the pipette method (U.S.D.A. Soil Cons. Serv., 1984). Specific gravities and saturated hydraulic conductivities were determined using the procedures recommended by Liu and Evett (1984).

Rainfall-Simulator Calibration

The rainfall simulator was calibrated by means of uniformity tests using 7-cm diameter collector cups. Eighteen collectors were equally spaced throughout the 2.0-m^2 area where a soil pan would be during a test. The collectors were on a level surface, approximately 1 m above the laboratory floor (about the same height as the soil surface at the center of a soil pan).

The Ground Based Precipitation Probe (GBPP) and related hardware and software were used to measure the sizes and estimate the velocities of drops produced by the rainfall simulator. Samples of 2 000 drops each were measured at three locations within the 2.0-m^2 area, approximately 1 m above the laboratory floor. The data from the three locations were combined to determine one drop size distribution, and the energies for the three locations were averaged.

Soil-Loss Tests

The following procedures were followed throughout the study in the tests to determine soil loss. The two soils to be included in a particular block were purposely selected, with no attempt at randomization. Within a block, the whole-plot (simulated-rainfall intensity) level to use first was chosen by a coin toss (even if the selected intensity level was the one most recently completed during the previous block, the simulator was disassembled and set up again). To insure randomness within a split plot (i.e., group of tests within the same block and at the same simulated-rainfall intensity), slips of paper containing the levels of moisture condition and soil type for each of the tests in the split plot were placed in a cup. A slip was drawn just before the pan was loaded to determine the soil and moisture condition for that particular test.

A pan (no distinction was made between the two pans) was filled with soil from one of the four piles. The pans were filled with an ordinary shovel, and care was taken to assure no large voids were left within the soil, especially along the sides and ends of the pan. If a dry test was scheduled, the surface was raked for several minutes down to a depth of approximately 10 cm. Any soil clods larger than about 3 cm were either removed or broken. Smaller clods were felt to be representative of the soil at that condition and were left.

If a prewetted test was scheduled, the surface of the soil in the pan was soaked with water at very low pressure. After a few minutes, the surface was raked and soaked again. The surface was thoroughly soaked again after a few minutes (after no water was standing) and the pan was left overnight. The next morning, the surface was again raked and soaked and left for 3 to 5 hours. Then the soil was raked and prepared much like for the dry tests.

Once the surface of the soil was prepared, three measurements each of moisture content and bulk density were made with the moisture-density gauge. Then the surface was smoothed again, and spilled soil was removed from the metal lip at the downslope end of the pan. The pvc trough was placed under the lip and a plastic tube was connected between the trough and a large plastic tank on the platform scales. The scales were placed in a channel along the outside wall of the laboratory, so that the tank was below floor level and away from the area wetted by the simulator. Once the trough was connected to the tank, the soil and trough were covered with plastic.

With the soil and runoff trough covered, the rainfall simulator was prepared for the test. A higher pressure (hence higher flowrate) was used for the first few minutes to fill the water lines on the simulator. Then the pressure was slowly lowered to the target level and watched for stability. The pressure often fluctuated as much as 4 kPa when water was turned on or off in other parts of the building, but it usually stayed at or very near the target setting. Once the water pressure was considered stable, a higher air pressure (about 100 kPa) was used to flush the water from the air lines. After the water was removed, the air pressure was slowly lowered to its target level. Occasionally, even though both the water and air pressures were set at the target levels, the spray patterns of the two nozzles appeared different from each other. When that happened, the air and water were shut off and the simulator was prepared again.

When the simulator was ready (target water and air pressures set and stable, patterns of the two nozzles appeared the same) the temperature and relative humidity of the air in the laboratory were measured with the digital hygrometer-thermometer and recorded. A cup was placed beside the soil pan to collect some of the simulated rainfall. Then the plastic was removed from the pan and runoff trough and a timer was started. Figure 3 shows a soil-loss test in progress.

After 60 minutes (all tests were the same length) the simulator was shut off. The temperature and relative humidity of the air in the laboratory were again measured and recorded, along with the temperature of the simulated rainfall collected in the cup beside the soil pan.

The runoff trough was dipped into the runoff-collection tank so that any soil remaining in the trough was mixed with the runoff. The weight of the tank with runoff was measured and recorded. The runoff was thoroughly stirred and three samples of approximately one liter each were collected. Sample bottles were dipped into the runoff near the bottom of the tank and allowed to fill. The runoff samples were tested for total solids concentration by the staff of the Agricultural Engineering Water Quality Laboratory (Janice Allison(1), 1986, 1987, personal communication).

Some water could reach the runoff trough without running off of the soil surface by falling onto the lip of the soil pan or directly into the trough. Therefore, four runoff tests (two per pan) were conducted with no soil at both intensity levels. The results represented how much of the water in the runoff tank after a soil-loss test was not runoff from the soil surface.

Runoff volume was calculated from the weight of runoff collected (weight of runoff and tank - weight of empty tank) assuming a density

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(1) Ms. Allison is a Laboratory Technologist with the Agricultural Engineering Department, The University of Tennessee, Knoxville, TN.

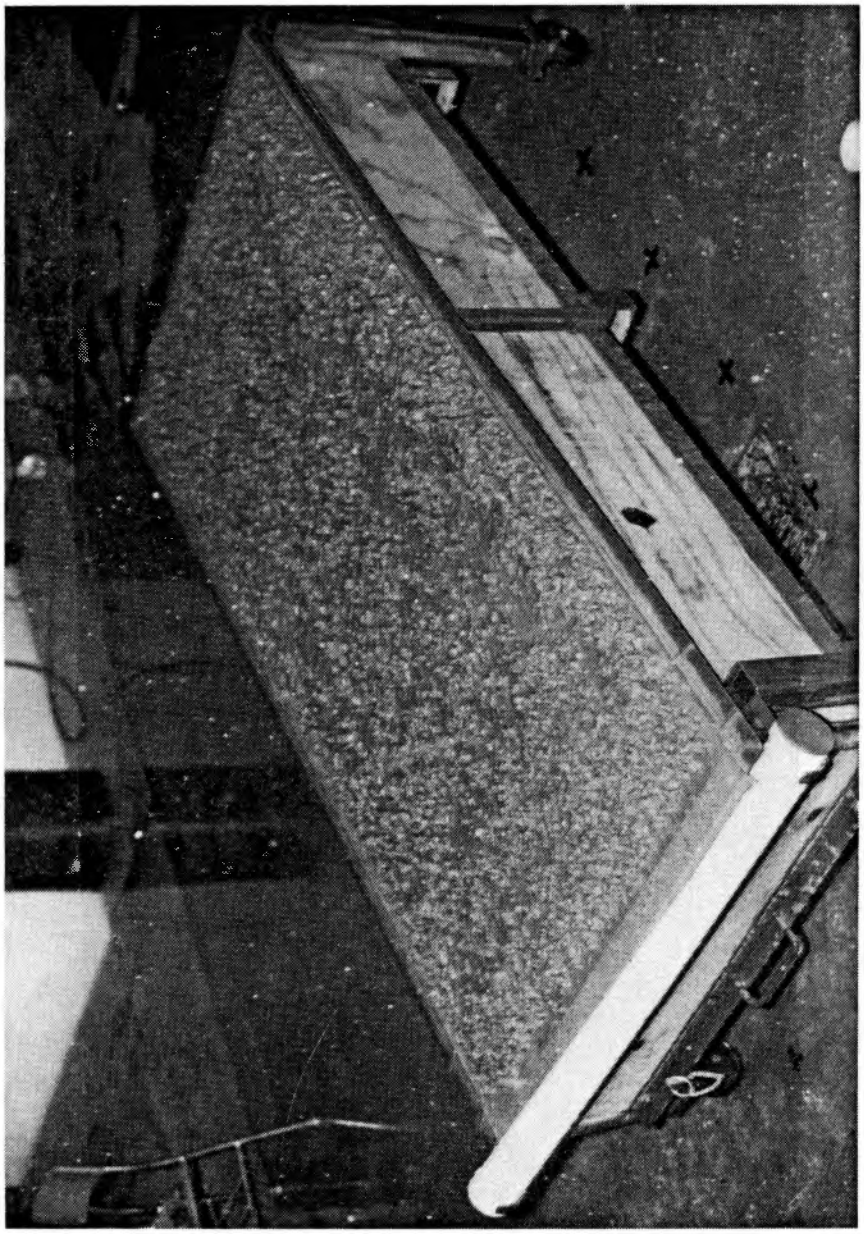

Figure 3. Soil-loss test in progress.

equal to that of pure water at the same temperature. The average volume from the no-soil tests at the same intensity was subtracted from each calculated runoff volume. Soil loss was calculated by multiplying the average of the three solids concentrations for a test by the total volume of runoff collected (before the no-soil value was subtracted).

It was originally intended that any water running out the soil-pan bottom would be collected and measured for a water-balance calculation. However, the water collected was mostly from somewhere other than flow out of the pan bottom. The amount was quite variable, so the measurements were not made. The condition of the soil when unloaded from the pan was noted and revealed whether or not there had been flow through the soil. It was also noted whether or not water could be seen flowing out of the pan bottom during a test.

After all of the measurements were made, the soil was returned to the outdoor pile and allowed to air-dry. The piles were occasionally raked and the pans of soil from different tests were mixed before the soil was reused.

Analysis of Data

After all of the data from all four blocks were collected, SAS, Version 5 (SAS Institute Inc., 1985a, b) on The University of Tennessee's IBM VM 4381-2 mainframe computer was used for the various analyses.

In selecting the model for the analysis of variance (ANOVA), most of the parameters were obvious. Intensity, soil, and moisture condition were fixed effects, with each level specifically chosen for the study.

The block effect was less understood, containing both fixed and random components. The soils studied in each block were purposely selected and the same experimental procedure was used within each block. A time factor was probably contained within the block effect, due to the blocks taking place at different times. Some kind of fatigue factor may have been present due to soils being reused. An element of random error was introduced by running a blocked experiment rather than a completely randomized design.

An approach considering block a fixed effect and including a random restriction error was selected. That approach limited the inference space of the study to the specific tests conducted, whereas random blocks would have been associated with a broader inference space. Since the same piles of soil were used throughout the study, the inference space for random blocks would have been the specific piles, rather than a broader space of the soils the piles were taken from. Because of other constraints placed on the study, a desirable broader inference space was not obtainable. Since all of a pile of soil was used during a block, the inference spaces for fixed and random blocks were little different, and the analysis for fixed blocks is more conventional.

The ANOVA model that best described the study as it was designed and conducted was the following (Dr. William Sanders(1), 1987, personal communication):

$$y_{ijklm} = \mu + B_i + \delta_{(i)} + I_j + BI_{ij} + w_{(ij)} + S_k + IS_{jk}$$
$$+ M_l + IM_{jl} + SM_{kl} + ISM_{jkl} + BISM_{ijkl}$$
$$+ \varepsilon_{(ijkl)m} \qquad (11)$$

for: $i = 1, 2, 3, 4;$

$j = 1, 2;$

$k = 1, 2, 3, 4;$

$l = 1, 2;$ and

$m = 1; 1, 2; 1, 2, 3;$ or $1, 2, 3, 4;$

(depending upon the levels of i, j, k, and l)

where:

y_{ijklm} = variable to be analyzed,

μ = overall mean,

B_i = effect of the ith block (fixed),

$\delta_{(i)}$ = first restriction error (random),

I_j = effect of jth intensity level (fixed),

BI_{ij} = interaction effect of the ith block at the jth intensity level,

$w_{(ij)}$ = second restriction error (random),

S_k = effect of the kth soil type (fixed),

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IS_{jk} = interaction effect of j^{th} intensity level with the k^{th} soil type,

M_l = effect of the l^{th} moisture condition (fixed)

IM_{jl} = interaction effect of j^{th} intensity level with the l^{th} moisture condition,

SM_{kl} = interaction effect of k^{th} soil type with the l^{th} moisture condition,

ISM_{jkl} = interaction effect of j^{th} intensity level with k^{th} soil type with l^{th} moisture condition,

$BISM_{ijkl}$ = pooled interaction effect, with interaction effects of block with each term after $w_{(ij)}$ confounded, and

$\varepsilon_{(ijkl)m}$ = within error of experiments within moisture conditions, soil types, intensity levels, and blocks.

The two restriction errors ($\delta_{(i)}$ and $w_{(ij)}$) were due to restrictions being placed upon complete randomization and were discussed by Anderson and McLean (1974). They were assumed to be normally and independently distributed, with means of 0. For example, the term $w_{(ij)}$ represents the fact that each time the simulator was set up for a particular intensity level it was somewhat different (hopefully very slightly). That difference appeared in each test until the simulator was set up again.

Although the restriction errors cannot be calculated and are often omitted from ANOVA models, their omission can lead to serious misinterpretations of results. The appearance of the restriction error implies that it is contained in the data for each term preceding it in the model. That implication requires that assumptions be made concerning any tests conducted for those terms.

The effects of block (B_i) and the first restriction error ($\delta_{(i)}$) are confounded and cannot be considered separately for hypothesis testing. While it might be desirable to look for a systematic time-related effect which would probably be contained within B_i, the presence of $\delta_{(i)}$ in the model precludes it. Differences among blocks can be observed, but those differences cannot be numerically separated into fixed effects and the random set-up effects. Only two interactions involving block were included in Equation (11): a whole-plot error (BI_{ij}) and a split-plot error (pooled block by all-other-terms ($BISM_{ijkl}$)). The appearance of the block by intensity interaction (BI_{ij}) insures at least a conservative test of the intensity effect (I_j) independent of the second restriction error ($w_{(ij)}$).

SAS PROC GLM and Type III sums of squares (SAS Institute Inc., 1985b) were used to test the significance of the parameters in Equation (11). The advantage of the Type III, or partial sums of squares is that each effect is treated independently of the others. For example, a significant block effect would not be due to a significant soil effect. SAS analyses were repeated with different terms in the model, so that the model used to calculate sums of squares for an effect did not contain the parameter that served as an error term (denominator of an F statistic) to test the significance of that effect (Dr. William Sanders, 1987, personal communication).

An approach whereby some sums of squares were pooled was employed in determining the proper error terms for hypothesis testing. If a test was not significant at approximately the 0.25 level, it was assumed that there was no difference between the numerator (effect) and denominator (error). Therefore, pooling the sums of squares and degrees of freedom yielded a better estimate of the true value with more degrees of freedom.

Some effects and interactions were further investigated by means of linear contrasts. More specific hypotheses could be tested with the contrasts than appear in standard ANOVA tables.

VI. RESULTS AND DISCUSSION

Simulated Rainfall

Table 4 contains information concerning the simulated rainfall for the study. Additionally, Figures 4 and 5 contain plots of the drop size distributions observed with the ground based precipitation probe (GBPP) for the two intensity levels selected for the study.

The information in Table 4 suggests that the properties of the simulated storms were different from properties of natural rain at the same intensities. The observed volume-mean drop diameters were smaller than those predicted by Laws and Parsons (1943). Drop distributions estimated with the average values reported by Park et al. (1983) had slightly lower volume-mean diameters, while predictions based upon Carter et al. (1974) indicated larger drops. Quimpo and Brohi (1986) showed that drop size distributions vary considerably among locations. Data collected with the GBPP at Knoxville, Tennessee have not been compiled at this time, so they were not available for comparison.

The USLE rainfall and runoff factors calculated from the GBPP data were less than those predicted by Wischmeier and Smith (1978) for natural rainfalls of the same intensities. However, Wischmeier and Smith (1958) reported that their original values were based primarily upon the drop distributions of Laws and Parsons (1943). Some adjustments were included by Wischmeier and Smith (1978), due partly to the Carter et al. (1974) data.

Table 4. Simulated-rainfall data.

Intensity (cm/h)	Uniformity (percent)		Extreme Depth Ratio(1)	Volume-mean Drop Diameter (mm)		USLE R Factor (0.1 kg/h)	
	C_u	C_v		Obs.(2)	Nat.(3)	Obs.(2)	Nat.(4)
5.2	84	19	1.9	1.84	2.54	34	74
8.0	86	19	1.9	2.05	2.75	87	147

(1) Ratio of maximum and minimum depths observed in uniformity tests.

(2) From GBPP data.

