Soil erodibility prediction for excavated materials
by William S Hartsog

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering
Montana State University

Abstract:
Laboratory erosion studies were conducted to determine the erodibility of soils from four Northern Great Plains surface coal mines. A drop-forming rainfall simulator was used to apply rainfall at a rate of 76.2 mm/hour for one-half hour duration to a 55.25 cm x 55.25 cm erosion plot. Statistical analyses of the laboratory erosion data were done using the BMDP statistics package. Regression equations using interrill and splash erosion measurements as dependent variables were expressed in terms of soil chemical and physical properties and plot slope. These equations can be used to estimate the sheet erosion component for erosion process models. Details on laboratory procedures, statistical analysis, and splash distribution, are presented along with a summary of erosion prediction methods.

SOIL ERODIBILITY PREDICTION FOR EXCAVATED MATERIALS

by

William S. Hartsog

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

June 1988

APPROVAL

of a thesis submitted by

William S. Hartsog

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

May 19, 1988 — Theodore J. Williams
Date — Chairperson, Graduate Committee

Approved for the Major Department

18 May '88 — Theodore E. Lang
Date — Head, Major Department

Approved for the College of Graduate Studies

June 10, 1988 — Henry L. Parsons
Date — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a doctoral degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. I further agree that copying of this thesis is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for extensive copying or reproduction of this thesis should be referred to University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106, to whom I have granted "the exclusive right to reproduce and distribute copies of the dissertation in and from microfilm and the right to reproduce and distribute by abstract in any format."

Signature William S. Hartsog

Date May 18, 1988

ACKNOWLEDGEMENTS

I would like to express my appreciation to the following people for their support and making this thesis possible.

Thanks to my thesis committee (Ted Williams, Tom Hanson, and Al Cunningham) for reviewing and editing the drafts of this thesis.

Thanks to the other members of my graduate committee (Chuck Milne, Don Reichmuth, Jim Schmitt, and Joe Armijo) for their time and advice.

A special thanks to Ted Williams and Ted Lang for their encouragement and support to work toward a doctoral degree.

Thanks to May Mace for her help with the typing and layout of the thesis. Thanks to Andy Lawrence of the U.S. Forest Service for assistance with the testing and figures.

To my wife Carolyn, thanks for being especially supportive and patient during the past three years.

TABLE OF CONTENTS

Page

LIST OF TABLES vii

LIST OF FIGURES viii

ABSTRACT ix

INTRODUCTION 1

THE EROSION PROCESS 4

  Components of Erosion 4
  Interrill and Rill Erosion 4
  Reasons for Laboratory Study 5
  Process Modeling 6

EROSION PREDICTION METHODS; STATE-OF-THE-ART 7

  Universal Soil Loss Equation 7
  Laboratory Erodibility Factors 10
  Erosion Process Models 11
    Erosion: Sources and Transport 11
    CREAMS Model 12
    Future of Process Models 13

EQUIPMENT AND METHODS 15

  The Rainfall Simulator 15
    Simulated Rainfall Properties 17
  The Erosion Plot 19
    Simulating Field Conditions 19
    Description of Laboratory Plot 20
  Measurements of Soil Splash and Runoff Erosion 21
    Laboratory Methods 21
    Test Duration Considerations 23
  Methods of Describing Soil Properties 24
    Soil Sampling Sites 24
    Topsoil and Spoil Properties........................25
      Chemical Properties 29
      Physical Properties 29
    Laboratory Erosion Data 30

TABLE OF CONTENTS - Continued

Page

DATA ANALYSIS 33

Methods of Analysis 33
Interrill Erosion Analysis 35
Importance of Slope 35
Variables Included 38
Interrill Erosion Equations 41
Splash Erosion Analysis 45
Importance of Slope 45
Variables Included 47
Splash Erosion Equations 47

DISCUSSION OF INTERRILL AND SPLASH EROSION ANALYSIS 50

Comparison of Interrill and Splash Equations 50
Comparison of Equations to USLE 50
Problems Related to Sample Variation 53

SPLASH DISTRIBUTION RESULTS 55

Splash Intensity Contours 55
Total Soil Splash 57
Splash Distance Versus Slope 59
Directional Splash Distribution 61

CONCLUSION 65

Soil Erodibility Equations 65
Splash Distribution 67
Future Study Needs 68

LITERATURE CITED 70

LIST OF TABLES

Table Page

1. Data used in interrill and splash erosion analyses....................................31
2. Independent variables, partial correlations, and F-to-enter values at the zero step of the interrill erosion regression analysis (linear, squared, and slope interaction forms of the variables are shown).................36
3. Interrill erosion regression coefficients and R-squared for the independent variables in their linear form...............................44
4. Interrill erosion regression coefficients and R-squared for the independent variables in their slope interaction form.......................44
5. Interrill erosion regression coefficients and R-squared for the independent variables in any combination (linear, quadratic, interaction).....................................44
6. Independent variables, partial correlations, and F-to-enter values at the zero step of the splash erosion regression analysis (linear, squared, and slope interaction forms of the variables are shown).................46
7. Splash erosion regression coefficients and R-squared for the independent variables in their linear form................................49
8. Splash erosion regression coefficients and R-squared for the independent variables in any combination (linear, quadratic, interaction)......49

LIST OF FIGURES

Figure Page

1. Equipment set up for erodibility tests................16
2. The rainfall simulator...................................16
3. Blotter paper system used to collect splash erosion.....................................22
4. Neoprene nylon apron used to collect splash erosion.....................................22
5. Average interrill erosion and splash erosion versus slope angle..........................37
6. Interrill erosion versus SAR (average values for 1-, 9-, and 20-percent tests)..................40
7. Contour map of splashed soil weight per unit area (grams/square inch)...........................56
8. Total soil splashed off the soil plot for spoils and topsoils from four mine sites tested in a wet and dry condition at 1-, 9-, and 20-percent slope angles...................58
9. The product of total soil splashed and average splash distance downslope for spoils and topsoils from four mine sites tested in a dry and wet condition at 1-, 9-, and 20-percent slope angles...................60
10. Proportion of splash direction.(Average percentage of splash for all soils in the dry and wet condition at 1-, 9-, and 20 percent slopes)...............................62

ABSTRACT

Laboratory erosion studies were conducted to determine the erodibility of soils from four Northern Great Plains surface coal mines. A drop-forming rainfall simulator was used to apply rainfall at a rate of 76.2 mm/hour for one-half hour duration to a 55.25 cm x 55.25 cm erosion plot. Statistical analyses of the laboratory erosion data were done using the BMDP statistics package. Regression equations using interrill and splash erosion measurements as dependent variables were expressed in terms of soil chemical and physical properties and plot slope. These equations can be used to estimate the sheet erosion component for erosion process models. Details on laboratory procedures, statistical analysis, and splash distribution, are presented along with a summary of erosion prediction methods.

INTRODUCTION

The Northern Great Plains receives about 25 to 35 cm (10 to 14 inches) of precipitation annually. According to Langbein and Schumm (1958), regions receiving this range of rainfall often have the most severe erosion and sedimentation rates. Particularly severe erosion has been observed in this region on construction sites and mine areas, but few quantitative data are available for prediction of erosion rates. Such data are vital if land managers, regulatory agencies, and industries are to anticipate and control erosion and the degradation of water quality that typically accompanies erosion.

One area of concern is increased erosion resulting from strip coal mining, a major industry in the Northern Great Plains. About 1.05 million hectares are underlain by surface-mineable deposits in the four-state area (Montana, North Dakota, South Dakota, Wyoming). Beneath this area lie 72.8 billion metric tons of surface-mineable coal, representing about 60 percent of the Nation's surface-mineable coal reserve (U.S. Dept. of Agriculture and others, 1975).

Under the Surface Environment and Mining program (SEAM)[1], the USDA Forest Service in 1977 initiated a study into erosion of spoil and topsoil mine materials in the Northern Great Plains. The U.S. Environmental Protection Agency (EPA) along with the Engineering Experiment Station at Montana State University provided funding and support because of the concern over sediment pollution. The objective of this research is to devise a method for predicting erodibility of mined materials in particular. However, the study is applicable to erodibility of excavated materials in general.

The general approach to the study was to collect soil samples from four active strip mines and subject them to simulated rainfall in the laboratory. (Note the broad use of the word "soil" herein to denote either excavated topsoil or spoil material.) The amount of soil displaced was correlated with physical and chemical characteristics of the soil sample and the slope of the soil surface. Factors found to influence soil displacement were quantified for use in equations that predict erodibility.

This report 1) defines sheet erosion, 2) discusses various techniques of erosion measurement, 3) considers the basis for testing and describes the test apparatus,

1. A United States Department of Agriculture, Forest Service, program to provide and apply technology in order to maintain or restore the quality of the environment and surface values on forest and grassland areas subject to mining.

4) presents data analysis, and 5) shows results along with potential uses for prediction of erosion. A separate discussion of splash erosion and distribution is also presented.

THE EROSION PROCESS

Components of Erosion

Erosion is one of the three components in the overall sedimentation process: erosion, transport, and deposition. Erosion due to rainfall and runoff has been the subject of intensive research for the last 50 years. Unfortunately the state-of-the-art in erosion prediction has not progressed to the point where accurate estimates of erosion can be made. Soil erosion by water consists of particle detachment and subsequent movement, with water providing the energy and acting as an entraining medium.

Interrill and Rill Erosion

Upland erosion includes both sheet and rill erosion. The rills are defined as locations of concentrated erosion caused by channelized flow. The remaining land surface between the rills is where more uniform sheet erosion occurs (Meyer and others 1972). Mulcher and Young (1972) showed that raindrop impact was the primary force in soil detachment and transport in sheet erosion.

Sheet erosion consists of interrill erosion and splash erosion. Interrill erosion is defined herein as the portion of the sheet erosion that is entrained in the sheet flow runoff and measured at a rill boundary as sediment in the surface runoff. Splash erosion is that portion of sheet erosion that is airborne and is transported beyond the rill boundary as splash. Interrill erosion provides a mechanism for sediment to be transported as a moving sheet to the rill system where concentrated flow and raindrop agitation are the mechanisms of transport.

Reasons for Laboratory Study

Because erosion prediction is an inexact science and there is a need for basic information, this study is directed toward measurement of both splash erosion and interrill erosion. A laboratory study was selected in order to allow close plot and environmental control while determining factors important to the sheet erosion process. A small plot size was selected so that intensive measurements of sediment in the surface runoff and soil splash could be made. The small plot size eliminates the erosion due to rilling so results can be attributed to interrill and splash erosion. Using the laboratory approach, the factors affecting erodibility of different soils can be determined within reasonable costs.

Process Modeling

Defining the erodibility of soil materials based on soil properties may provide input into current erosion prediction models such as the Universal Soil Loss Equation, U.S.L.E., (Wischmeier and Smith 1978) that have factors to account for other variables such as rainfall, slope, length of slope, vegetation and conservation measures. The basic information on interrill and splash erosion will also be useful to researchers developing new erosion and sediment process models such as the watershed model and road sediment model developed by Simons and others (1976) at Colorado State University, and the CREAMS Model developed by the USDA, SEA-AR and edited by Knisel (1980).

EROSION PREDICTION METHODS; STATE-OF-THE-ART

Universal Soil Loss Equation

Wischmeier and Smith presented the Universal Soil Loss Equation (U.S.L.E.) in 1978 in USDA Agriculture Handbook No. 537. The method currently is widely used in the field; many investigators believe that it represents the state-of-the-art for estimating soil erosion. The equation was developed from over 10,000 plot-years of field data from the Midwest. It was originally formulated on basic erosion principles, but the statistical relationships formed during model development caused the equation to be largely empirical.

The U.S.L.E. was developed to predict combined sheet and rill erosion that is transported to the boundary of an agricultural field. The equation is not intended to cover sedimentation processes such as transport beyond the field boundary and erosion in gullies and streambanks.

The form of the U.S.L.E. is the product:

$$A = R\ K\ L\ S\ C\ P$$

where:

A = the computed sheet and rill soil loss per unit-of-area calculated from the product of six other factors. The estimate represents average annual soil loss (tons per acre) due to rainstorms on a small field-size upland area.

R = the rainfall factor, a measure of the erosive potential due to rainfall for an average year. This factor accounts for differences in rainfall frequency, duration, and intensity by summing the individual storm's erosivity index for a normal 1-year period. Research data show that soil losses are directly related to the erosivity index: the product of a rainstorm's total kinetic energy times its maximum 30-minute intensity.

K = the soil-erodibility factor, a measure of the average soil loss per unit of R under arbitrarily selected conditions (a plot 22.1 meters long, with a uniform 9-percent slope that is in continuous fallow and tilled up and down the slope). Any differences in soil loss under these fixed conditions are explained by differences in the soil-erodibility factor, which is a function of the soil physical and chemical properties.

L = the slope length factor, which accounts for increased surface runoff that accumulates as the length of a field increases. This factor is expressed as the ratio of a field slope length to that of a 22.1-meter slope length with the same soil type and gradient.

S = the slope-gradient factor expressed as the ratio of the soil loss from a field on any given gradient to that from a 9-percent slope.

C = the cropping-management factor accounts for plant or mulch cover and soil surface conditions. C is expressed as the ratio of soil loss from a field with given cropping and management conditions to the loss from a field in a fallow condition.