(3) Calculated for natural rainfall at same intensities, based on: Laws, J. O. and D. A. Parsons. 1943. The relation of raindrop-size to intensity. Trans., Am. Geophys. Un. 24:452-460.

(4) Calculated for natural rainfall at same intensities, based on: Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S.D.A. Agr. Handbook No. 537. U.S. Gov. Printing Off. Washington, D.C. 58 pp.

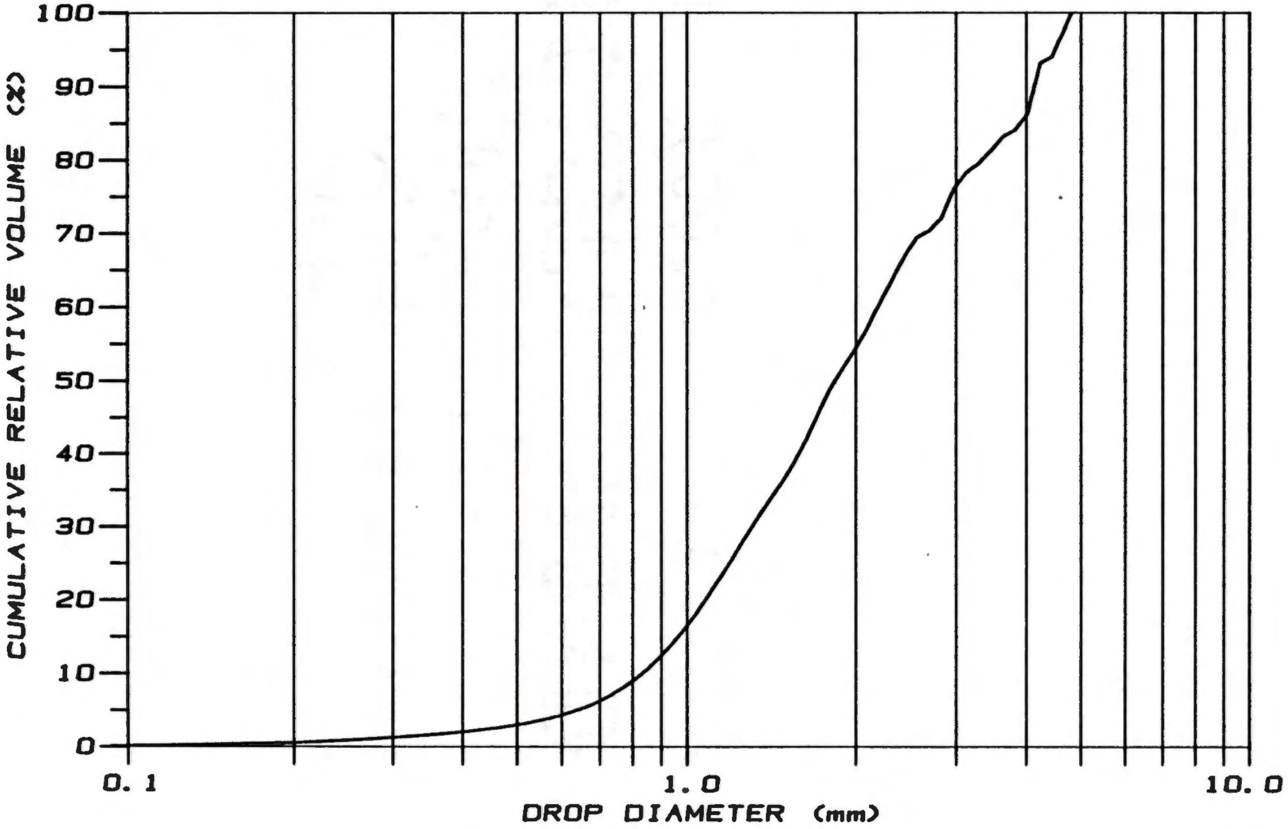


Figure 4. Cumulative relative volume versus drop diameter for 5.2 cm/h intensity.

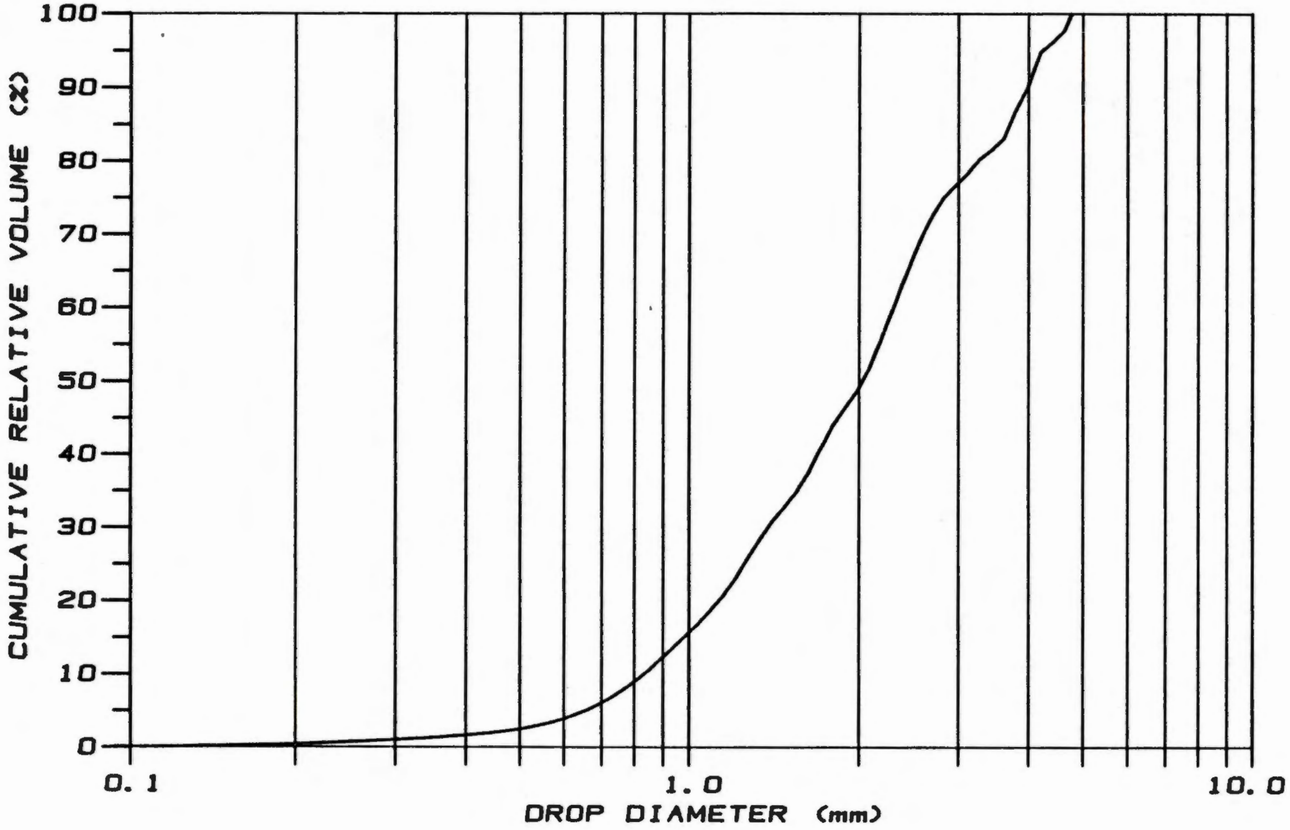


Figure 5. Cumulative relative volume versus drop diameter for 8.0 cm/h intensity.

The differences should not introduce any problems. For the purposes of this study, soil erodibility was assumed independent of the rainfall properties. Rainfall intensity (thus energy) was investigated qualitatively (i.e., low or high) rather than quantitatively to test the validity of that assumption.

The relationship between energy and intensity might affect the tests. The impact energy affects detachment, which affects soil loss. Surface crusting is also affected, which affects infiltration, which affects runoff, which affects soil loss. Varying the relationship between energy and intensity could result in findings based upon situations different from those normally encountered in nature. However, conditions also vary considerably in nature.

The GBPP employs a laser and light-sensing circuitry to measure the diameters and transit times (i.e., times for drops to pass through laser beam) of raindrops. Such laser devices are fairly recent innovations with respect to measurements on raindrops in realistic settings. They make droplet-data collection much simpler and faster than it was with the flour-pellet method described by Carter et al. (1974). However, assumptions must be made in order to analyze the data collected. Errors due to coincidence (Kohl et al. 1985), orientation of the laser beam, or variations in droplet shapes may be contained within those data. Care must be taken in the interpretation of such data.

The GBPP-determined values listed in Table 4 are probably indicative of the situation encountered with the rainfall simulator. The drops may not have reached terminal velocity, even though they were emitted from the simulator nozzles with some initial velocity, rather than starting from rest. The simulator may not have been far enough above the laboratory floor for the drops to achieve terminal velocity.

The uniformity and depth-ratio values included in Table 4 indicate how well the intensity values described the actual applications of water to the soil surfaces. Christiansen's C_u's were included because they are widely used in the field of irrigation. However, the coefficient of variation (C_v), or the ratio of a sample's standard deviation and mean, is a more descriptive value.

The fact that C_v was the same at both intensity levels means that as intensity was increased, variability was also increased, even though the ratios of the maximum and minimum depths observed during uniformity tests were the same. While natural rainfall is usually quite uniform, with Christiansen's C_u usually greater than 90 percent (Dr. R. D. von Bernuth, 1986, personal communication), achieving high uniformity within a small area, with reasonable drop size distributions and drop velocities, and acceptable intensities is a difficult task. Adding more nozzles to the simulator could increase uniformity, but would also increase intensity. Smaller nozzles would emit less water, but most have smaller drop size distributions.

Soil Properties

Table 5 lists several properties of the four soils selected for the study. Bulk density, moisture content, and saturated hydraulic conductivity are more variable and were not included. Structure

Table 5. Soil properties.

USDA Textural Classification(1)	Mean Particle Diameter (µm)		Particle Size Variation		Spec. Grav.(4)	TOC (%)	Structure	USLE K(5) (h/m^2)
	d_{50}	d_g(2)	s_g(2)	M(3)				
Sandy loam	140	36	13.7	2170	2.68	0.8	fine granular	0.23
Fine sandy loam	98	26	12.8	2890	2.69	0.5	fine granular	0.30
Silt loam	7.8	7.6	6.94	4780	2.61	1.9	fine granular	0.41
Clay loam	5.3	6.7	13.5	3120	2.64	1.8	fine subangular blocky	0.34

(1) From Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4 In: Soil survey manual. U.S.D.A. Soil Conserv. Serv. Washington, D.C. pp. 52-57.

(2) Approximated from d_{84} and d_{16}.

(3) Texture parameter presented by: Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Cons. 26(5):189-193.

(4) Organic matter included in soil.

(5) Converted to metric units from nomograph in Figure 1, page 18. Necessary assumptions discussed in text.

strength was not included because, as Wischmeier et al. (1971) reported, it is dependent upon moisture content and judgment. Particle size distributions for the mineral portions of the four soils are included in Figure 6.

Figure 7 includes a soil textural triangle with textures of the four study soils noted. The classifications used in this report were determined from more specific criteria presented by the Soil Survey Staff (1981), which also refer to the size distribution within the sand class (diameters from 50 to 2 000 μm). When the sand fraction was not divided into component classes, the sandy loam appeared very similar to the fine sandy loam, as indicated by their respective points in Figure 7. The areas from which both soils were obtained were mapped Staser fine sandy loam (U.S.D.A. Soil Cons. Serv., 1955, 1959). The silt loam was borderline between silt loam and silty clay loam, being only 0.5-percent clay (probably less than the precision of the measurement) below the silty clay loam classification. The clay loam was also close to a silty clay loam; about 1-percent too high in sand. From a textural standpoint, the soils are clearly divided into two coarser-textured (sandy loam and fine sandy loam) and two finer-textured (silt loam and clay loam) loams.

The differences in Table 5 between the d_{50} and d_g values for a soil (log-linear interpolation was used to estimate d_{84}, d_{50}, and d_{16} from the PSD-test data) indicate that the PSD's for the coarser-textured loams were not log normal. The finer-textured loams had more nearly log-normal PSD's, especially the silt loam. The geometric standard-deviation approximations are represented by the slopes of

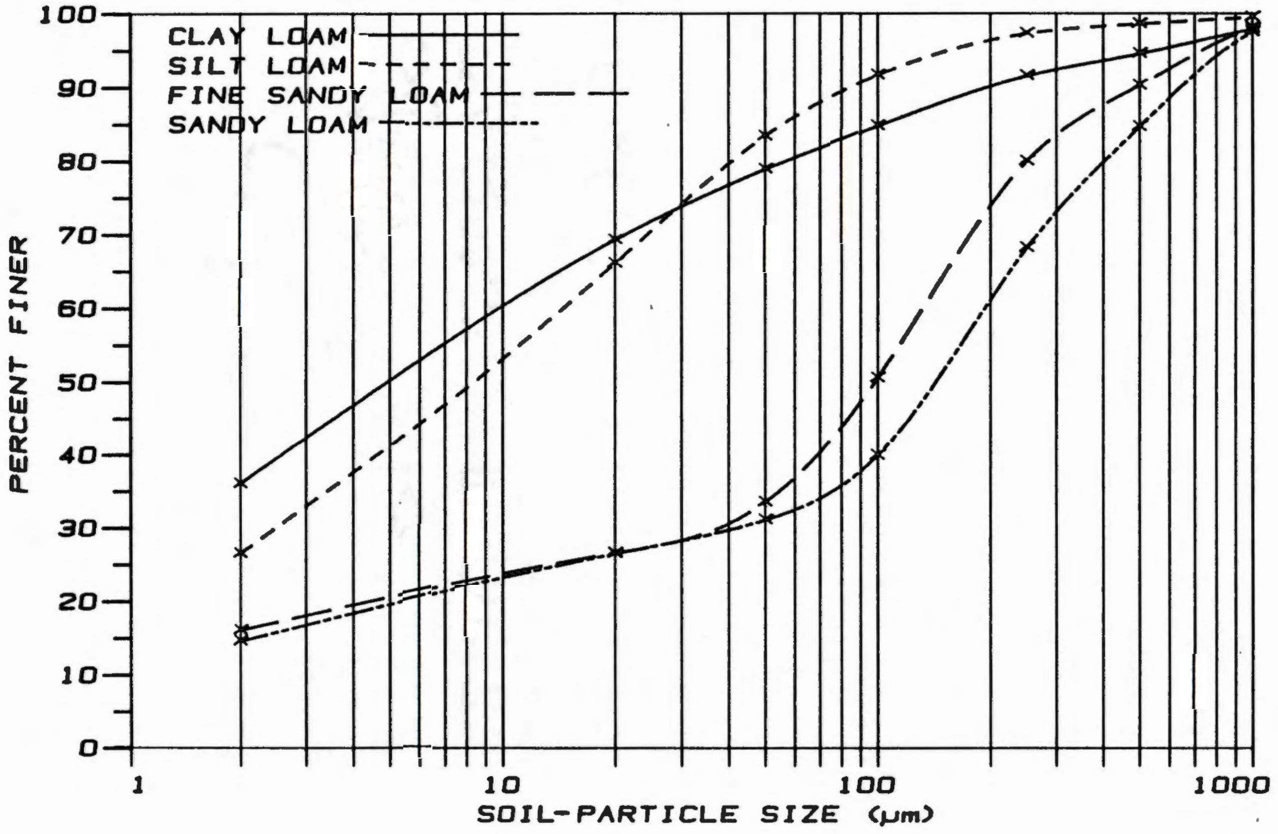
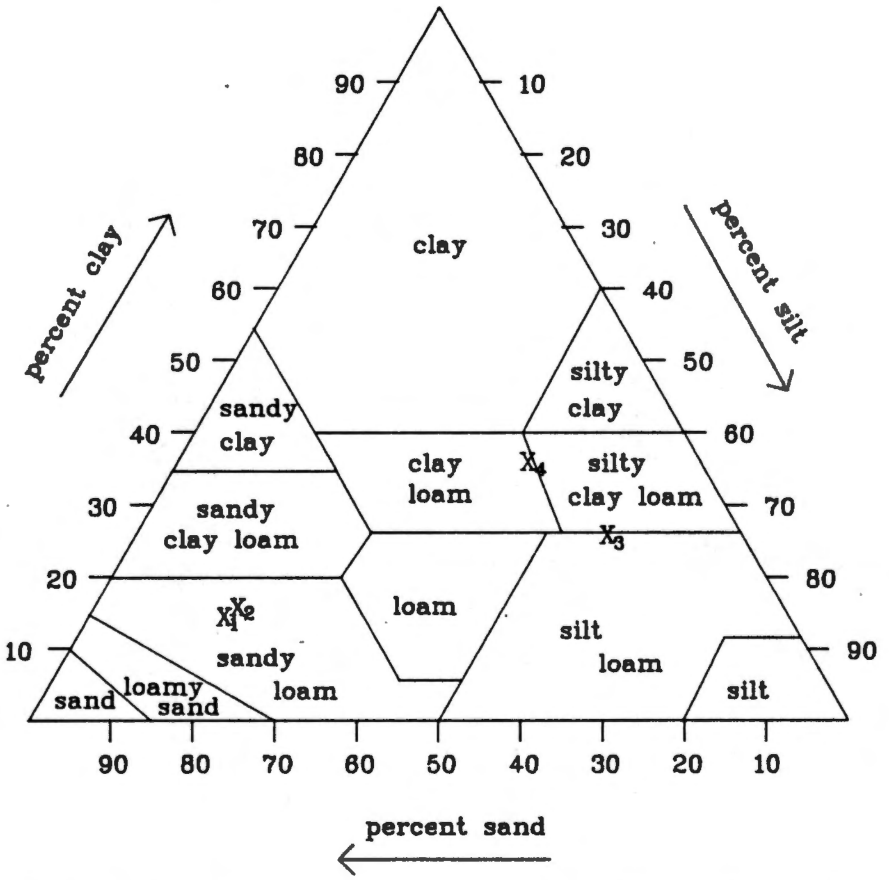


Figure 6. Particle size distributions for mineral portions of the four study soils.