P = the factor for erosion control efforts, defined as the ratio of the soil loss using terracing, strip cropping, or contouring to losses with up and down slope straight-row farming..

The Agricultural Research Service and Soil Conservation Service and others have done extensive work in an attempt to adapt the equation to the widely varying soil and climatic conditions in the United States. Because the U.S.L.E. is the most commonly used tool presently available, others have modified it for specific uses to estimate erosion under varying conditions, such as construction sites (Wischmeier and Meyer 1973), urban areas (Meyer 1974), and forested areas (Curtis and others 1977).

Likewise, the U.S.L.E. is the accepted method currently available for estimating erosion on strip mines (USDA, SCS, EPA 1977) and can be modified for rough approximations of erosion for portions of a year or single-storm events. In spite of its inaccuracy for short-term estimates, it does provide an erosion model that isolates the contribution of the six factors (R,K,S,L,C,P). This makes it feasible to separate out any one factor and study it in detail as is done in the study reported herein where the K-value or soil erodibility is the topic.

The U.S.L.E. provides a nomographic solution (Wischmeier and others 1971) for estimating K-values based upon soil properties. Accuracy of this method is questionable in areas where it has not been verified, and it is recommended that local values for K be established using field sized plots.

One of the objectives of this study is to provide insight into the possibility of estimating K-values from laboratory tests.

Laboratory Erodibility Factors

Using a laboratory rainfall simulator to estimate soil erodibility for field situations is a questionable method. The laboratory measurements indicate erodibility due to sheet erosion but give no measure of a soil's erodibility due to rill erosion. This indicates that laboratory determined erodibilities will not be directly applicable to field sites where rilling is the dominant erosion process.

Where soils are resistant to rill erosion, Meyer, Foster, and Romkins (1975) show that erosion measured at successive downslope sections approached a constant level as length of slope increased. Thus, this finding shows that the sheet erosion component for these rill-resistant soils is strongly related to the total erosion on a slope. Their results also showed that sheet erosion was approximately equal to total erosion on rill-susceptible soils so long as the length of slope was short enough that rills were not fully developed.

Trott and Singer (1979) showed that laboratory-determined K factors for some soils give better estimates of soil erodibility than Wischmeier's nomograph. These results could indicate that the nomograph erodibility solution is not applicable for the properties of these soils or that interrill erosion is dominant for these soils. With proper understanding of the foregoing, results in this report on the erodibility of mine soils, determined from sheet flow on small plots, may be helpful in estimating K-values for the U.S.L.E.

Erosion Process Models

Erosion: Sources and Transport

The failure to separate the sources of erosion (sheet and rill) and failure to properly understand the sediment transport process are viewed by many scientists as major shortcomings in the U.S.L.E. The U.S.L.E. has proven satisfactory for corn belt soils along with certain other soils that are homogeneous enough to allow the lumping of sheet and rill erosion along with sediment transport into one equation. For areas of widely varying soils, there is no reason to believe that it is feasible to combine the processes of erosion and transport into a simple equation. Combining different processes into a single field-boundary, sediment-yield measurement, as is done with the U.S.L.E., results in an empirical approach that is largely site-specific. Considering the wide variety of soils in the Northern Great Plains and noting that activities like strip mining create soils containing a composite of many different materials, it does not seem practical to estimate each new soil's erodibility using field-sized plots. An alternate approach is to measure sheet erosion on small plots in the laboratory and rely on process-oriented models to predict rill erosion and sediment transport for field-sized areas.

CREAMS Model

Recognition of the shortcomings of the U.S.L.E. and other erosion prediction methods has resulted in the development of process-oriented models. The CREAMS Model is a direct result of the U.S.L.E.'s failure to separate the erosion and sediment transport processes. The CREAMS Model and Colorado State University Watershed Model are two possible methods of estimating sediment yields from strip mine or construction areas. Erosion process models are relatively new and have not been refined, especially for a situation as complex as surface mine soils. Nevertheless, a different approach to erosion and sediment prediction is needed as evidenced by the large expenditure of time and money spent on established methods that are not universally applicable. Ideally, a process approach to the erosion problem will result in a better understanding of basic relationships, which is needed to improve erosion prediction and control.

Future of Process Models

Currently there is a large project under way to develop a highly refined new erosion process model based on fundamental hydrologic and erosion processes by the USDA-Agricultural Research Service (ARS). The USDA-Water Erosion Prediction Project (WEPP) is headed by G.R.Foster with the National Soil Erosion Research Laboratory, located at Purdue University and should be completed by the mid-1990's. (General Report, USDA-Water Erosion Prediction Project, January 5, 1987.)

The use of process models could greatly reduce the number of field-sized erosion plots required if the models adequately describe the erosion and transport process. This approach will require field verification of rill erosion and sediment transport estimates but may eventually greatly reduce the total number of field-sized studies.

EQUIPMENT AND METHODS

The basic equipment used for these erodibility tests consists of a rainfall simulator, a box containing the soil sample, and a tilting platform that permits variations in slope. Figure 1 shows the equipment as set up in the laboratory. The soil sample was carefully aligned beneath the rainfall simulator to obtain uniform rainfall coverage.

The Rainfall Simulator

The rainfall simulator selected to conduct this study is a "Nevada type" infiltrometer (Figure 2) designed by Meeuwig (1971) and modified by Malekuti and Gifford (1978). This rainfall simulator is similar in concept to the polyethylene drop-forming apparatus presented by Chow and Harbaugh (1965). The plexiglass water chamber is 61 cm by 61 cm, with 23-gauge stainless steel tubes pressed into holes drilled into the lower surface. Raindrops are formed by 518 stainless steel tubes uniformly distributed on a 55.88-cm-square grid pattern. The tubes terminate as needles of 0.012 mm inside diameter. The entire water chamber oscillates on three 2.54-cm-radius cams to better distribute the raindrop pattern. A float system was added to the

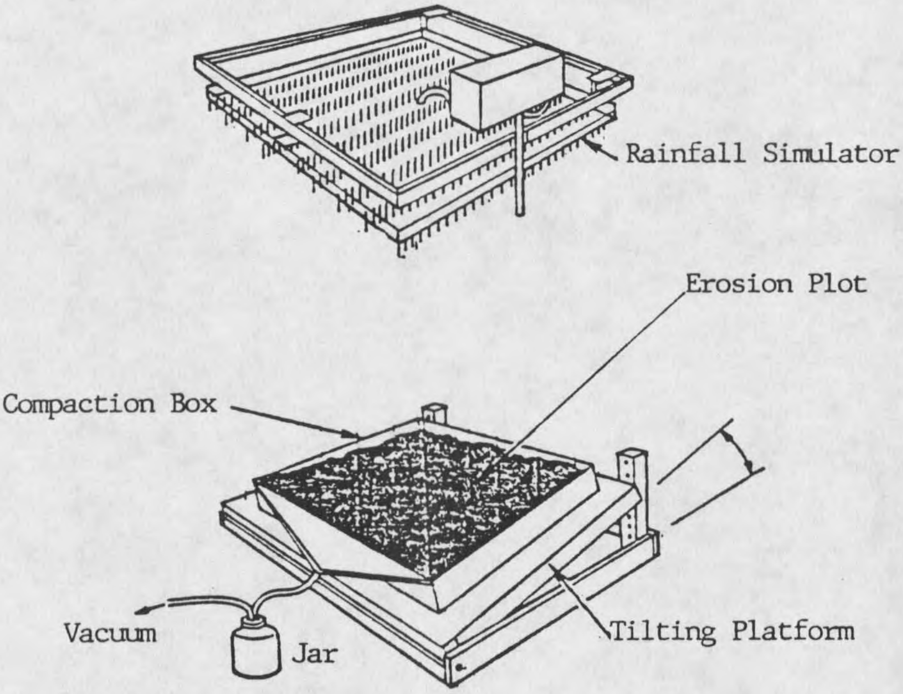


Figure 1. Equipment set up for erodibility tests.

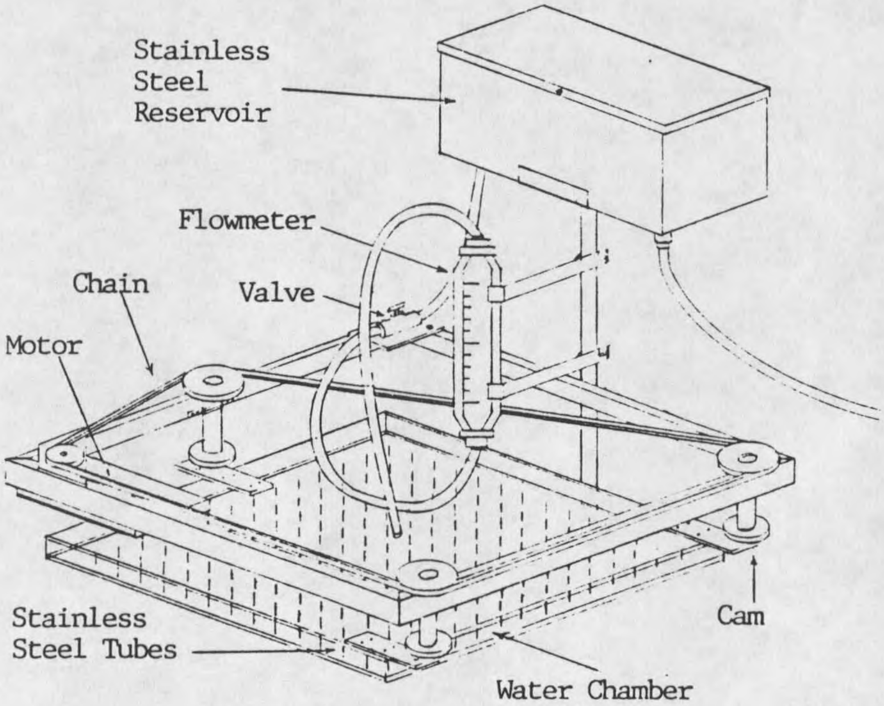


Figure 2. The rainfall simulator.

supply reservoir to maintain a constant head. A flowmeter and valve regulate the flowrate to the water chamber and consequently the rainfall rate.

Studies by other investigators (Sherard and others 1973) indicate that the chemical properties of eroding water can affect erosion rate, especially in soils that are dispersible due to sodium levels. The rainfall simulator's small size makes it practical to use distilled water in order to more closely simulate the chemical properties of natural rain.

Simulated Rainfall Properties

One of the main advantages of this simulator is close monitoring and control of the energy, intensity, and quantity of rainfall. To obtain useful data on the erodibility of different soils, the physical properties of the artificial rainfall must be known and be reproducible. Therefore drop size, mass, and fall distance are of primary importance. These factors will determine the velocity, momentum, and kinetic energy delivered to the soil. Measured drop size was 2.5 mm, as closely as could be determined using calipers. Chow and Harbaugh (1965) calculated drop size with the 0.012-mm-inside-diameter needles as 2.39 mm, which supports our measurements. The average fall distance for the drops was 2.9 meters. In this distance a 2.5-mm drop will attain a velocity of approximately 5.73 meters per second as determined from Laws' publication (1941). This velocity is 77 percent of the terminal velocity of a 2.5-mm-diameter raindrop.

The kinetic energy produced by this rainfall simulator for a 30-minute event with a 76.2-mm-per-hour intensity, a 2.9-meter fall height, and a 5.73-meters-per-second velocity, is 0.0625 joules per cm^2. The energy in a 30-minute natural rainstorm with a 3-inch- per-hour (76.2-mm-per-hour) intensity was calculated as 1610.9 foot-tons per acre (0.1080 joules per cm^2), using the relationship presented in Wischmeier and Smith (1958):

$$Y = [916 + 331 \text{ Log}_{10} X] Q$$

where Y is the kinetic energy in foot-tons per acre, X is the intensity in inches-per-hour, and Q is the total inches of rain at this intensity. The natural storm yields a higher energy, 0.1080 joules per cm^2 versus 0.0625 joules per cm^2 for the rainfall simulator, mainly because natural raindrops have reached their terminal velocity. Therefore, this rainfall simulator produces 58 percent of the energy produced by a natural rainstorm with a 76.2-mm-per-hour intensity. By comparison, a 1/2-hour duration natural rainstorm that produces the same energy as the rainfall simulator (.0625 joules per cm_2) would have an intensity of approximately 47.1 mm per hour.

Laws and Parson (1943) showed there is a relationship between average drop size and rainfall intensity for natural rainstorms. A 2.5-mm mean size raindrop would have an intensity of 50.8 mm per hour. The uniform drop size and lower energy produced by the rainfall simulator makes it impossible to simulate relationships between energy, intensity, and drop size that exist in natural rainstorms. There are other factors such as momentum, depth of water film, and spatial distribution of momentum and energy that further complicate the similitude problem. The 76.2-mm-per-hour rainfall simulator intensity was selected so that the energy per unit time could be kept relatively high, and also because several other investigators working with drop-forming and sprinkler-head type simulators have used similar intensities. The selected intensity should be satisfactory for determining the erodibility of selected materials and also provide data that is comparable with data from other studies.

The Erosion Plot

Simulating Field Conditions

The erodibility study was conducted in a laboratory so that rainfall simulator conditions and other environmental problems such as wind and temperature could be easily controlled. At locations where soil samples were taken, the conditions near the surface were measured in the field and were reproduced in the laboratory. Near-surface moisture contents and soil bulk densities were determined for spoils and topsoil with nuclear moisture-density equipment at each mine site. For each soil the field moisture was reproduced and the field bulk density obtained by compacting the material into a steel compaction box with a Proctor compaction hammer.