X_1 = sandy loam

X_2 = fine sandy loam

X_3 = silt loam

X_4 = clay loam

Figure 7. Soil textural triangle showing the four study soils.(1)

(1) Based on the classifications in: Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4 In: Soil survey manual. U.S.D.A. Soil Conserv. Serv. Washington, D.C. pp. 51-56.

lines from the 16-percent points to the 84-percent points in Figure 6 (log-linear extrapolation was used to estimate d_{16} for the silt loam and clay loam). The values were not very different for the sandy loam, fine sandy loam, and clay loam. They were lower for the silt loam, due to its high concentration of silt-size particles.

The silt loam had less coarse material (sand) than the clay loam, even though it had a larger d_{50}. Only 8.3 percent of the particles in the silt loam had diameters greater than 100 μm, as opposed to 15.4 percent of the particles in the clay loam. That seemingly minor difference can be important. Wischmeier et al. (1971) reported that the relative erodibilities of two silty soils depended partly upon their associated sand-to-clay ratios.

The density of organic matter is less than that of the mineral portion of a soil. Therefore, the specific gravities shown in Table 5 vary inversely with the TOC values. The finer-textured loams had higher TOC values (hence contained more organic matter) than the coarser-textured loams.

The subangular blocky structure observed in the clay loam is more typical of subsoil than topsoil. The site from which the clay loam was removed was steeper than the other sites and was mapped as eroded (U.S.D.A. Soil Cons. Serv., 1959). Erosion was not an obvious problem at the site, even though it had not been cultivated for several months. However, the previous summer had been abnormally dry, so less erosion probably occurred than on an average year. The high clay content is also typical of subsoil, but the clay content was still higher under the plow layer, as the description in Appendix 1 shows.

Figure 8 shows the results of the saturated hydraulic-conductivity tests (adjusted to 20 °C). The classifications noted are from the Soil Survey Staff (1981). They are somewhat different than those in the previous edition (Soil Survey Staff, 1951) that Wischmeier et al. (1971) consulted for their nomograph. The points labeled P and D on the plots for each soil were at the overall-average (arithmetic-mean) bulk densities for the prewetted and dry tests, respectively.

The most unexpected results from the saturated hydraulic-conductivity tests were for the clay loam. A typical range for a clay loam is from 0.25 to 1.5 cm/h (Hansen et al., 1979). The major observation during the clay loam tests was the stability of the soil aggregates. The soil looked much the same dry and after soaking for 24 hours. That quality was noticeably different for the other soils, which appeared to lose their structures when saturated.

The saturated hydraulic conductivity of the silt loam did not appear to increase with decreases in bulk density below about 1 200 kg/m^3, as can be seen from the points in Figure 8. That appeared to be caused by settling, due to the aggregates not being water stable. Considerable settling was observed in the prewetted silt loam soil-loss tests. The structure appeared good when the soil was dry, but weakened when it was saturated. The test columns were packed dry and the bulk density was calculated, but the bulk density

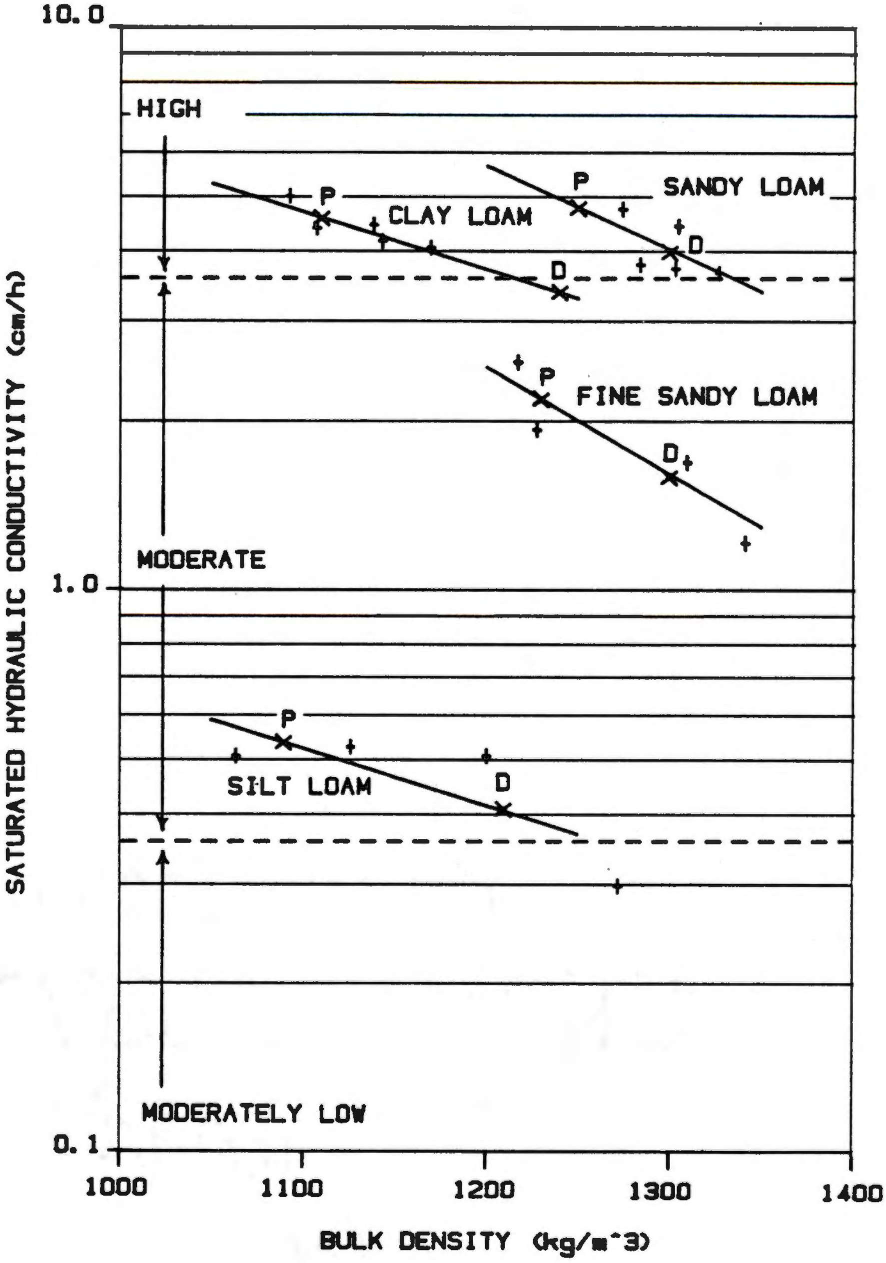


Figure 8. Saturated hydraulic conductivity versus bulk density for the four study soils.(1)

(1) Points labeled P and D were at the arithmetic-mean bulk densities for the prewetted and dry soil-loss tests, respectively. Hydraulic conductivity classes from: Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4 In: Soil survey manual. U.S.D.A. Soil Conserv. Serv. Washington, D.C. pp. 35-37.

of the soil during the tests, after saturating, was probably greater (same mass, less volume) than the dry value. It should be noted that more soil-loss tests were conducted with the silt loam than the other soils. During the early tests at the low intensity level of block 1, the aggregates appeared more stable, but the saturated hydraulic-conductivity tests were conducted after the soil-loss tests were completed.

Wischmeier et al. (1971) referred to the Soil Survey Manual (Soil Survey Staff, 1951) for assigning permeability classes to be used with their nomograph, with some additional guidelines of their own. However, those permeability rates were reported as "very tentatively suggested rates through saturated undisturbed cores under a 1/2-inch head of water" (Soil Survey Staff, 1951). Rates through undisturbed cores at a constant head that low would probably be different from the values in Figure 8, measured by the falling-head method (Liu and Evett, 1984). The revised Soil Survey Manual (Soil Survey Staff, 1981) uses classes based on saturated hydraulic conductivity, rather than permeability. Lacking a definite means to classify the permeabilities of the soils, the sandy loam, fine sandy loam, and clay loam were assigned to class 4 (slow to moderate) and the silt loam was assigned to class 5 (slow) to determine the K values reported in Table 5.

The M values were similar for the clay loam and fine sandy loam. The clay loam had a higher organic matter content (assuming the TOC to organic-matter ratio was similar for both soils), which suggests lower erodibility. However, the clay loam had subangular blocky structure, which suggests higher erodibility than the granular structure observed in the fine sandy loam. Based upon the K values in Table 5, the most erosion would be expected from the silt loam, followed by the clay loam and fine sandy loam. The least would be expected from the sandy loam.

Erosion Study

Table 6 contains the results of the laboratory soil-loss tests. As previously noted, moisture condition denotes a preparation procedure and not a specific moisture content. Randomization occurred in the order of intensity levels within a block and among tests within an intensity level within a block. After block 1 was completed, the number of subsamples was decreased from four to two. A more complete listing of results is included in Appendix 2.

The different numbers of subsamples within a block were due to some tests being disregarded because of problems experienced during the tests, usually settling of the soil at the lip of the pan. Those tests were repeated before the intensity level was changed. However, because the orders of those tests were not included in the randomization, their results were not included in Table 6 or the corresponding analyses.

As discussed previously, it was not possible to calculate a water balance for a test. The only information available concerning drainage through the soils was from observations made during and after a test. The only tests to consistently have drainage out of the bottom of the pans were those for the prewetted silt loam and those

Table 6. Results from soil-loss study.

Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Volume (m^3)	Soil Loss (kg)
1	5.2	Fine sandy loam	Dry	0.079	0.39
				0.073	0.45
				0.074	0.44
				0.057	0.28
			Prewetted	0.079	0.59
				0.068	0.47
				0.073	0.53
		Silt loam	Dry	0.040	0.16
				0.037	0.21
				0.030	0.18
				0.043	0.34
			Prewetted	0.009	0.05
				0.013	0.11
				0.034	0.35
	8.0	Fine sandy loam	Dry	0.126	2.21
				0.122	1.85
				0.119	1.61
				0.118	1.38
			Prewetted	0.118	1.77
				0.114	2.03
				0.106	1.42

Table 6. (Continued)

Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Volume (m^3)	Soil Loss (kg)
1	8.0	Silt loam	Dry	0.098	1.45
				0.087	1.85
				0.094	1.74
				0.094	1.80
			Prewetted	0.039	0.31
				0.051	0.60
				0.058	0.66
				0.051	0.49
2	5.2	Fine sandy loam	Dry	0.069	0.65
				0.069	0.55
			Prewetted	0.053	0.67
				0.068	0.70
		Clay loam	Dry	0.002	0.00(1)
				0.001	0.00
			Prewetted	0.000	0.00
				0.003	0.00
	8.0	Fine sandy loam	Dry	0.135	2.60
				0.112	2.46
			Prewetted	0.124	3.06
				0.134	2.31

Table 6. (Continued)

Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Volume (m^3)	Soil Loss (kg)
2	8.0	Clay loam	Dry	0.004	0.01
				0.002	0.01
			Prewetted	0.013	0.05
				0.003	0.02
3	5.2	Silt loam	Dry	0.048	0.80
				0.048	0.76
			Prewetted	0.020	0.19
				0.014	0.14
		Sandy loam	Dry	0.052	0.27
				0.053	0.29
			Prewetted	0.060	0.38
				0.055	0.47
	8.0	Silt loam	Dry	0.088	2.00
				0.088	2.15
			Prewetted	0.067	0.77
				0.060	0.56
		Sandy loam	Dry	0.094	0.68
				0.096	0.70

Table 6. (Continued)

Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Volume (m^3)	Soil Loss (kg)
3	8.0	Sandy loam	Prewetted	0.125	1.33
				0.116	1.17
4	5.2	Sandy loam	Dry	0.051	0.23
				0.038	0.15
			Prewetted	0.051	0.33
				0.034	0.25
		Clay loam	Dry	0.001	0.00
				0.000	0.00
			Prewetted	0.002	0.00
				0.000	0.00
	8.0	Sandy loam	Dry	0.082	1.11
				0.096	1.33
			Prewetted	0.115	1.02
				0.100	1.09
		Clay loam	Dry	0.004	0.02
			Prewetted	0.011	0.07
				0.006	0.04

(1) Samples shown with 0.00 kg soil loss had too little runoff to sample.

for both the dry and prewetted clay loams. Some of the prewetted fine sandy loams drained through. It was not possible to be sure whether flow out of the pan bottoms was overly restricted, but drainage probably should have been provided from the ends and sides also. Water could pond at the lip of the pan, even if it did not appear to flow over the surface of the soil.

Qualitative Factors

Analysis of variance (ANOVA) tests were conducted to investigate the independence of the effects of soil and rainfall, and possible effects or interactions involving moisture. Qualitative levels of intensity, soil type, and moisture condition were used, rather than quantitative measurements. All tests of significance were conducted at the 0.05 level, except for those regarding the pooling of sums of squares and degrees of freedom. The data shown in plots demonstrating significant interactions were least-square means obtained with the LSMEANS option of PROC GLM (SAS Institute Inc., 1985b). Least-square means were necessary to reduce the effect of unequal subsampling on the mean values. They were calculated with the model used to generate the sum of squares for the interaction significance test.

Runoff Volume. Although the experiment was designed to investigate soil loss rather than runoff volume, their interrelationship made it desirable to qualitatively investigate the runoff volume. One of the blocks (3) was significantly different from the other three, which suggests that something was not consistent throughout the study. It was not possible to determine what caused the inconsistency, and no apparent causes were observed during the study. However, the inconsistency must be considered in any application of the results of this study.

The effects on runoff volume of intensity, soil type, and moisture condition were all significant, as was expected. Moisture condition, which concerned more than just moisture content, affected runoff from the silt loam more than from the others. An increase in intensity affected runoff from the clay loam less than from the others. A detailed presentation of the runoff-volume analysis follows.

Table 7 contains the ANOVA for the runoff-volume data. The data appeared normally distributed with equal variances, so no transformations of the data were necessary.

The pooled block interaction (BISM) was not significant at the 0.05 level when tested against the within error (ε). However, it was significant at the 0.25 level, so the sums of squares were not pooled and BISM was used as the error term (denominator in an F statistic) for the block by intensity interaction (BI) test. BISM was not significant and block was assumed to be a fixed effect, which suggested testing all effects against the within error. However, since BISM was not poolable and some uncertainty was involved with the block effect, the more conservative choice of error term was made.

BI was assumed to contain the $w_{(ij)}$ restriction error, whereas BISM was assumed not to. Since the resulting test of BI was not significant at the 0.25 level, the restriction error due to running a

Table 7. Analysis of variance for runoff volume.

Source(1)	df	Type III Sum of Squares	F
Block (B)	3	0.00050	2.24
first restriction error (δ)	0		
Intensity (I)	1	0.02669	360(2)
Block*Intensity (BI)	3	0.00026	1.23(3)
second restriction error (w)	0		
Soil (S)	3	0.06790	305(2)
Intensity*Soil (IS)	3	0.00617	27.7(2)
Moisture Condition (M)	1	0.00037	5.02(2)
Intensity*Moisture Condition (IM)	1	0.00003	0.45
Soil*Moisture Condition (SM)	3	0.00497	22.3(2)
Intensity*Soil*Moisture Condition (ISM)	3	0.00071	3.19
Block*Intensity*Soil* Moisture Condition (BISM)	10	0.00070	1.42
Within (ε)	44	0.00219	
Total(4)	75	0.12685	
Pooled BISM and BI	13	0.00096	1.49

Table 7. (Continued)

Source(1)	df	Type III Sum of Squares	F
Contrasts			
$B_3=(B_1+B_2+B_4)/3$	1	0.00040	5.44(2)
IS without clay loam	2	0.00029	1.94
SM without silt loam	2	0.00046	3.10

(1) Parameters refer to Equation (11), page 52.

(2) Significant at 0.05 level.

(3) Not significant at 0.25 level when tested against BISM.

(4) Type III sums of squares do not necessarily sum to total sum of squares.

split-plot experiment was assumed negligible compared to the block interactions, and the interaction between block and intensity was assumed to be no different from the interactions among block and the other terms in the model. Therefore, the BI and BISM sums of squares and degrees of freedom were pooled, and the resulting mean square, block by all-other-terms interaction with 13 degrees of freedom, was used as the error term for all other tests shown in Table 7.

The values in Table 7 show that while the block main effect was not significant, a linear contrast demonstrated that block 3 was significantly different from the others with respect to runoff volume. Whether the significant effect was block 3 (B_3) or the first restriction error associated with block 3 ($\delta_{(3)}$) could not be determined. Only the combination of B and δ could be tested. Nothing was observed during the study to explain the differences among blocks, and nothing unique about block 3 was apparent from Table 6.

The significance of intensity, soil, and moisture condition was expected. Runoff was already known to be affected by them. Intensity only interacted significantly with soil, which was due to the lack of runoff from the clay loam. Figure 9 visually demonstrates the interaction by the lines for the two intensity levels not being parallel. Figure 9 and similar plots do not represent functional relationships, only a way to visualize an interaction. The spacing along the abscissa is arbitrary. Infiltration was both highest and most stable on the clay loam, so very little runoff was observed.

The significant soil by moisture condition interaction shown in Figure 10 was due to moisture condition affecting the silt loam more

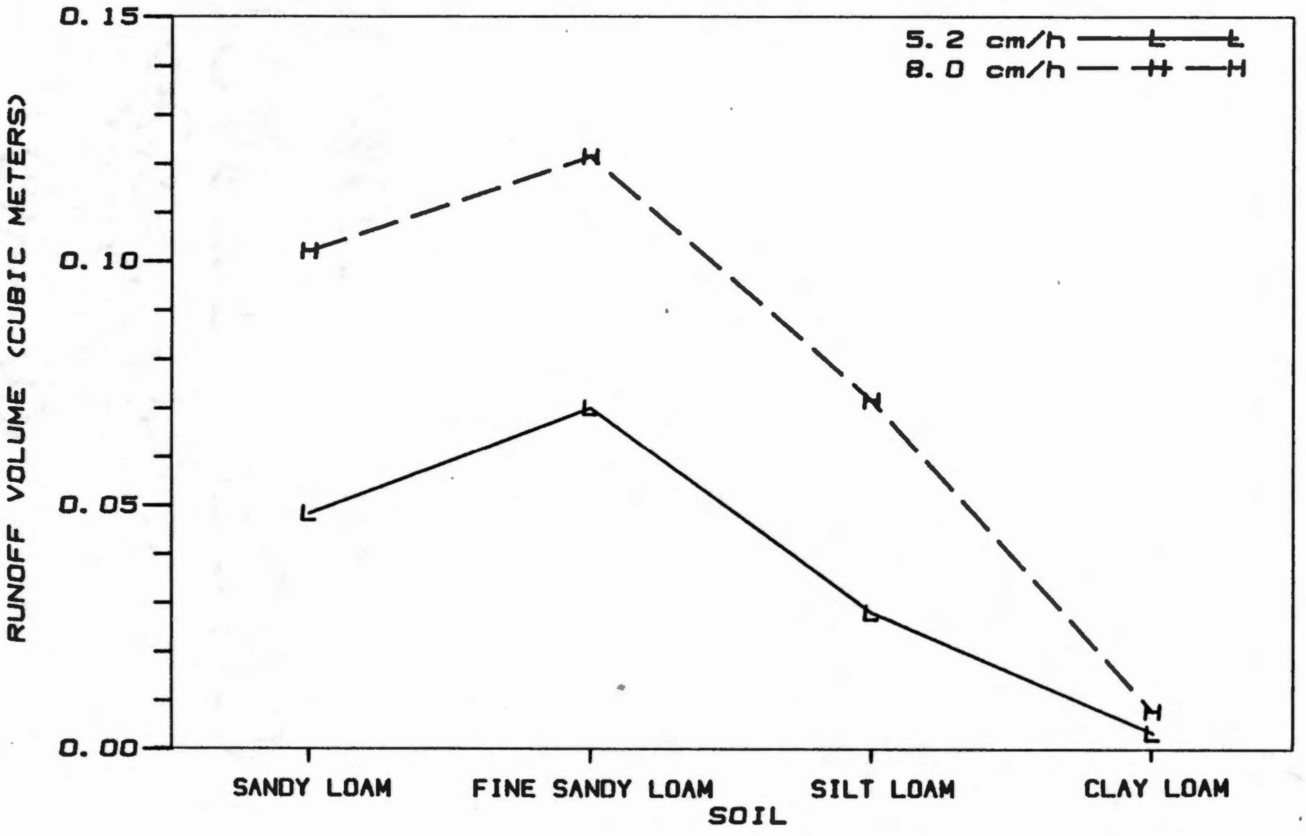


Figure 9. Intensity by soil interaction for runoff volume.

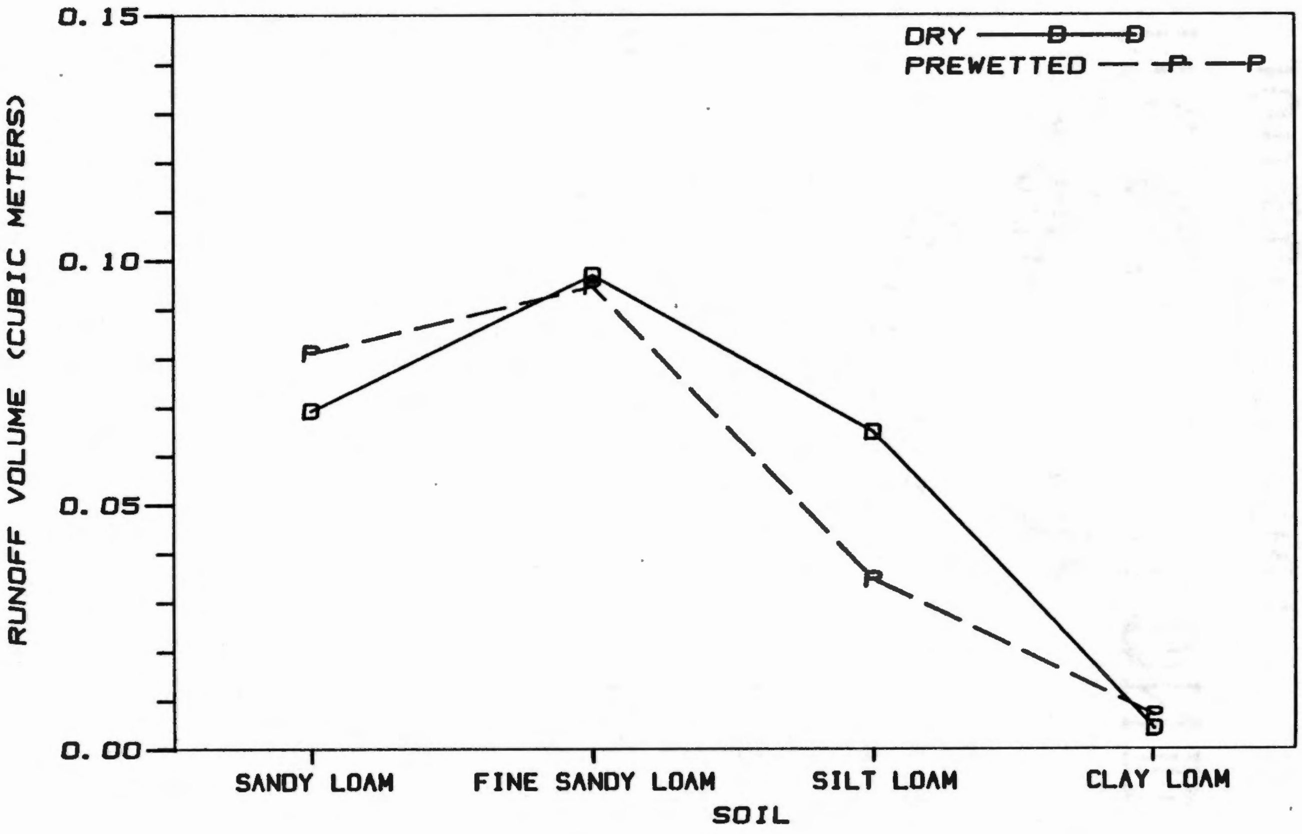


Figure 10. Soil by moisture condition interaction for runoff volume.

than the other soils. Less runoff was observed from prewetted silt loam than from dry, while the other soils showed relatively little variation. The wet silt loam formed clumps, and holes were left in the surface which greatly increased infiltration in the first part of the simulated storm. The appearances of the other soils changed less, even though they were treated the same. After the silt loam had settled somewhat, the runoff appeared about the same as in the dry case. If the duration of the tests had been different, the interaction may have been either more or less pronounced.

Soil Loss. As in the runoff-volume study, one of the four blocks (1) was significantly different from the other three with respect to soil loss. However, it was not the same block (block 3 was different for runoff volume). Block 1 was quite different from the others, although it could not be determined what was different about it. More subsamples were included and it took longer to complete than the other blocks. However, that was not expected to affect the results. There was also a longer time lapse between blocks 1 and 2 than any others. The block effect was probably due to soil properties changing throughout the study, but that could not be tested as a statistical hypothesis.

Soil loss from the clay loam was less affected by an increase in intensity than the losses from the other soils, similar to the effect observed in the runoff-volume study. Moisture condition affected soil loss from the silt loam more than from the other soils, which were affected very little. A more detailed presentation of the soil-loss analysis follows.

Table 8 contains the ANOVA for the soil-loss study. The variability of the soil-loss data appeared to increase with magnitude (the spatial variability of the storm intensity also increased with magnitude), so a square root transformation was used to stabilize the variances. The transformed soil-loss data appeared normally distributed with equal variances.

The pooled block interaction (BISM) was significant when tested against the within error (ε). Therefore, BISM was used as the error term to test the block by intensity interaction (BI). BI was not significant at approximately the 0.25 level, so the sums of squares and degrees of freedom for BI and BISM were pooled. The resulting mean square with 13 degrees of freedom was used as the error term for the other tests shown in Table 8. As in the runoff-volume study, the setup error associated with the simulator (restriction error $w_{(ij)}$) was assumed to be negligible, and the interaction between block and intensity did not appear different from the interactions among block and the other terms in the model.

The block effect was significant, with block 1 appearing quite different from the others. As discussed before, there is no way to know whether the significant effect was B_1, $\delta_{(1)}$, or both. Only their sum could be tested. However, it seemed odd that one block was significantly different from the others in both the runoff-volume and soil-loss studies, but it was not the same block.

Table 8. Analysis of variance for soil loss.(1)

Source(2)	df	Type III Sum of Squares	F
Block (B)	3	0.375	6.18(3)
first restriction error (δ)	0		
Intensity (I)	1	4.118	204(3)
Block*Intensity (BI)	3	0.087	1.64(4)
second restriction error (w)	0		
Soil (S)	3	7.501	123(3)
Intensity*Soil (IS)	3	0.681	11.2(3)
Moisture Condition (M)	1	0.049	2.44
Intensity*Moisture Condition (IM)	1	0.035	1.75
Soil*Moisture Condition (SM)	3	0.941	15.5(3)
Intensity*Soil* Moisture Condition (ISM)	3	0.156	2.58
Block*Intensity*Soil* Moisture Condition (BISM)	10	0.176	2.53(3)
Within (ε)	44	0.307	
Total(5)	75	16.658	
Pooled BISM and BI	13	0.263	2.90(3)

Table 8. (Continued)

Source(2)	df	Type III Sum of Squares	F
Contrasts			
$B_1=(B_2+B_3+B_4)/3$	1	0.332	16.4(3)
$B_2=B_3=B_4$	2	0.001	0.02
IS without clay loam	2	0.129	3.18
SM without silt loam	2	0.010	0.25

(1) Soil-loss variable is square root of observed soil loss.

(2) Parameters refer to Equation (11), page 52.

(3) Significant at 0.05 level.

(4) Not significant at approximately 0.25 level when tested against BISM.

(5) Type III sums of squares do not necessarily sum to total sum of squares.

In the first block, and particularly the first intensity level (5.2 cm/h), the silt loam was noticeably less erodible. The soils were expected to change very little as long as they were allowed to dry and were mixed before being reused. Each pile contained enough soil to fill the pans more than six times, but that may not have been enough. The prewetted silt loam was allowed to drain overnight before it was removed from the pans, but it was still very wet and dried in large clods. Although the clods were broken, the soil probably did not return to its original state.

Table 9 contains averages (arithmetic means) of moisture-content and bulk-density data from the soils during the tests. However, bulk-density data were not complete. Values for some of the tests were estimated from the incomplete data. The estimates appeared to agree well with the available data.

The stability of the aggregates appeared to decrease considerably with time for the silt loam. The dry soil looked much the same at any time after the large clods were broken or removed. However, as the data in Table 9 show, the moisture contents of the silt loams were higher in block 3 than block 1, even though the procedure was not intentionally changed during the study. The higher moisture contents were most noticeable for the prewetted soils. Apparently more of the water applied in prewetting was absorbed in the upper soil, whereas earlier more of it drained into the lower part. A similar effect was observed with the fine sandy loam (blocks 1 and 2), but it was less obvious. The other two soils did not appear in

Table 9. Average bulk densities and moisture contents.

Soil	Moisture Condition	Block	Bulk Density[1] (kg/m^3)	Moisture Content (%)
Sandy loam	Dry	3	1300	8
		4	1300	9
	Prewetted	3	1240	35
		4	1250	37
Fine sandy loam	Dry	1	1300	10
		2	1300	13
	Prewetted	1	1230	36
		2	1220	41
Silt loam	Dry	1	1230	14
		3	1180	17
	Prewetted	1	1090	42
		3	1080	51
Clay loam	Dry	2	1230	12
		4	1240	11
	Prewetted	2	1120	29
		4	1100	34

(1) Bulk-density data were incomplete. Values were estimated, based upon incomplete data.

block 1, so they were involved in fewer tests. The trend was less apparent for them.

An average difference in bulk density between blocks 1 and 3 of approximately 50 kg/m^3 was observed for the dry silt loam. No other soil exhibited as large a difference within a moisture-condition level. As stated previously, the bulk-density data were not complete. However, based on the available data, the bulk density within a moisture-condition level appeared stable, except for the dry silt loam. Raking the soil wet resulted in lower bulk densities than raking dry for all soils. Yet, only the silt loam showed such a decrease in bulk density for the dry condition, even though the increase in moisture content between two blocks was approximately the same for the fine sandy loam.

The intensity and soil main effects (overall averages) were expected to be highly significant, and they were. However, significant interactions were observed. Figure 11 shows the intensity by soil interaction. The contrast in Table 8 showed that the interaction was not significant if the clay loam was not considered (just as in the runoff-volume study), and that seems apparent in Figure 11 (the least-square mean estimate was slightly negative for the clay loam at low intensity). Since there was little runoff, little detached soil could be transported.