Description of Laboratory Plot

The compaction box (55.25 cm x 55.25 cm x 10.16 cm deep), shown in Figure 1 also served as the container for the erosion plot. The box has a pattern milled into the bottom to allow rainfall that infiltrates through the soil to drain from the box. A nonwoven filter fabric used in road construction placed on the bottom of the box prevents plugging of the drainage system. The three upper sides of the box have a beveled lip, raised 2.54 cm above the soil surface. The lip serves as a sharp boundary and deflects precipitation that falls outside the soil plot boundary away from the soil plot. The downslope edge of the box was flush with the compacted soil surface to allow free drainage of surface runoff. This runoff was concentrated into a trough molded to the edge of box and measured at five-minute intervals. The box was placed on a tilting platform beneath the rainfall simulator, and each erosion test was replicated twice at slope angles of 1, 9, and 20 percent. The 1-percent slope was selected as the minimum that would provide adequate control of surface runoff. The 9-percent slope represents the basic slope used in the development of the U.S.L.E. Twenty percent slope was selected as the maximum because mining law requires that reclaimed lands be graded to slopes of 20 percent or less.

Measurements of Soil Splash and Runoff Erosion

The erosion plot was equipped to measure the contribution of soil splash (soil splashed over the plot boundary) at the same time sediment in the surface runoff (interrill erosion) was being measured.

Laboratory Methods

The first replication employed a grid of blotter papers (Figure 3), which caught soil splashed off the erosion plot. Soil splashed onto the middle three rows of blotter papers, centered on the downslope edge of the plot, provided a measure of splash erosion below the lower plot boundary. The process was so time consuming that for the second replication of the tests a neoprene-nylon apron system was used to catch the soil splash (Figure 4). The soil was rinsed off each apron into a sample bottle, which reduced the collection of soil splash to a single measurement for each apron. The neoprene-nylon aprons did not provide data as to splash distance off the plot however. Splashed soil, collected on a 30.5-cm-wide apron centered on the downslope-

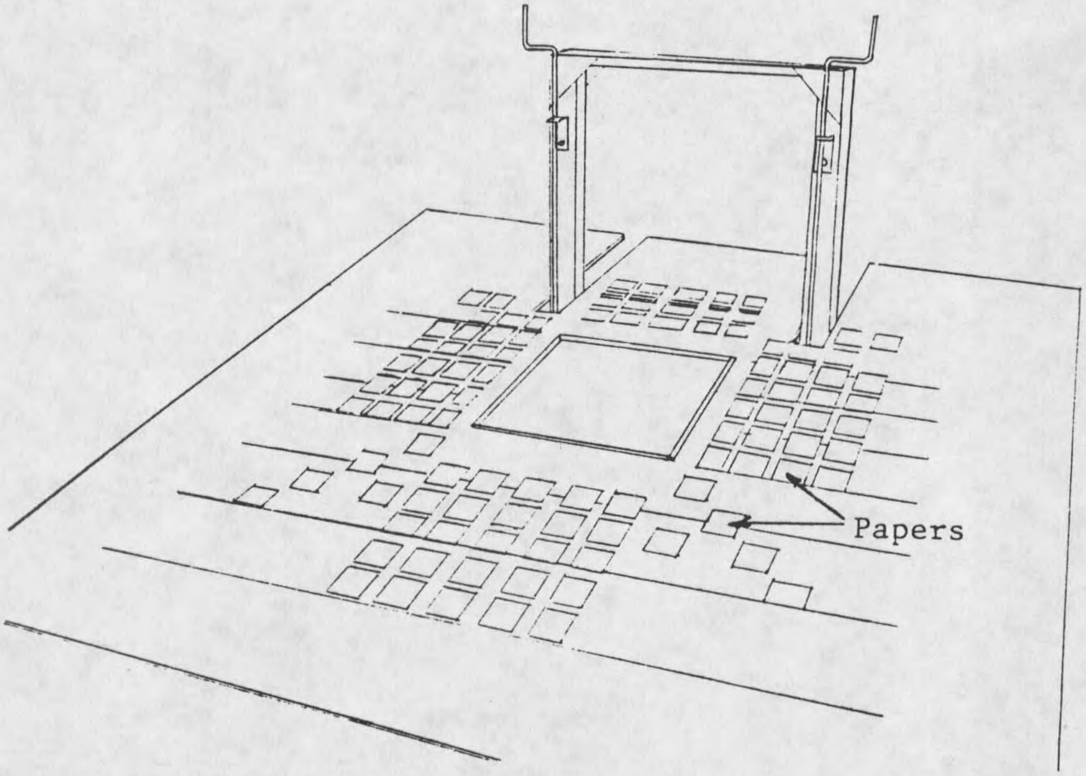


Figure 3. Blotter paper system used to collect splash erosion.

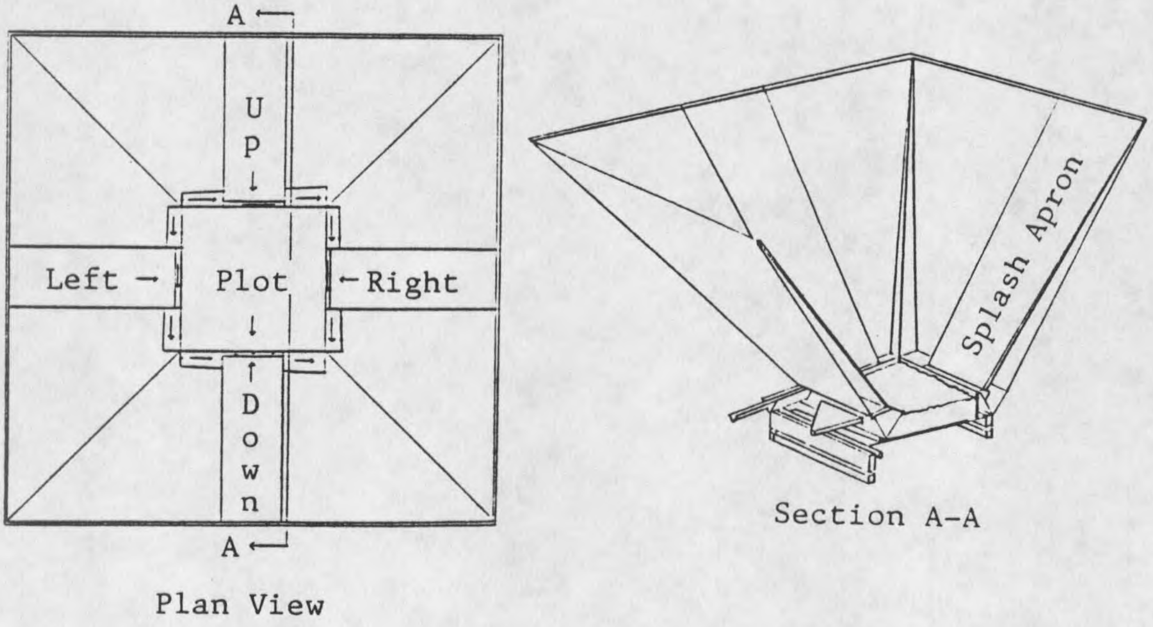


Figure 4. Neoprene nylon apron used to collect splash erosion.

edge of the erosion plot, was used to determine the soil splash erosion below the lower plot boundary.

Contour maps of splash intensity from the blotter paper replication showed that data from the center 30.5-cm strip were almost completely free of the edge effects of the plot. The splash data for both replications were then multiplied by a correction factor (plot width/strip width) so that the splash erosion and interrill erosion data both would be based on a 55.25-cm-wide plot. For both replications, the splash erosion was determined from the oven-dry weight of splashed soil. Soil sediment in the surface runoff (interrill erosion) as oven-dry soil weight was determined by filtering and oven drying the runoff samples.

Test Duration Considerations

Eight soils (topsoil and spoils from four mines) were tested for 30 minutes in a dry condition and wet condition at each of the three selected slope angles. The dry condition test had the same soil moisture content as when it was compacted into the sample box (field moisture content). The wet-condition test was the condition of the soil sample 24 hours after the 30-minute dry-condition rainfall simulator run.

Detailed erosion tests with the rainfall simulator were conducted to refine experimental procedures. The 30-minute duration for the test was chosen after studying time distribution of erosion. Rainfall simulator runs of six hours or longer were made on several of the soils at the nine percent slope. These runs indicated that 30-minute erosion tests on soils initially in the wet condition were more representative of the constant erosion rate reached during the longer term six-hour runs. High erosion rates at the start of the initially dry runs were thus eliminated. The values of interrill and splash erosion, resulting from 30-minute runs on soils in the wet condition are the basic measures of soil erodibility in this paper.

In addition to the basic runoff and splash measurements made below the lower plot boundary during the erosion tests, data on soil splash in all directions was collected. A later section, "Splash Distribution," summarizes the results of these additional measurements.

Methods of Describing Soil Properties

Soil Sampling Sites

This study specifically concentrates on unvegetated topsoil and spoils from four coal strip mining sites in the Northern Great Plains region. Two mine sites are in south-central Montana on the western edge of the extensive Fort Union Formation that encompasses much of the Northern Great Plains. Another site on the eastern Montana border is near the center of the Fort Union Formation, and the fourth mine site in west-central North Dakota is near the eastern edge of the formation. Soils in this formation generally become more fine-grained from west to east. The mines are not identified at their request, since the results cannot be considered as representative of an entire mine. Materials selected for this study can only be considered to be typical of the topsoils and spoils in the small area sampled at each mine location. Through laboratory tests and data analysis, erodibility of these soils is correlated to slope and the physical and chemical properties of these materials. Test results yield erodibility measurements directly related to the four study sites and provide information that may be useful for estimating the erodibility of other soils in the area based on soil properties.

Topsoil and Spoil Properties

Topsoil and spoil material were analyzed for physical and chemical properties. A list of soil properties that other investigators had found to be related to soil erodibility was compiled. Many of these came from Veon and Miller's (1978) review of soil erodibility.

Soil properties used in this study were limited to those easily determined or commonly measured on coal strip mines and are defined in the following list.

EI - Interrill Erosion: the oven-dry weight of soil sediment collected in the surface runoff from the erosion plot. Raindrop impact is the primary erosional force in soil detachment, and this sediment is transported to the lower plot boundary in the surface runoff. Sediment transport capacity of the surface runoff is greatly enhanced by raindrop agitation of the sheet flow.

ES - Splash Erosion: the oven-dry weight of soil splashed over the lower boundary of the erosion plot. Soil splash was measured separately since it passed over the runoff collection trough at the lower plot boundary. Splash erosion provides loose material for the interrill erosion process, and it also transports material directly into rills or gullies.

SL - Slope: the gradient of the erosion plot expressed as a percentage.

INF - Infiltration: the number of centimeters of water absorbed into the soil.

GT3 - The proportion by weight of particles in a soil that are larger than 3.0 mm diameter expressed as a percentage.

GT2 - The proportion by weight of particles in a soil that are larger than 2.0 mm diameter (fine gravel) expressed as a percentage.

SA - The proportion by weight of particles in a soil that are between 61 microns and 2.0 mm in diameter (sand) expressed as a percentage.

LT61 - The proportion by weight of particles in a soil that are less than .061 mm diameter (silt plus clay) expressed as a percentage.

MWD - Mean Weight Diameter (in mm) = $\Sigma\ x_i * w_i$ (Farmer and Van Haveren 1971), where: x_i is the mean diameter in mm of each size fraction, w_i is the proportion of the total sample weight in the corresponding fraction, and the summation is over the total number of size fractions into which the sample is partitioned.

FMWD - LT61 divided by MWD (Farmer and Van Haveren 1971).

BD - Bulk Density: oven-dry weight of a soil sample divided by the volume of the sample (gm/cc).

SAR - Sodium Adsorption Ratio: a ratio for soil extracts used to express the relative activity of sodium ions in exchange reactions with soil:

SAR = $Na/[(Ca + Mg)/2]^{.5}$ where Na, Ca, and Mg are expressed in milliequivalents per liter.

EC - Electrical Conductivity of the soil water extract expressed in mmhos/cm.

OC - Organic Content: the percentage of the total dry weight of a soil that is organic matter.

LL - Liquid Limit: the maximum moisture content that a soil can have and still possess a slight shear strength.

PH - pH is a measure of the acidity (or alkalinity) of a soil expressed as the negative logarithm of the hydrogen ion activity.

SG - Specific Gravity: the ratio of the density of the soil grains in a sample to the density of water.

CLAY - The proportion by weight of particles in a soil that are less than 0.002 mm (clay) in size expressed as a percentage.

SILT - Silt content as defined in the U.S.L.E.: the proportion by weight of particles in a soil that are between 0.002 mm and 0.10 mm in diameter expressed as a percentage.

SAND - Sand content as defined in the U.S.L.E.: the proportion by weight of particles in a soil that are between 0.10 mm and 2.0 mm in diameter expressed as a percentage.

M - The M soil parameter defined in the U.S.L.E. as: M = (SILT) (SILT + SAND), the product of silt content and the sum of silt plus sand content using the U.S.D.A. soil classification and Wischmeier's (silt + sand) definition.