Figure 12 shows the soil by moisture interaction. The contrast in Table 8 showed that the interaction was not significant if the silt loam was not included, and that seems apparent in Figure 12. Both runoff volume and soil loss were lower for the prewetted silt loam

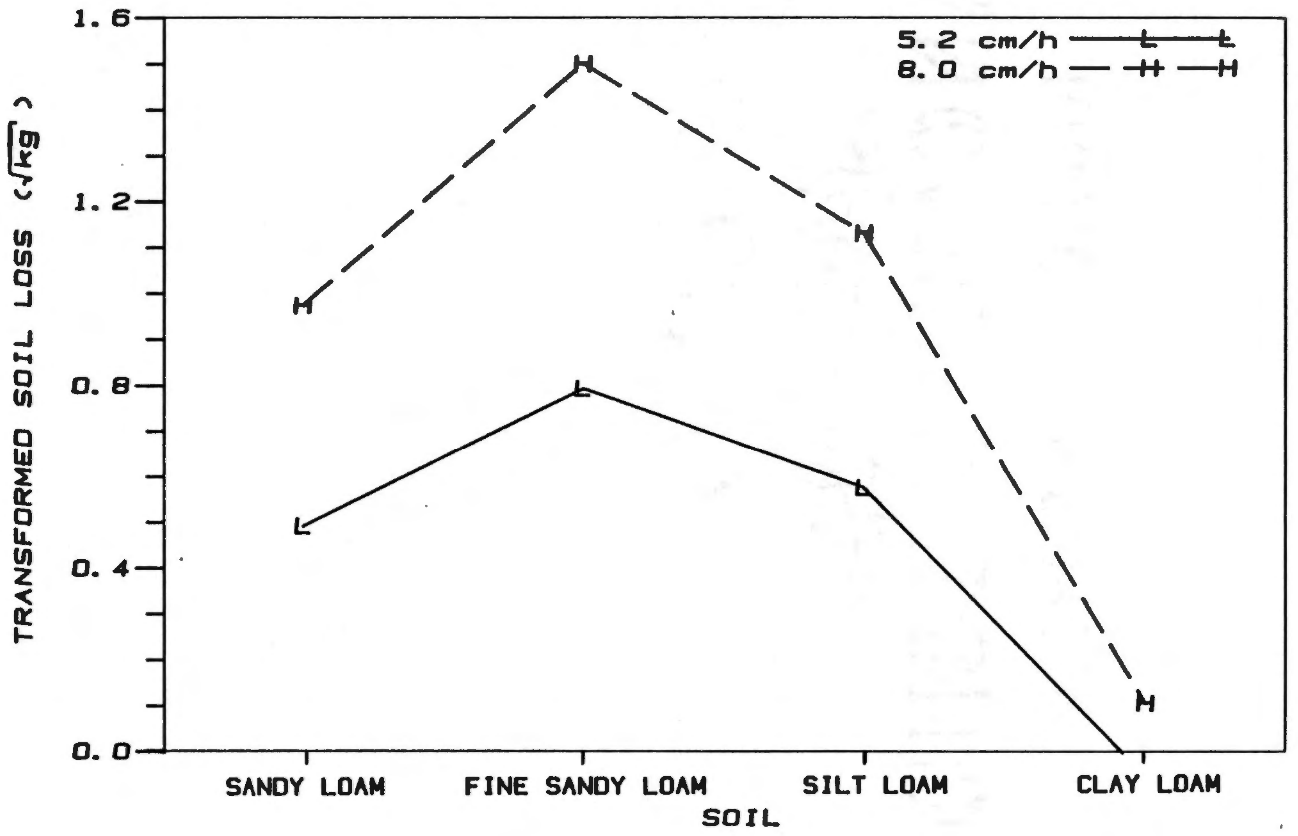


Figure 11. Intensity by soil interaction for soil loss.

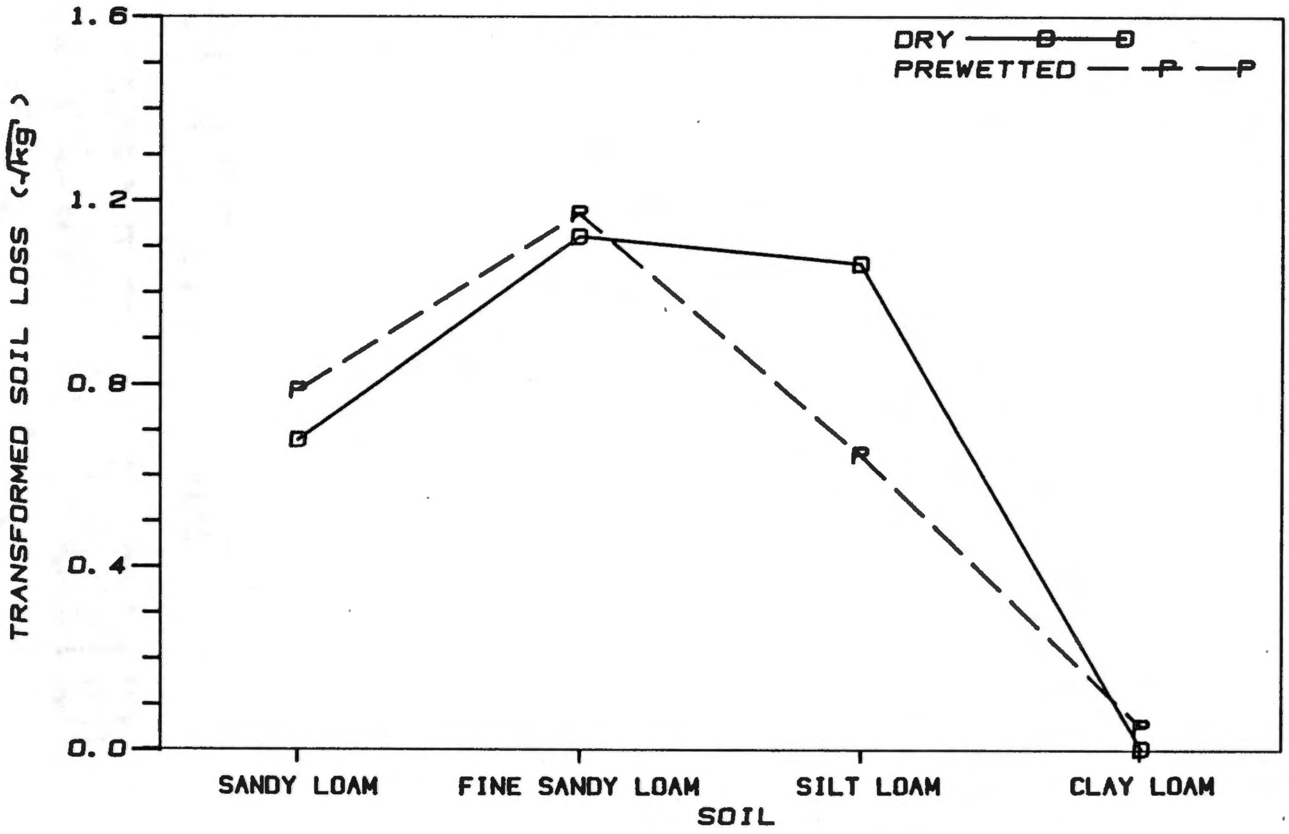


Figure 12. Soil by moisture condition interaction for soil loss.

than for the dry, although the concentration of solids in the runoff from the prewetted soil was greater.

The main effects (overall averages) for the sandy loam and silt loam, and their responses to intensity changes were similar. However, their responses to moisture-condition changes were quite different. The levels of moisture condition involved more than just moisture content. Bulk density was lower for the prewetted tests, and raking probably affected infiltration differently for the wet and dry soils.

Summary. One block significantly different from the other three was observed in both the runoff-volume and soil-loss studies, although not the same block (3 and 1, respectively) was different. The experimental design precluded distinguishing between any systematic and random block effects. It was also impossible to differentiate among factors that could have contributed to a systematic effect. The significant block effects were accounted for in the hypothesis tests of the ANOVA-model terms.

The silt loam was most affected by moisture condition with respect to both runoff volume and soil loss. However, observations made during the tests suggested that the duration of the tests (all tests were one hour) might influence the effect.

Quantitative Factors

Uncertainty about the mean values computed with an ANOVA model was indicated by the significant block effect. Furthermore, caution must be used when applying the findings of any study to situations other than those included in the tests. Only four soils were included in this study, and the properties of those soils may have changed during the study. However, a quantitative investigation may still indicate important trends.

Table 10 contains the least-square means calculated with SAS PROC GLM (SAS Institute Inc., 1985b) for the transformed soil-loss variable (square root of observed soil loss). The least-square means were used because of unequal numbers of subsamples throughout the experiment. Arithmetic means would allow block 1 to have too much influence on the mean values, because of its higher numbers of subsamples. However, since the least-square means are based on a prediction equation, it is possible to predict negative values (e.g., clay loam, low intensity) even though negative soil loss (soil gain) was impossible.

The least-square mean values in Table 10 were squared (negative values were taken as 0's) for average soil losses (kg) from the 2.0-m^2 area. Those values were adjusted to represent the unit-plot A values included in Table 10. An L factor of 0.3 was used (2.0-m length, 9-percent slope) and a value of 1 was assigned to the factors S, C, and P.

The soils in this study differed from the continuous-fallow plots defined by Wischmeier and Smith (1978) in that they had not been kept free of vegetation for two years, and contained some root material. Furthermore, Foster (1982) suggested that the USLE does not apply to slope lengths less than about five meters. Shorter lengths are less affected by rill erosion, although the effect of length

Table 10. Unit-plot A values from ANOVA means.(1)

Soil	Intensity (cm/h)	Moisture Condition	Mean transformed soil loss ($\sqrt{kg}$)	Unit plot A value (t/ha)
Sandy loam	5.2	Dry	0.43	3.14
		Prewetted	0.55	4.98
	8.0	Dry	0.92	14.06
		Prewetted	1.03	17.46
Fine sandy loam	5.2	Dry	0.75	9.38
		Prewetted	0.83	11.53
	8.0	Dry	1.49	36.91
		Prewetted	1.51	37.82
Silt loam	5.2	Dry	0.69	7.86
		Prewetted	0.46	3.54
	8.0	Dry	1.43	34.12
		Prewetted	0.83	11.37
Clay loam	5.2	Dry	-0.05(2)	0.00
		Prewetted	-0.05(2)	0.00
	8.0	Dry	0.06	0.06
		Prewetted	0.16	0.40

(1) From LSMEANS option of PROC GLM (SAS Institute Inc. 1985. SAS user's guide: statistics, version 5 edition. SAS Institute Inc., Cary, NC. pp. 433-506.).

(2) A negative value was predicted, even though impossible. Assumed 0 in calculation of A.

probably depends upon other factors as well. The soil losses observed in this study were expected to be less than USLE predictions.

The results of the Mazurak and Mosher (1968) study suggested that much more soil would be detached by splash from the fine sandy loam than from the clay loam. However, that was based only on soil-particle sizes, so the sandy loam and fine sandy loam would have very nearly the same amounts of soil detached, and the silt loam and clay loam would have very nearly the same amounts of soil detached. The Mazurak and Mosher (1968) findings indicated that the size fractions medium sand, fine sand, and very fine sand (particle diameters between 50 and 500 μm) are the least resistant to splash detachment. Soils with most of their particles in those size fractions (53.6 and 56.8 percent for the sandy loam and fine sandy loam, respectively) might be affected differently by the short slope length (2 m) than soils with fewer particles in those size fractions (15.2 and 15.7 percent for the silt loam and clay loam, respectively).

The USLE K values included in Table 11 were calculated using the USLE R values estimated with the GBPP. The regression method for relating A and R (Wischmeier, 1972) was employed to obtain the K values, with the intercept term omitted from the regression model (Foster, 1982). With only two values for R it was necessary to require the least-squares line to pass through the origin. The values included in Table 11 represent averages over the entire study. The dry values are probably more comparable to nomograph values. The proportion of storms associated with antecedent moisture contents as high as those in the prewetted tests is probably small.

Table 11. USLE K values from mean unit-plot A values.(1)

Soil	Moisture Condition	K Value (h/m^2)
Sandy loam	Dry	0.15
	Prewetted	0.19
Fine sandy loam	Dry	0.40
	Prewetted	0.42
Silt loam	Dry	0.37
	Prewetted	0.13
Clay loam	Dry	0.00
	Prewetted	0.00

(1) Based on calculated unit-plot A values in Table 10 and R values estimated from GBPP data.

The eight K values in Table 11 were compared to the parameters in Equation (7), page 29, with SAS PROC CORR (SAS Institute Inc., 1985a), and the resulting correlations are shown in Table 12. None of the observed correlations was significant, the highest being with TOC (-0.57) and saturated hydraulic conductivity (-0.55). Significance in this case refers to the test of the null hypothesis that the true correlation is 0. As in other tests, significance was tested at the 0.05 level. Although Wischmeier et al. (1971) found K to be highly correlated with M, the low correlation observed in this study was probably due to the atypical infiltration characteristics of the clay loam used in this study. The question of which diameter and variability terms to use in the dimensional analysis was not answered, since none of the possibilities was significantly correlated with K.

Table 12. Correlations of soil properties with K values.

Soil Property	Symbol(1)	Correlation with K(2)
Mass-mean diameter	d_{50}	0.38
Geometric-mean diameter	d_g	0.36
Geometric standard deviation	s_g	-0.22
M(3)	M	0.09
Specific gravity(4)	G	0.37
Bulk density	B	0.43
Water content	W	0.00
Saturated hydraulic conductivity	p	-0.55
Organic-carbon content	o	-0.57

(1) Symbols used in text.

(2) K values from Table 11.

(3) Texture parameter suggested by: Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Cons. 26(5):189-193.

(4) Organic matter included in soil.

The d_{50} was selected over the geometric-mean diameter because it represented the center of the PSD regardless of the shape of the curve, rather than the center of some idealized PSD. Table 13 shows correlations for π_2 through π_6 with π_1 from Equation (8), page 35. Both possibilities for π_2 and π_3 were included. Because of the importance of the M parameter in previous studies (Wischmeier et al., 1971; Roth et al., 1974) and its higher correlation to π_1 in this study, M was selected as the PSD variability term (π_2). However, fractions rather than percentages were used to calculate M, so that it ranged from 0 (100 percent clay - diameters less than 2 μm, or 100 percent fine sand or larger - diameters greater than 100 μm) to 1 (100 percent very fine sand and silt - diameters between 2 and 100 μm) rather than from 0 to 10 000. Similarly, because specific gravity is a well known expression for particle density and was highly correlated to π_1, it was selected for the particle density term (π_3). Three of the five independent pi-terms were significantly correlated with π_1; π_4 (moisture content) and π_6 were not.

The dependent pi-term (π_1) may be too highly influenced by particle size. While an interaction between saturated hydraulic conductivity and particle size may address infiltration, perhaps the d_{50} particle sizes vary over too wide of a range. Another length term, possibly a depth to a restrictive layer, may also interact with saturated hydraulic conductivity but overshadow K less. Such a depth term might also be more appropriate in π_6 (the term similar to a squared Froude number). However, the effect of depth was not investigated in this study.

Table 13. Correlations of pi-terms with π_1.(1)

Pi Term	Definition(2)	Correlation with π_1
π_1	Kpd	1.00
π_2	s_g	0.53
π_2	M	-0.75(3)
π_3	$\frac{D}{B}$	-0.53
π_3	G	0.85(3)
π_4	$\frac{W}{B}$	0.08
π_5	o	-0.88(3)
π_6	$\frac{p^2}{gd}$	-0.49

(1) The mass-mean diameter (d_{50}) was used for d in π_1 and π_6.

(2) Symbols used in text.

(3) Significant at 0.05 level.

The form of f_3 in Equation (9), page 35, was investigated. With only four soils, a narrow range of PSD's and organic contents, possible instability of soil properties during the study, and simulated storms that may not have closely approximated natural rainfall, the results may not be applicable to cases not included in this study. However, they may indicate trends to investigate in other studies.

In order to determine an equation, the independent pi-terms (π_2 through π_6), along with transformations and combinations of those pi-terms were investigated as predictor variables using SAS PROC STEPWISE (SAS Institute Inc., 1985b). Because of the wide range of values for π_1 (four orders of magnitude) the natural logarithm of π_1 was used as the dependent variable.