In five of the eight cases, there was not enough soil to prepare three soil samples (one for each slope 1%, 9%, and 20%) required to complete the second replication. When this occurred, enough soil was gathered in the same area of the mine as the original sample to complete the second replication. These samples were also tested because of the variation in soil characteristics.

Chemical Properties. Chemical analyses (L.E. Allison and others 1969) were made on each soil to determine pH, electrical conductivity, cations (calcium, magnesium and sodium) and sodium-adsorption-ratio (SAR) and organic content (J.R. Sims and V.A. Haby 1970).

Physical Properties. Physical analyses to characterize the topsoil and spoil material from each mine included grain size analysis, specific gravity, and the Atterburg limits (liquid limit, plastic limit, and plasticity index). Because erosion tests deal with wet soil, a wet-sieve analysis was conducted on the coarser fractions of each sample. Materials passing the number 10 sieve were tested using hydrometer procedures to determine the distribution of the finer grains. The wet-sieve analysis and the hydrometer method were combined to give the complete grain size distribution. Specific gravity was measured with an air pycnometer. Atterburg limits (Means and Parcher 1963) are measures of soil moisture content under specific conditions that are related to engineering properties of the soil. The liquid limit is the highest moisture content at which a soil still possesses a small degree of shear resistance. The plastic limit is the lowest moisture content at which a soil behaves plastically and does not crumble. The difference between the liquid limit and the plastic limit is defined as the plasticity index. Preliminary screening of these variables using correlation methods showed that liquid limit was the only Atterburg quantity related to erosion measurements.

Laboratory Erosion Data

Table 1 presents the more relevant physical and chemical soil properties that were compiled for each mine topsoil and spoil, as determined from the results of the physical and chemical tests.

Table 1. Data Used in Interrill and Splash Erosion Analyses.

CODE		EI	ES	SL	INF	GT3	GT2	SA	LT61	MWD	FMWD
1	1S1	127.2	24.3	1	0.13	2.0	3.0	25.0	72.0	.383	188
2	1S1	254.7	41.0	9	0.15	2.0	3.0	25.0	72.0	.383	188
3	1S1	292.9	49.2	20	0.16	2.0	3.0	25.0	72.0	.383	188
4	1T1	127.2	22.4	1	0.19	2.3	3.5	43.0	53.5	.376	142
5	1T1	258.4	35.3	9	0.20	2.3	3.5	43.0	53.5	.376	142
6	1T1	436.7	59.4	20	0.22	2.3	3.5	43.0	53.5	.376	142
7	1S2	130.3	18.3	1	0.39	6.0	7.0	31.0	62.0	.394	157
8	1S2	269.0	61.4	9	0.27	6.0	7.0	31.0	62.0	.394	157
9	1S2	445.9	107.7	20	0.20	6.0	7.0	31.0	62.0	.394	157
10	1T2	110.8	23.0	1	0.4	1.0	1.5	13.5	85.0	.223	381
11	1T2	260.0	59.8	9	0.39	1.0	1.5	13.5	85.0	.223	381
12	1T2	345.1	77.8	20	0.32	1.0	1.5	13.5	85.0	.223	381
13	2S1	81.8	21.1	1	0.16	3.7	4.0	41.0	55.0	.341	161
14	2S1	136.9	29.6	9	0.18	3.7	4.0	41.0	55.0	.341	161
15	2S1	214.0	47.2	20	0.19	3.7	4.0	41.0	55.0	.341	161
16	2T1	105.8	24.5	1	0.07	4.0	4.5	39.0	56.5	.348	162
17	2T1	136.6	33.6	9	0.16	4.0	4.5	39.0	56.5	.348	162
18	2T1	132.6	33.9	20	0.12	4.0	4.5	39.0	56.5	.348	162
19	2S2	81.4	17.2	1	0.62	3.7	4.0	41.0	55.0	.341	161
20	2S2	149.7	34.6	9	0.72	3.7	4.0	41.0	55.0	.341	161
21	2S2	267.2	64.3	20	0.50	3.7	4.0	41.0	55.0	.341	161
22	2T2	74.5	27.0	1	1.04	1.5	2.0	53.0	45.0	.32	141
23	2T2	121.6	50.8	9	0.98	1.5	2.0	53.0	45.0	.32	141
24	2T2	191.1	74.5	20	0.96	1.5	2.0	53.0	45.0	.32	141
25	3S1	34.2	7.7	1	0.36	1.0	1.3	29.7	69.0	.199	347
26	3S1	52.2	6.3	9	0.37	1.0	1.3	29.7	69.0	.199	347
27	3S1	112.8	38.9	20	0.38	1.0	1.3	29.7	69.0	.199	347
28	3T1	49.7	31.3	1	0.57	1.2	1.8	24.2	74.0	.233	318
29	3T1	63.1	34.1	9	0.55	1.2	1.8	24.2	74.0	.233	318
30	3T1	232.0	103.5	20	0.56	1.2	1.8	24.2	74.0	.233	318
31	3S2	43.0	8.7	1	0.74	1.0	1.3	29.7	69.0	.19	347
32	3S2	100.4	25.6	9	1.04	1.0	1.3	29.7	69.0	.19	347
33	3S2	99.0	42.2	20	0.79	1.0	1.3	29.7	69.0	.19	347
34	3T2	65.4	24.7	1	1.5	10.5	11.8	26.8	61.5	.956	64
35	3T2	133.5	50.9	9	1.33	10.5	11.8	26.8	61.5	.956	64
36	3T2	184.0	77.2	20	1.29	10.5	11.8	26.8	61.5	.956	64
37	4S1	82.2	37.8	1	0.03	0.2	0.5	51.5	48.0	.17	282
38	4S1	275.5	35.3	9	0.07	0.2	0.5	51.5	48.0	.17	282
39	4S1	519.3	48.9	20	0.06	0.2	0.5	51.5	48.0	.17	282
40	4T1	103.8	34.3	1	0.08	0.7	1.0	61.0	38.0	.375	101
41	4T1	240.9	74.6	9	0.34	0.7	1.0	61.0	38.0	.375	101
42	4T1	504.1	104.7	20	0.32	0.7	1.0	61.0	38.0	.375	101
43	4S2	144.2	28.1	1	0.07	9.5	11.0	40.8	48.3	.791	61
44	4S2	231.9	48.9	9	0.05	9.5	11.0	40.8	48.3	.791	61
45	4S2	331.6	56.4	20	0.02	9.5	11.0	40.8	48.3	.791	61
46	4T2	103.3	19.4	1	0.89	0.7	1.0	61.0	38.0	.375	101
47	4T2	152.5	58.6	9	0.99	0.7	1.0	61.0	38.0	.375	101
48	4T2	331.9	97.9	20	0.89	0.7	1.0	61.0	38.0	.375	101

Table 1. (Continued).