An equation which appeared to fit the test data ($r^2 = 0.96$) was the following:

$$\ln(\pi_1) = 7.584 + 4.516 \ln(\pi_2) \exp(\pi_5) - 10.06 \pi_5 \ln(\pi_2) \qquad (12)$$

where:

ln( ) = the natural logarithm of a value, and

exp( ) = the base of natural logarithms raised to a value.

Equation (12) is equivalent to the following:

$$\pi_1 = \frac{1970\, \pi_2^{4.52 \exp(\pi_5)}}{\pi_2^{10.1\, \pi_5}} \qquad (13)$$

or:

$$K = \frac{1970\ M^{4.52\ \exp(o)}}{p\ d\ M^{10.1\ o}} \qquad (14)$$

where:

K = USLE soil-erodibility term (h/m^2),

M = particle-size term (Wischmeier et al., 1971, calculated from fractions rather than percentages),

o = total organic carbon (percent),

p = saturated hydraulic conductivity (cm/h at 20 °C and observed bulk density), and

d = mass-mean diameter (d_{50}) (μm).

It must be noted that although the π's in Equations (12) and (13) were dimensionless, some had units (e.g., cm-$\mu m/m^2$ or 10^{-8} for π_1; percent for π_5).

Table 14 shows a comparison of K values calculated from the laboratory tests, from Equation (14), and the nomograph values included in Table 5, page 62. The values from Equation (14) agree fairly well with the values from the test data; however, it is necessary to investigate the performance for other data to determine the utility of the equation.

To study the effect of varying M on K values predicted with Equation (14), three new sets of soil properties (not corresponding to actual soil tests) were investigated. Those properties are given in Table 15. Since different M values could correspond to different

Table 14. Comparison of observed and predicted USLE K values.

Soil	Moisture Condition	USLE K Value (h/m^2)		
		Obs.(1)	Calc.(2)	Nom.(3)
Sandy loam	Dry	0.15	0.17	0.23
	Prewetted	0.19	0.14	
Fine sandy loam	Dry	0.40	0.63	0.30
	Prewetted	0.42	0.46	
Silt loam	Dry	0.37	0.18	0.41
	Prewetted	0.13	0.14	
Clay loam	Dry	0.00	0.00	0.34
	Prewetted	0.00	0.00	

(1) From Table 11.

(2) From Equation (14).

(3) From Table 5, page 62; value not dependent upon moisture condition.

Table 15. Properties of three soils.

USDA Textural Classification(1)	d_{50} (μm)	M(2)	Saturated Hydraulic Conductivity (cm/h)(3)
Silt loam	30	1.0	0.68
Sandy clay loam	30	0.390	1.3
Loam	30	0.182	0.43

(1) From Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4 In: Soil survey manual. U.S.D.A. Soil Conserv. Serv. Washington, D.C. pp. 52-57.

(2) Texture parameter presented by: Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Cons. 26(5):189-193. Table values calculated from fractions rather than percentages.

(3) Average value for given soil type from: Rawls, W. J., D. L. Brakensiek, and K. E. Saxton. 1982. Estimation of soil water properties. Trans., ASAE 25(5):1316-1320,1328.

values of d_{50} and saturated hydraulic conductivity, the d_{50} was held constant at 30 μm and a typical saturated hydraulic conductivity (Rawls et al., 1982) was assigned to the resulting soil. Figure 13 shows possible particle size distributions for the soils in Table 15. Each soil was assumed to be in the slow to moderate permeability class (4), have fine granular structure, and contain 1.2-percent organic carbon (2-percent organic matter). Table 16 contains K values for the three soils.

To study the effect of varying organic-matter content on K values predicted with Equation (14), the loam soil properties shown in Table 15 were investigated at 0-, 1-, 2-, 3-, and 4-percent organic matter (0-, 0.6-, 1.2-, 1.7-, and 2.3-percent organic carbon, respectively). The resulting K values are shown in Table 17.

The K values calculated with Equation (14) for the synthesized soil data appeared unreasonable, even though the conditions were not unreasonable. Tables 16 and 17 clearly showed that much more data are necessary to determine an equation which would be widely applicable. The unexpected response observed for the clay loam was one reason Equation (14) was not applicable to typical soils. A water-stable aggregates term might reduce the influence of TOC. However, such a term would not apply in this study. Only the clay loam had aggregates that were water stable, at least by the end of the study. An engineering property such as shear strength might also be useful.

Finally, K values were calculated from the soil-loss data for each block and the R values estimated from the GBPP data, with separate values calculated for dry and prewetted moisture conditions.

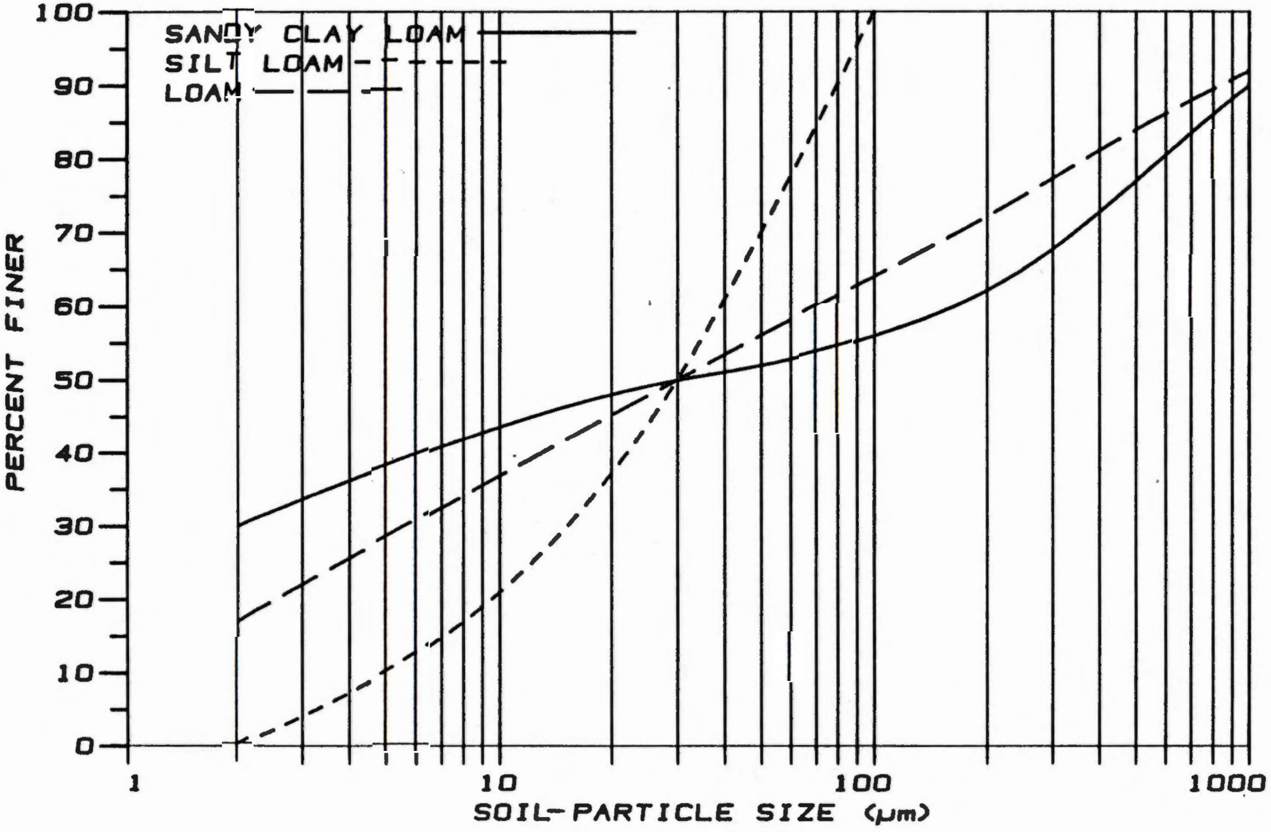


Figure 13. Three possible particle size distributions for a 30-µm d_{50}.

Table 16. K values for three soils at 2-percent organic matter.(1)

Soil	USLE K Value (h/m^2) Calculated(2)	USLE K Value (h/m^2) Nomograph(3)
Silt loam	96.6	0.89(4)
Loam	3.33	0.37
Sandy clay loam	1.12	0.19

(1) For soil properties included in Table 15 and 1.2-percent organic carbon (2-percent organic matter).

(2) From Equation (14).

(3) Converted to metric units from nomograph in Figure 1, page 18. Permeability class 4 (slow to moderate) and fine granular structure assumed for each soil.

(4) Extrapolated.

Table 17. K values for a typical loam soil and different organic-matter contents.(1)

Organic-Matter Content (%)	Organic-Carbon Content (%)	USLE K Value (h/m^2) Calc.(2)	USLE K Value (h/m^2) Nom.(3)
0	0	0.72	0.48
1	0.6	6.51	0.43
2	1.2	3.33	0.37
3	1.7	0.04	0.32
4	2.3	0.00	0.27

(1) For loam included in Table 15 and Figure 14, assuming organic matter contains 58-percent organic matter.

(2) From Equation (14).

(3) Converted to metric units from nomograph in Figure 1, page 18. Permeability class 4 (slow to moderate) and fine granular structure assumed.

Those values are included in Table 18. Data from all of the tests included in Appendix 2 were used, including tests omitted from the ANOVA studies. For every case except the prewetted sandy loam, the calculated K values within a moisture condition increased between the first and second blocks in which a soil appeared. Those values can also be compared to the nomograph values in Table 5, page 62, with the clay loam values the only ones greatly different.

Table 18. USLE K values from measured soil-loss values.

Soil	Moisture Condition	Block	K value (h/m^2)
Sandy loam	Dry	3	0.133
		4	0.215
	Prewetted	3	0.235
		4	0.194
Fine sandy loam	Dry	1	0.339
		2	0.459
	Prewetted	1	0.306
		2	0.490
Silt loam	Dry	1	0.298
		3	0.391
	Prewetted	1	0.093
		3	0.121
Clay loam	Dry	2	0.002
		4	0.002
	Prewetted	2	0.006
		4	0.009

VII. CONCLUSIONS AND RECOMMENDATIONS

Erodibility values based on the nomograph presented by Wischmeier et al. (1971) did not always agree with the erodibilities observed in this study. Since the nomograph values represent averages over many conditions and storms, they could not be expected to predict such specific atypical cases. Only two storm sizes and two antecedent moisture levels per soil were observed, with only one depth, slope, and set of surface dimensions. However, often the desired predictions of soil loss are for specific conditions and a particular storm or short time period, rather than long term.

If a method were available to accurately predict soil loss for specific conditions, values for longer time periods could be estimated from them. However, because of the narrow range of soil properties observed in this study and the possible instability of some of those properties, much more data would be necessary for such predictions. The results of this study can be used to indicate possible trends and compare with subsequent findings.

One important trend was the effect of strong structure, demonstrated by a higher hydraulic conductivity than expected for a clay loam. While two soils (sandy loam and clay loam) had approximately the same hydraulic conductivities, there was much more runoff (and therefore soil loss) from the sandy loam. The sandy loam had granular structure, which is desirable, but quickly lost it with raindrop impact. Small aggregates were observed that had splashed off of the clay loam during tests, but had stayed together as aggregates.

One of the principle differences between the expected (from the Wischmeier et al. (1971) nomograph) and observed erodibilities was the effect of the subangular blocky structure in the clay loam. The large water-stable aggregates allowed almost all of the water that struck the surface to enter the soil, rather than becoming runoff and transporting soil. The other three loams had granular structures, which were expected to be more favorable to lower erodibilities, but their structures were weaker and the aggregates disappeared more quickly after being saturated and impacted by water drops.

The results of this study indicated that structure should be addressed, probably more strongly than in the nomograph (Wischmeier et al., 1971). Possible approaches include a fraction of water-stable aggregates (Luk, 1979), specific portions of TOC content (Chesters et al., 1957; Romkens et al., 1977), or chemical compounds in the clay fraction (Roth et al., 1974, Trott and Singer, 1983).

The significant interactions observed among intensity and soil and among soil and moisture condition underscore the need to test soils under a variety of storms and at a variety of antecedent moisture contents to obtain useful long term average values of erodibility. Each soil interacts somewhat differently with storm size and antecedent moisture, and the same is probably true of slope steepness and length and other factors.

It may not be possible to reuse soils to the extent they were reused in this study. Working with the soils while they were saturated appeared to affect them such that they did not return to their original conditions, particularly the silt loam. However, similar problems were not reported by other researchers. The silt loam was the most tested soil, and it is impossible to know definitely whether it was most affected because it was most sensitive, because it was most worked, or both. Although plots in the field would not normally be disturbed as much as the soil was disturbed in this study (i.e., saturated soils could dry in situ before being worked again), repeated use of the same plots may affect the soil more than expected.

Although the findings of this study were less definite than was hoped, the research objectives were met. The laboratory tests were conducted as planned, although a better means of controlling the soil properties or recognizing the amounts of changes in those properties would have been helpful. The observed soil losses were related to the test conditions and soil properties. However, the properties measured for the soils may not have been representative of the entire study. The relationship among the dimensionless quantities would include any errors corresponding to the soil properties.

Finally, comparing more data from other researchers would have been worthwhile, but such data were not available for all of the properties needed. Although the data from this study were insufficient to determine a widely applicable soil-erodibility relationship, the research methods proposed still hold promise for future work.

LIST OF REFERENCES

American Society of Agricultural Engineers. 1984. ASAE Standards 1984. ASAE. St. Joseph, MI. pp. 46-53.

Anderson, V. L. and R. A. McLean. 1974. Design of experiments: a realistic approach. Marcel Dekker, Inc. New York, NY. 418 pp.

Barnett, A. P. and J. S. Rogers. 1966. Soil physical properties related to runoff and erosion from artificial rainfall. Trans., ASAE 9(1):123-125,128.

Bates, C. G. 1924. The erosion problem: erosion is the cause of many calamities. J. Forestry 22(5):498-505.

Bennett, H. H. 1939. Soil conservation. McGraw-Hill Book Company, Inc., New York, NY. 993 pp.

Bennett, H. H. and W. R. Chapline. 1928. Soil erosion: a national menace. USDA Circ. No. 33. U.S. Gov. Printing Off. Washington, D.C. 36 pp.

Bubenzer, G. D. and B. A. Jones. 1971. Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Trans., ASAE 14(4):625-628.

Carter, C. E., J. D. Greer, H. J. Braud, and J. M. Floyd. 1974. Raindrop characteristics in South Central United States. Trans., ASAE 17(6):1033-1037.

Chesters, G., O. J. Attoe, and O. N. Allen. 1957. Soil aggregation in relation to various soil constituents. Soil Sci. Soc. Am. Proc. 21(3):272-277.

Chow, V. T. 1959. Open-channel hydraulics. McGraw-Hill Book Company, Inc., New York, NY. pp. 98,99.

Christiansen, J. E. 1942. Irrigation by sprinkling. California Agr. Exp. Sta. Res. Bul. 670. Univ. of California, Berkeley, CA. p. 94.

Farrell, D. A. , W. C. Moldenhauser, and W. E. Larson. 1974. Splash correction factors for soil erosion studies. Soil Sci. Soc. Am. Proc. 38(3):510-514.

Foster, G. R. 1982. Relation of USLE factors to erosion on rangeland. Agr. Rev. and Man. ARM-W-26. U.S.D.A. Agr. Res. Service (Western Region), Oakland, CA. pp.17-35.

Foster, G. R. and W. H. Wischmeier. 1974. Evaluating irregular slopes for soil loss prediction. Trans., ASAE 17(2):305-309.

Foster, G. R., L. D. Meyer, and C. A. Onstad. 1977. An erosion equation derived from basic erosion principles. Trans., ASAE 20(4):678-682.

Free, G. R. 1960a. Erosion characteristics of rainfall. Agr. Engr. 41(7):447-449,455.

Free, G. R. 1960b. Research tells how much soil we can afford to lose. Crops and Soils 12(8):21.

Hansen, V. E., O. W. Israelson, and G. E. Stringham. 1979. Irrigation principles and practices, fourth edition. John Wiley & Sons, New York, NY. 417 pp.

Isaacson, E. de St Q., and M. de St Q. Isaacson. 1975. Dimensional methods in engineering and physics. John Wiley & Sons, New York, NY. 220 pp.

Jackson, M. L. 1958. Soil chemical analysis. Prentice-Hall, Inc., Englewood Cliffs, NJ. 498 pp.

Kinnell, P. I. 1974. Splash erosion: some observations on the splash-cup technique. Soil Sci. Soc. Am. Proc. 38(4):657-660.

Knisel, W. G., editor. 1980. CREAMS: a field scale model for chemicals, runoff, and erosion from agricultural management systems. U.S.D.A. Cons. Res. Rep. No. 26, USDA-SEA-AR, Tuscon AZ. 643 pp.

Kohl, R. A., R. D. von Bernuth, and G. Huebner. 1985. Technical Note: Drop size distribution measurement problems using a laser unit. Trans., ASAE 28(1):190-192.

Komura, S. 1976. Hydraulics of slope erosion by overland flow. J. Hyd. Div., ASCE 102(HY10):1573-1586.

Laflen, J. M. 1982. Special problems of the USLE: soil erodibility (K). Agr. Rev. and Man. ARM-W-26. U.S.D.A. Agr. Res. Service (Western Region), Oakland, CA. pp.63-72.

Laws, J. O. and D. A. Parsons. 1943. The relation of raindrop-size to intensity. Trans., Am. Geophys. Un. 24:452-460.

Lindstrom, M. J. and W. B. Voorhees. 1980. Planting wheel traffic effects on interrow runoff and infiltration. Soil Sci. Soc. Am. J. 44(1):84-88.

Liu, C. and J. B. Evett. 1984. Soil properties: testing, measurement, and evaluation. Prentice-Hall, Inc., Englewood Cliffs, NJ. pp. 15-25, 183-196.

Luk, S. H. 1979. Effect of soil properties on erosion by wash and splash. Earth Surface Processes 4(3):241-255.

Mazurak, A. P. and P. N. Mosher. 1968. Detachment of soil particles in simulated rainfall. Soil Sci. Soc. Am. Proc. 32(5):716-719.

Mazurak, A. P. and P. N. Mosher. 1970. Detachment of soil aggregates by simulated rainfall. Soil Sci. Soc. Am. Proc. 34(5):798-800.

Mech, S. J. 1965. Limitations of simulated rainfall as a research tool. Trans., ASAE 8(1):66,75.

Meyer, L. D. 1965. Simulation of rainfall for soil erosion research. Trans., ASAE 8(1):63-65.

Meyer, L. D. 1982. Soil erosion research leading to development of the universal soil loss equation. Agr. Rev. and Man. ARM-W-26. U.S.D.A. Agr. Res. Service (Western Region), Oakland, CA. pp.1-16.

Meyer, L. D. and W. C. Harmon. 1984. Susceptibility of agricultural soils to interrill erosion. Soil Sci. Soc. Am. J. 48(5):1152-1157.

Meyer, L. D. and W. H. Wischmeier. 1969. Mathematical simulation of the process of soil erosion by water. Trans., ASAE 12(6):754-758,762.

Mohammed, D. and R. A. Kohl. 1986. Infiltration response to kinetic energy. ASAE Paper No. 86-2106. ASAE, St. Joseph MI.

Mosley, M. P. 1974. Experimental study of rill erosion. Trans., ASAE 17(5):909-913,916.

Musgrave, G. W. 1947. The quantitative evaluation of factors in water erosion-a first approximation. J. Soil and Water Cons. 2(3):133-138,170.

Nicholson, J. H. and J. E. Snyder. 1939. Manual for soil erosion control in the Tennessee Valley: engineering phase. Tenn. Valley Auth. 128 pp.

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(5):590-592.

Park, S. W., J. K. Mitchell, and G. D. Bubenzer. 1982. Splash erosion modeling: physical analyses. Trans., ASAE 25(2):357-361.

Park, S. W., J. K. Mitchell, and G. D. Bubenzer. 1983. Rainfall characteristics and their relation to splash erosion. Trans., ASAE 26(3)795-804.

Quimpo, R. G. and A. B. Brohi. 1986. On the frequency distribution of raindrop sizes. J. Irr. and Drain. Engr. 112(2):119-129.

Ramser, C. E. 1917. Prevention of the erosion of farm lands by terracing. USDA Bull. No. 512. U.S. Gov. Printing Off. Washington, D.C. 40 pp.

Rangeley, W. R. 1986. Global water issues. Civil Engr. 56(12):60-62.

Rawls, W. J. 1983. Estimating soil bulk density from particle size analysis and organic matter content. Soil Sci. 135(2):123-125.

Rawls, W. J., D. L. Brakensiek, and K. E. Saxton. 1982. Estimation of soil water properties. Trans., ASAE 25(5):1316-1320,1328.

Romkens, 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(5):954-960.

Rose, C. W., J. R. Williams, G. C. Sander, and D. A. Barry. 1983. A mathematical model of soil erosion and deposition processes: I. theory for a plane land element. Soil Sci. Soc. Am. J. 47(5):991-995.

Roth, C. B., D. W. Nelson and M. J. M. Romkens. 1974. Prediction of subsoil erodibility using chemical, mineralogical and physical parameters. EPA-660/2-74-043. U.S. E.P.A., Washington, D.C.

Rowlison, D. L. and G. L. Martin. 1971. Rational model describing slope erosion. J. Irr. and Drain. Div., ASCE 97(IR1):39-50.

SAS Institute Inc. 1985a. SAS user's guide: basics, version 5 edition. SAS Institute Inc., Cary, NC. 1290 pp.

SAS Institute Inc. 1985b. SAS user's guide: statistics, version 5 edition. SAS Institute Inc., Cary, NC. 956 pp.

Schwab, G. O., R. K. Frevert, T. W. Edminster, and K. K. Barnes. 1966. Soil and water conservation engineering, second edition. John Wiley & Sons, Inc., New York, NY. p. 181.

Shelton, C. H., R. D. von Bernuth, and S. P. Rajbhandari. 1985. A continous-application rainfall simulator. Trans., ASAE 28(4):1115-1119.

Smith, D. D. and D. M. Whitt. 1948. Evaluating soil losses from field areas. Agr. Engr. 29(9):394-396,398.

Smith, D. D. and W. H. Wischmeier. 1957. Factors affecting sheet and rill erosion. Trans. Am. Geophys. Un. 38(6):889-896.

Smith, R. M. and W. L. Stamey. 1965. Determining the range of tolerable erosion. Soil Sci. 100(6):414-424.

Soil Survey Staff. 1951. Soil survey manual. Agr. Handbook No. 18. U.S. Gov. Printing Off. Washington, D.C. 503 pp.

Soil Survey Staff. 1981. Examination and description of soils in the field. Chapter 4 In: Soil survey manual. U.S.D.A. Soil Conserv. Serv. Washington, D.C. 107 pp.

Stamey, W. L. and R. M. Smith. 1964. A conservation definition of erosion tolerance. Soil Sci. 97(3):183-186.

Steichen, J. M. 1984. Infiltration and random roughness of a tilled and untilled claypan soil. Soil Tillage Res. 4:251-262.

Thompson, A. L. and L. G. James. 1985. Water droplet impact and its effect on infiltration. Trans., ASAE 28(5):1506-1510,1520.

Trott, K. E. and M. J. Singer. 1983. Relative erodibility of 20 California range and forest soils. Soil Sci. Soc. Am. J. 47(4):753-759.

University of Kentucky. date unknown. Design manual for the SEDIMOT II hydrology and sedimentology model. Univ. of Kentucky - College of Agric., Dept. of Agric. Engr. Lexington, KY.

U.S.D.A. Forest Service. 1936. Handbook of erosion control engineering on the national forests. U.S. Government Printing Off. Washington, D.C. 90 pp.

U.S.D.A. Soil Conservation Service. 1955. Soil survey: Knox County, Tennessee. U.S. Gov. Printing Off. Washington, D.C.

U.S.D.A. Soil Conservation Service. 1959. Soil survey: Blount County, Tennessee. U.S. Gov. Printing Off. Washington, D.C.

U.S.D.A. Soil Conservation Service. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. Soil Survey Inv. Rep. No. 1. U.S. Gov. Printing Off. Washington, D.C.

Van Doren, C. A. and L. J. Bartelli. 1956. A method of forecasting soil loss. Agr. Engr. 37(5):335-341.

Vanoni, V. A., editor. 1975. Sedimentation engineering. ASCE Man. and Rep. on Engr. Prac. No. 54., Reprinted 1977. ASCE. New York, NY. 745 pp.

Wilkerson, J. B., R. D. von Bernuth, L. R. Wilhelm, and F. D. Tompkins. 1985. Microcomputer interface for measurement of water droplets. Proceedings of Agri-Mation I Conference. ASAE Publication 01-85. ASAE. St. Joseph, MI. pp. 239-244.

Wischmeier, W. H. 1959. A rainfall erosion index for a universal soil-loss equation. Soil Sci. Soc. Am. Proc. 23(3):246-249.

Wischmeier, W. H. 1960. Cropping-management factor evaluations for a universal soil-loss equation. Soil Sci. Soc. Am. Proc. 24(4):322-326.

Wischmeier, W. H. 1972. Upslope erosion analysis. Chapter 15 In: Environmental impact on rivers (river mechanics III). H. W. Shen, Publisher. Colorado State Univ., Fort Collins, CO. 26 pp.

Wischmeier, W. H. 1976. Use and misuse of the universal soil loss equation. J. Soil and Water Cons. 31(1):5-9.

Wischmeier, W. H. and J. V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Sci. Soc. Am. Proc. 33(1):131-137.

Wischmeier, W. H. and D. D. Smith. 1958. Rainfall energy and its relationship to soil loss. Trans., Am. Geophys. Un. 39(2):285-291.

Wischmeier, W. H. and D. D. Smith. 1960. A universal soil-loss equation to guide conservation farm planning. Trans., 7th Int. Congress of Soil Sci., Madison, Wisc. pp. 418-425.

Wischmeier, W. H. and D. D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the rocky mountains, guide for selection of practices for soil and water conservation. U.S.D.A. Agr. Handbook No. 282. U.S. Gov. Printing Off. Washington, D.C. 47 pp.

Wischmeier, W. H. and D. D. Smith. 1978. Predicting rainfall erosion losses, a guide to conservation planning. U.S.D.A. Agr. Handbook No. 537. U.S. Gov. Printing Off. Washington, D.C. 58 pp.

Wischmeier, W. H., C. B. Johnson, and B. V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil and Water Cons. 26(5):189-193.

Wischmeier, W. H., D. D. Smith, and R. E. Uhland. 1958. Evaluation of factors in the soil-loss equation. Agr. Engr. 39(8):458-462,474.

Woodburn, R. 1948. The effect of structural condition on soil detachment by raindrop action. Agr. Engr. 29(4):154-156.

Zingg, A. W. 1940. Degree and length of land slope as it affects soil loss in runoff. Agr. Engr. 21(2):59-64.

APPENDIXES

APPENDIX 1

EXCERPTS FROM SOIL DESCRIPTIONS

The following material is part of descriptions from soil pits located near the sites from which the study soils were obtained. The study soils were scraped off of the top (approximately 15 cm) of the sites. Soils are variable, so the area scraped for the study soil may not be exactly like the corresponding description.

In each case the study soil corresponding to the description is noted at the top of the page (the classifications of the study soils were based upon laboratory analyses, while the classifications given in the descriptions were based on the judgment of the persons making the descriptions). The notation in the descriptions follows the recommendations of the Soil Survey Staff (1981).

Each soil was from a udic moisture regime. Three of the four described soils (corresponding to the fine sandy loam, silt loam, and clay loam) were well drained with no water table observed. The described soil corresponding to the sandy loam was moderately well drained and flooded.

Sandy Loam

Classification: coarse-loamy, thermic Ochreptic Udifluvent

Parent Material: alluvium from mixed-noncalcareous and sedimentary

Diagnostic Horizons: 0 to 14 cm ochric

Described By: Jenkins and Vories

Date: 10-06-86

Ap -- 0 to 14 cm; dark yellowish brown (10YR 4/4) loamy sand; weak fine granular structure; very friable; many fine roots throughout; many fine and medium interstitial and tubular pores; 3 % gravel; clear smooth boundary.

Bw -- 14 to 43 cm; dark brown (10YR 4/3) sandy loam; weak medium subangular blocky structure; friable; few to common fine roots between peds; many fine and medium interstitial and tubular pores; 3 % gravel; beginnings of structure, some clay; fine stratification; clear smooth boundary.

C1 -- 43 to 90 cm; dark yellowish brown (10YR 4/4) sandy loam; medium massive structure; very friable; few fine 5 mm faint yellowish brown (10YR 5/4) mottles; very few fine roots throughout; many fine and medium interstitial and tubular pores; 3 % gravel; soft massive mottles; fine stratification; clear wavy boundary.

C2 -- 90 to 120 cm; dark yellowish brown (10YR 4/4); black (2.5Y 2/0) loam; medium massive structure; very friable; many fine 5 mm faint yellowish brown (10YR 5/4) mottles; very few fine roots throughout; many fine and medium interstitial and tubular pores; 3 % gravel; soft massive mottles; manganese nodules; fine stratification; clear wavy boundary.

C3 -- 120 cm; dark yellowish brown (10YR 4/4); black (2.5Y 2/0) silt loam; medium massive structure; very friable; many fine 5 mm faint dark yellowish brown (10YR 4/4) mottles; very few fine roots throughout; many fine and medium interstitial and tubular pores; 3 % gravel; soft massive mottles; manganese nodules; fine stratification.

Fine Sandy Loam

Classification: coarse-loamy, mixed, thermic Ochreptic Hapludalf

Parent Material: alluvium from mixed-metamorphic and sedimentary

Diagnostic Horizons: 0 to 12 cm ochric; 12 to 73 cm argillic

Described By: Jenkins and Lambert

Date: 06-18-86

Ap -- 0 to 12 cm; dark yellowish brown (10YR 4/4) sandy loam; weak fine granular structure; friable; common very fine and fine roots throughout; few to common micro and fine interstitial and tubular pores; abrupt smooth boundary.

Bt1 -- 12 to 41 cm; dark brown (7.5YR 4/4); strong brown (7.5YR 4/6) sandy loam; weak fine and medium subangular blocky structure; friable; few discontinuous faint dark brown (7.5YR 4/4) clay films on faces of peds; very few micro and fine roots between peds; few to common micro and fine interstitial and tubular pores; clear wavy boundary.

Bt2 -- 41 to 73 cm; dark brown (7.5YR 4/4); strong brown (7.5YR 4/6) sandy loam; weak fine and medium subangular blocky structure; friable; common medium 5-15 mm faint yellowish brown (10YR 5/6) mottles; common discontinuous distinct dark brown (7.5YR 4/4) clay films on faces of peds; very few micro roots between peds; few to common micro and fine interstitial and tubular pores; abrupt smooth boundary.

2Bw -- 73 to 92 cm; dark brown (7.5YR 4/4); strong brown (7.5YR 5/6) loamy fine sand; weak fine subangular blocky structure; very friable; few fine 5 mm faint yellowish brown (10YR 5/4) mottles; few discontinuous faint dark brown (7.5YR 4/4) clay films on faces of peds; very few micro roots between peds; common fine and medium interstitial and tubular pores; clear wavy boundary.

2Bt -- 92 cm; dark brown (7.5YR 3/4); strong brown (7.5YR 4/6) sandy loam; weak fine subangular blocky structure; friable; common medium 5-15 mm faint yellowish brown (10YR 5/4) mottles; few discontinuous faint dark brown (7.5YR 3/4) clay films on faces of peds; very few micro roots between peds; few to common micro and fine interstitial and tubular pores.

Silt Loam

Classification: fine-loamy, mixed, thermic Typic Argiudoll

Parent Material: alluvium from mixed-metamorphic and sedimentary

Diagnostic Horizons: 0 to 30 cm molic; 30 to 100 cm argillic

Described By: Lambert and Jenkins

Date: 06-17-86

Ap -- 0 to 10 cm; dark brown (10YR 3/3) loam; moderate fine granular structure; friable; few micro and fine roots throughout; few micro interstitial and tubular pores; abrupt smooth boundary.

AB -- 10 to 30 cm; dark brown (10YR 3/3) loam; weak fine subangular blocky structure; friable; few micro and fine roots throughout; few micro interstitial and tubular pores; clear wavy boundary.

Bt1 -- 30 to 50 cm; dark yellowish brown (10YR 4/4); dark brown (10YR 4/3) clay loam; weak medium subangular blocky structure; firm; common continuous faint dark yellowish brown (10YR 4/4) clay films on faces of peds; few micro and fine roots between peds; common micro and fine interstitial and tubular pores; clear smooth boundary.

Bt2 -- 50 to 72 cm; dark yellowish brown (10YR 4/4); dark brown (10YR 4/3) clay loam; moderate medium subangular blocky structure; friable; common continuous faint dark yellowish brown (10YR 4/4) clay films on faces of peds; very few micro and fine roots between peds; common micro and fine interstitial and tubular pores; clear wavy boundary.

2Bt3 -- 72 to 95 cm; dark brown (7.5YR 4/4); dark yellowish brown (10YR 4/6) clay loam; weak medium subangular blocky structure; friable; common continuous faint dark brown (7.5YR 4/4) clay films on faces of peds; common discontinuous distinct black (10YR 2/1) manganese or iron-manganese stains on faces of peds; very few micro roots between peds; common fine interstitial and tubular pores; gradual wavy boundary.

2Bt4 -- 95 cm; dark brown (7.5YR 4/4); dark yellowish brown (10YR 4/6) clay loam; moderate medium subangular blocky structure; friable; many continuous faint dark brown (7.5YR 4/4) clay films on faces of peds; few discontinuous distinct black (10YR 2/1) manganese or iron-manganese stains on faces of peds; very few micro roots between peds; few micro interstitial and tubular pores.

Clay Loam

Classification: clayey, acid, thermic Typic Paleudult

Parent Material: alluvium from igneous-coarse; residuum from limestone

Diagnostic Horizons: 0 to 16 cm ochric; 16 to 100 cm argillic

Described By: Jenkins and Vories

Date: 10-03-86

Ap -- 0 to 16 cm; dark yellowish brown (10YR 3/4) silt loam; weak fine subangular blocky structure; firm; many fine roots throughout; many fine and medium interstitial and tubular pores; abrupt smooth boundary.

Bt1 -- 16 to 36 cm; dark red (2.5YR 3/6); dark brown (7.5YR 3/2) clay; moderate medium subangular blocky structure; very firm; common discontinuous faint dark reddish brown (2.5YR 3/4) clay films on faces of peds; common fine roots between peds; few to common fine interstitial and tubular pores; few manganese nodules, fine; gradual smooth boundary.

Bt2 -- 36 to 56 cm; dark reddish brown (2.5YR 3/4); dark brown (7.5YR 3/2) clay; moderate medium subangular blocky structure; firm; common discontinuous faint dark red (2.5YR 3/6) clay films on faces of peds; few to common fine roots between peds; few to common very fine and fine interstitial and tubular pores; common manganese nodules, fine; gradual smooth boundary.

Bt3 -- 56 to 84 cm; dark reddish brown (2.5YR 3/4); dark brown (7.5YR 3/2) clay; moderate medium subangular blocky structure; firm; common discontinuous faint dark red (2.5YR 3/6) clay films on faces of peds; few fine roots between peds; few to common very fine and fine interstitial and tubular pores; 5 % gravel; many manganese nodules, fine and medium; gradual smooth boundary.

2Bt4 -- 84 cm; dark red (2.5YR 3/6) clay; weak medium subangular blocky structure; firm; many continuous faint dark red (2.5YR 3/6) clay films on faces of peds; very few very fine and fine roots between peds; few very fine and fine interstitial and tubular pores; loss of manganese and pebbles; shiny red clay residuum.

APPENDIX 2

DATA FROM SOIL-LOSS STUDY

The following pages contain the data collected during the laboratory experiments. As discussed in the text, the order of experiments was randomized. Extra tests were conducted which were not included in the randomization. Data from the extra tests were not included in Table 6, page 71, or used in the statistical analyses. Data from those tests were used to calculate the values in Table 18, page 107, and are included in this section.

All tests lasted one hour. The values for runoff mass include the no-soil runoff discussed in the text. The one-hour runoff-mass averages for the no-soil tests were 4.4 and 7.2 kg for the 5.2 and 8.0 cm/h intensities, respectively. Water temperature for the no-soil tests was 27 °C.

The values in this section should agree with those in Table 6, page 71. However, round-off error would probably preclude reproducing those values exactly.

Table 19. Soil-loss test data.

Test Number	Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Mass(1) (kg)	Sediment Concentration (kg/m^3)
1	1	5.2	Fine Sandy Loam	Dry	83.6	4.71
2			Fine Sandy Loam	Prewetted	Disregarded	
3			Silt Loam	Dry	44.0	3.73
4			Silt Loam	Dry	41.7	5.06
5			Silt Loam	Prewetted	Disregarded	
6			Fine Sandy Loam	Dry	77.4	5.76
7			Silt Loam	Prewetted	13.8	3.53
8			Fine Sandy Loam	Dry	78.6	5.65
9			Fine Sandy Loam	Prewetted	83.4	7.06
10			Fine Sandy Loam	Prewetted	71.8	6.51
11			Fine Sandy Loam	Prewetted	77.6	6.77
12			Fine Sandy Loam	Dry	61.2	4.51
13			Silt Loam	Prewetted	17.5	6.49
14			Silt Loam	Prewetted	38.6	9.08
15			Silt Loam	Dry	34.4	5.17
16			Silt Loam	Dry	47.4	7.10
17(2)			Silt Loam	Prewetted	40.9	8.43
18(2)			Fine Sandy Loam	Prewetted	76.7	7.44
19(2)			Silt Loam	Prewetted	4.8	0.00(3)
20(2)			Silt Loam	Prewetted	5.2	0.00
21		8.0	Fine Sandy Loam	Prewetted	124.5	14.17
22			Silt Loam	Dry	105.3	13.73
23			Fine Sandy Loam	Dry	133.2	16.56
24			Fine Sandy Loam	Prewetted	Disregarded	
25			Silt Loam	Dry	93.9	19.63
26			Silt Loam	Dry	101.0	17.17

Table 19. (Continued)

Test Number	Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Mass(1) (kg)	Sediment Concentration (kg/m^3)
27	1	8.0	Silt Loam	Prewetted	46.4	6.73
28			Silt Loam	Prewetted	58.2	10.23
29			Fine Sandy Loam	Dry	129.2	14.27
30			Silt Loam	Prewetted	65.0	10.17
31			Fine Sandy Loam	Prewetted	120.8	16.73
32			Fine Sandy Loam	Dry	125.8	12.73
33			Fine Sandy Loam	Dry	124.7	11.03
34			Silt Loam	Dry	100.5	17.87
35			Silt Loam	Prewetted	57.8	8.53
36			Fine Sandy Loam	Prewetted	113.1	12.50
37(2)			Fine Sandy Loam	Prewetted	118.6	9.20
38(2)			Fine Sandy Loam	Dry	137.4	16.43
39(2)			Fine Sandy Loam	Prewetted	120.5	15.10
40	2	8.0	Fine Sandy Loam	Dry	142.3	18.26
41			Fine Sandy Loam	Prewetted	130.6	23.40
42			Fine Sandy Loam	Prewetted	140.8	16.36
43			Fine Sandy Loam	Dry	118.8	20.70
44			Clay Loam	Dry	11.4	0.92
45			Clay Loam	Dry	9.1	0.64
46			Clay Loam	Prewetted	19.9	2.63
47			Clay Loam	Prewetted	10.5	1.59
48		5.2	Fine Sandy Loam	Dry	73.1	8.90
49			Clay Loam	Prewetted	3.7	0.00
50			Fine Sandy Loam	Prewetted	57.6	11.61
51			Clay Loam	Dry	6.7	0.00
52			Clay Loam	Dry	5.3	0.00

Table 19. (Continued)

Test Number	Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Mass$^{(1)}$ (kg)	Sediment Concentration (kg/m^3)
53	2	5.2	Clay Loam	Prewetted	7.1	0.00
54			Fine Sandy Loam	Dry	73.2	7.56
55			Fine Sandy Loam	Prewetted	71.9	9.78
56	3	8.0	Silt Loam	Dry	95.3	21.00
57			Silt Loam	Prewetted	73.8	10.42
58			Silt Loam	Prewetted	66.7	8.38
59			Sandy Loam	Dry	100.7	6.72
60			Sandy Loam	Prewetted	132.1	10.04
61			Sandy Loam	Prewetted	122.7	9.51
62			Silt Loam	Dry	95.3	22.52
63			Sandy Loam	Dry	102.6	6.80
64		5.2	Silt Loam	Prewetted	24.0	8.00
65			Sandy Loam	Prewetted	63.9	5.89
66			Sandy Loam	Prewetted	59.2	7.89
67			Silt Loam	Dry	51.9	15.36
68			Sandy Loam	Dry	56.4	4.78
69			Sandy Loam	Dry	57.5	4.98
70			Silt Loam	Dry	52.7	14.32
71$^{(2)}$			Silt Loam	Dry	55.6	12.29
72			Silt Loam	Prewetted	18.6	7.26
73$^{(2)}$			Sandy Loam	Dry	66.4	4.58
74	4	8.0	Sandy Loam	Dry	89.0	12.44
75			Clay Loam	Dry	Disregarded	
76			Clay Loam	Prewetted	17.8	3.78
77			Sandy Loam	Prewetted	121.7	8.38
78			Sandy Loam	Dry	103.1	12.93

Table 19. (Continued)

Test Number	Block	Intensity (cm/h)	Soil	Moisture Condition	Runoff Mass(1) (kg)	Sediment Concentration (kg/m^3)
79	4	8.0	Clay Loam	Dry	11.2	1.52
80			Sandy Loam	Prewetted	107.5	10.08
81			Clay Loam	Prewetted	13.5	2.68
82(2)			Clay Loam	Dry	9.6	1.18
83		5.2	Sandy Loam	Prewetted	54.9	6.07
84			Clay Loam	Dry	5.2	0.00
85			Clay Loam	Prewetted	6.7	0.00
86			Sandy Loam	Dry	54.9	4.23
87			Sandy Loam	Dry	42.3	3.60
88			Sandy Loam	Prewetted	38.7	6.48
89			Clay Loam	Prewetted	4.8	0.00
90			Clay Loam	Dry	3.5	0.00

(1) Mass of runoff with sediment before no-soil value subtracted.

(2) Not included in original randomization of experiments. Therefore, not included in Table 6, page 71, or the corresponding analyses.

(3) Sediment concentration of 0.00 resulted from insufficient runoff for sampling.

Table 20. Test conditions.

Test Number(1)	Date (YYMMDD)	Mean Air Temperature (°C)	Mean Rel. Humidity (%)	Water Temperature (°C)	Pan	Moisture Content (%)	Bulk Density(2) (kg/m^3)
1	860610	30	69	26	2	9.6	1271
2	860611	29	71	26	1	27.6	1259
3	860611	28	71	26	2	13.8	1218
4	860612	30	65	25	1	14.9	1210
5	860612	29	66	26	2	28.0	1136
6	860613	28	69	24	2	9.9	1298
7	860613	29	59	24	1	37.6	1104
8	860614	27	69	24	1	10.5	1298
9	860614	28	64	24	2	28.2	1243
10	860615	30	59	26	2	29.1	1253
11	860615	30	59	26	1	34.9	1239
12	860618	27	53	22	1	7.9	1295
13	860618	28	47	22	2	44.4	1095
14	860619	29	67	25	1	43.5	1093
15	860620	30	70	26	2	12.6	1248
16	860621	30	63	26	1	11.3	1260
17(3)	860621	30	50	24	2	53.3	1079
18(3)	860625	28	52	24	2	25.5	1267
19(3)	860625	29	47	24	1	47.6	1089
20(3)	860627	31	59	26	2	30.2	1120
21	860726	32	67	27	2	31.0	1231
22	860726	30	69	27	1	21.8	1185
23	860727	33	59	28	2	13.8	1292
24	860728	32	67	28	2	34.6	1240
25	860728	31	70	28	1	15.1	1218
26	860729	32	55	27	2	10.9	1263

Table 20. (Continued)

Test Number(1)	Date (YYMMDD)	Mean Air Temperature (°C)	Mean Rel. Humidity (%)	Water Temperature (°C)	Pan	Moisture Content (%)	Bulk Density(2) (kg/m^3)
27	860729	31	66	28	1	35.4	1106
28	860730	31	49	24	2	55.0	1070
29	860731	27	71	26	2	9.6	1303
30	860731	28	77	26	1	42.3	1091
31	860801	30	68	27	2	47.5	1220
32	860802	30	60	26	1	11.7	1309
33	860803	29	62	26	1	9.5	1314
34	860803	29	56	24	2	13.2	1220
35	860804	30	59	26	2	38.4	1093
36	860805	30	55	26	1	47.8	1210
37(3)	860806	31	52	26	2	41.0	1228
38(3)	860807	29	70	27	1	12.4	1290
39(3)	860810	30	69	27	1	42.7	1229
40	861022	22	66	20	1	12.7	1295
41	861023	20	70	19	1	45.5	1212
42	861023	22	73	20	2	43.0	1220
43	861024	23	63	20	1	9.1	1305
44	861025	20	80	21	2	10.0	1263
45	861027	21	76	21	1	11.4	1244
46	861027	21	70	20	2	29.8	1125
47	861028	21	67	19	1	28.0	1124
48	861101	21	76	20	1	14.2	1307
49	861101	21	77	20	2	27.2	1132
50	861104	22	72	21	1	40.3	1222
51	861104	22	68	20	2	11.4	1224
52	861106	22	67	19	2	13.7	1196

Table 20. (Continued)

Test Number[1]	Date (YYMMDD)	Mean Air Temperature (°C)	Mean Rel. Humidity (%)	Water Temperature (°C)	Pan	Moisture Content (%)	Bulk Density[2] (kg/m^3)
53	861106	22	68	20	1	30.9	1116
54	861112	18	76	18	1	15.3	1304
55	861112	19	74	18	2	35.5	1242
56	861117	20	79	19	1	17.6	1164
57	861118	21	68	18	1	53.7	1071
58	861119	18	62	17	2	53.2	1067
59	861119	19	68	17	1	5.7	1301
60	861123	20	72	18	2	29.9	1255
61	861125	20	77	18	1	33.8	1242
62	861128	19	72	18	1	15.8	1208
63	861128	19	73	18	2	7.3	1298
64	861130	19	60	17	1	60.7	1070
65	861130	20	60	17	2	38.3	1238
66	861205	19	53	16	1	38.3	1240
67	861206	20	51	17	2	17.5	1176
68	861208	20	63	17	1	9.6	1299
69	861209	21	69	18	2	9.1	1305
70	861212	19	58	17	1	18.2	1176
71(3)	861213	18	47	15	1	15.7	1201
72	861214	19	58	16	2	36.9	1102
73(3)	861215	19	61	17	1	11.4	1316
74	861217	20	65	16	2	10.3	1295
75	861218	18	60	14	1	13.1	1209
76	861219	19	59	16	2	28.2	1126
77	861221	19	54	14	1	30.5	1263
78	870113	19	59	15	1	11.2	1295

Table 20. (Continued)

Test Number(1)	Date (YYMMDD)	Mean Air Temperature (°C)	Mean Rel. Humidity (%)	Water Temperature (°C)	Pan	Moisture Content (%)	Bulk Density(2) (kg/m^3)
79	870114	18	60	14	2	13.3	1201
80	870115	19	67	16	1	46.1	1224
81	870119	19	54	14	2	35.8	1097
82(3)	870120	19	50	14	1	7.9	1281
83	870205	19	43	14	1	33.4	1253
84	870210	19	49	14	2	10.6	1242
85	870210	19	53	14	1	36.9	1094
86	870212	20	50	15	1	7.9	1313
87	870216	19	52	15	2	7.3	1313
88	870222	19	61	16	1	36.9	1249
89	870222	19	66	16	2	36.1	1098
90	870225	20	49	15	1	12.3	1227

(1) Test numbers correspond to test numbers in Table 19.

(2) Bulk density data were incomplete. Values shown were estimated, based upon available data.

(3) Not included in original randomization of experiments. Therefore, not included in Table 6, page 71, or the corresponding analyses.

VITA

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