	CODE	BD	SAR	EC	OC	LL	PH	SG	CLAY	SILT	SAND	M
1	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
2	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
3	1S1	1.5	10.7	6.0	4.4	40.0	7.7	2.88	33.0	49.5	14.5	3168
4	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
5	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
6	1T1	1.5	7.0	3.8	1.1	28.0	8.0	2.79	18.0	45.0	33.5	3533
7	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
8	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
9	1S2	1.5	14.4	1.4	0.5	36.6	8.7	2.49	14.5	58.0	20.5	4553
10	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
11	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
12	1T2	1.5	5.5	1.25	1.3	36.3	8.6	2.75	28.5	60.5	9.5	4235
13	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
14	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
15	2S1	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
16	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
17	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
18	2T1	1.5	0.3	0.95	1.5	25.2	7.8	2.72	18.5	53.5	23.5	4120
19	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
20	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
21	2S2	1.5	1.8	1.37	0.3	18.8	7.4	2.68	17.0	62.0	17.0	4898
22	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
23	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
24	2T2	1.5	0.1	0.55	1.5	19.8	8.0	2.53	9.0	49.0	40.0	4361
25	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
26	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
27	3S1	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
28	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
29	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
30	3T1	1.5	0.7	0.45	2.6	31.0	7.8	2.85	17.2	71.0	10.0	5751
31	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
32	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
33	3S2	1.4	2.8	3.2	0.3	22.2	8.5	2.78	14.2	73.5	11.0	6211
34	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
35	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
36	3T2	1.5	0.2	0.9	2.4	26.6	7.3	2.69	8.2	60.5	19.5	4840
37	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
38	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
39	4S1	1.5	31.4	3.3	1.1	60.8	7.8	2.84	27.0	28.5	44.0	2066
40	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
41	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
42	4T1	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
43	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
44	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
45	4S2	1.5	29.5	5.5	0.8	39.9	8.3	2.77	26.0	28.5	34.5	1796
46	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
47	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871
48	4T2	1.4	0.2	1.0	4.6	20.0	7.8	2.71	12.0	33.0	54.0	2871

DATA ANALYSIS

This chapter includes a discussion of the general approach to the data analysis and the statistical methods used to analyze the erosion data. Equations are first developed for interrill erosion using erosion test data. This is followed by a parallel development of splash erosion equations from splash erosion data.

Methods of Analysis

The soil properties in Table 1 provide the independent variables for a multiple regression analysis that attempts to relate the amount of soil eroded to soil properties and slope angle. Dependent variables are interrill erosion (EI) and splash erosion (ES). The problem was approached by analyzing interrill erosion and splash erosion as two separate models. Erosion predicted by each model can be summed to estimate the total sheet erosion if desired.

A stepwise multiple regression program (BMDP2R) from the BMDP (April 1985) package was used to analyze the data. Throughout this study a five percent probability level of significance was selected to evaluate whether or not an individual independent variable would be included in the models. To evaluate whether an independent variable is significantly related to a dependent variable in a stepwise regression analysis, one must consider the total number of independent variables in the analysis. When a large number of independent variables are in a stepwise analysis, chances are good that one or more of the independent variables will be found to have a significant regression relationship to the response, even though no significant relationship exists. With this possibility in mind, variables found to be significant were compared to previous research results as a means of verification. Variables not found significant in previous work are recommended for verification in future studies.

Partial correlations between the response variable (interrill erosion or splash erosion) and the independent variables were used to determine the most important soil characteristics. Stepwise regression equations were generally limited to only the variables that had significant partial correlations with the response. Partial correlations and F-values at the zero step of the stepwise regressions were determined for all the independent variables in the following forms: linear, quadratic, and all combinations of first-order interactions. Other possible transformations on the variables were also considered during preliminary analyses.

Interrill Erosion Analysis

Table 2 displays some of the F-values and partial correlations between the independent variables and interrill erosion. The partial correlations indicate that the linear variables were generally better predictors of interrill erosion than squared transformations of the variables.

Importance of Slope

The linearity of the data is demonstrated in Figure 5, which is a plot of the average interrill erosion at 1-, 9-, and 20-percent slope angles. Average erosion at each slope was calculated by summing the erosion from 16 test observations (two replications X eight soils) and dividing by 16. The graph shows that slope is linearly associated with interrill erosion within the range of 1-20 percent. This result verifies the linear relationship between slope and interrill erosion derived by Foster and others (1977). Plots of interrill erosion versus slope for each of the individual soils also showed that most of the soils had a linear association between erosion and slope. All of the soils showed a positive relationship between erosion and slope; however, the steepness of the relationships varied considerably. This indicates a possibility of slope interactions with one or more of the soil properties. For this reason, the slope-soil property interactions were

Table 2. Independent variables, partial correlations, and F-to-enter values at the zero step of the interrill erosion regression analysis (linear, squared, and slope interaction forms of the variables are shown).

VARIABLE TRANSFORMATION	VARIABLE	PARTIAL CORR.	F TO ENTER
LINEAR :	SL	.67475	38.45
	INF	-.31266	4.98
	LT61	-.18245	1.58
	MWD	.04253	.08
	FMWD	-.17372	1.43
	BD	.14280	.96
	SAR	.35372	6.58
	EC	.15699	1.16
	OC	.15026	1.06
	LL	.34576	6.25
	PH	.06234	.18
	SG	-.00811	.01
	CLAY	.26458	3.46
	SILT	-.43916	10.99
	SAND	.31091	4.92
	M	-.47565	13.45
SQUARED : (QUADRATIC)	SLSQ	.65303	34.20
	INFSQ	-.28141	3.96
	LT61SQ	-.15929	1.20
	MWDSQ	-.00450	.00
	FMWDSQ	-.18043	1.55
	BDSQ	.14279	.96
	SARSQ	.30136	4.59
	ECSQ	.15272	1.10
	OCSQ	.15446	1.12
	LLSQ	.33745	5.91
	PHSQ	.05985	.17
	SGSQ	-.00446	.00
	CLAYSQ	.26267	3.41
	SILTSQ	-.45152	11.78
	SANDSQ	.28972	4.21
	MSQ	-.48871	14.43
SLOPE : INTERACTIONS	INFXSL	.13241	.82
	LT61XSL	.55624	20.61
	MWDXSL	.50955	16.13
	FMWDXSL	.40607	9.08
	BDXSL	.67969	39.50
	SARXSL	.62581	29.61
	ECXSL	.52491	17.49
	OCXSL	.53482	18.43
	LLXSL	.78004	71.48
	PHXSL	.67702	38.93
	SGXSL	.67353	38.19
	CLAYXSL	.70671	45.90
	SILTXSL	.40526	9.04
	SANDXSL	.75360	60.46

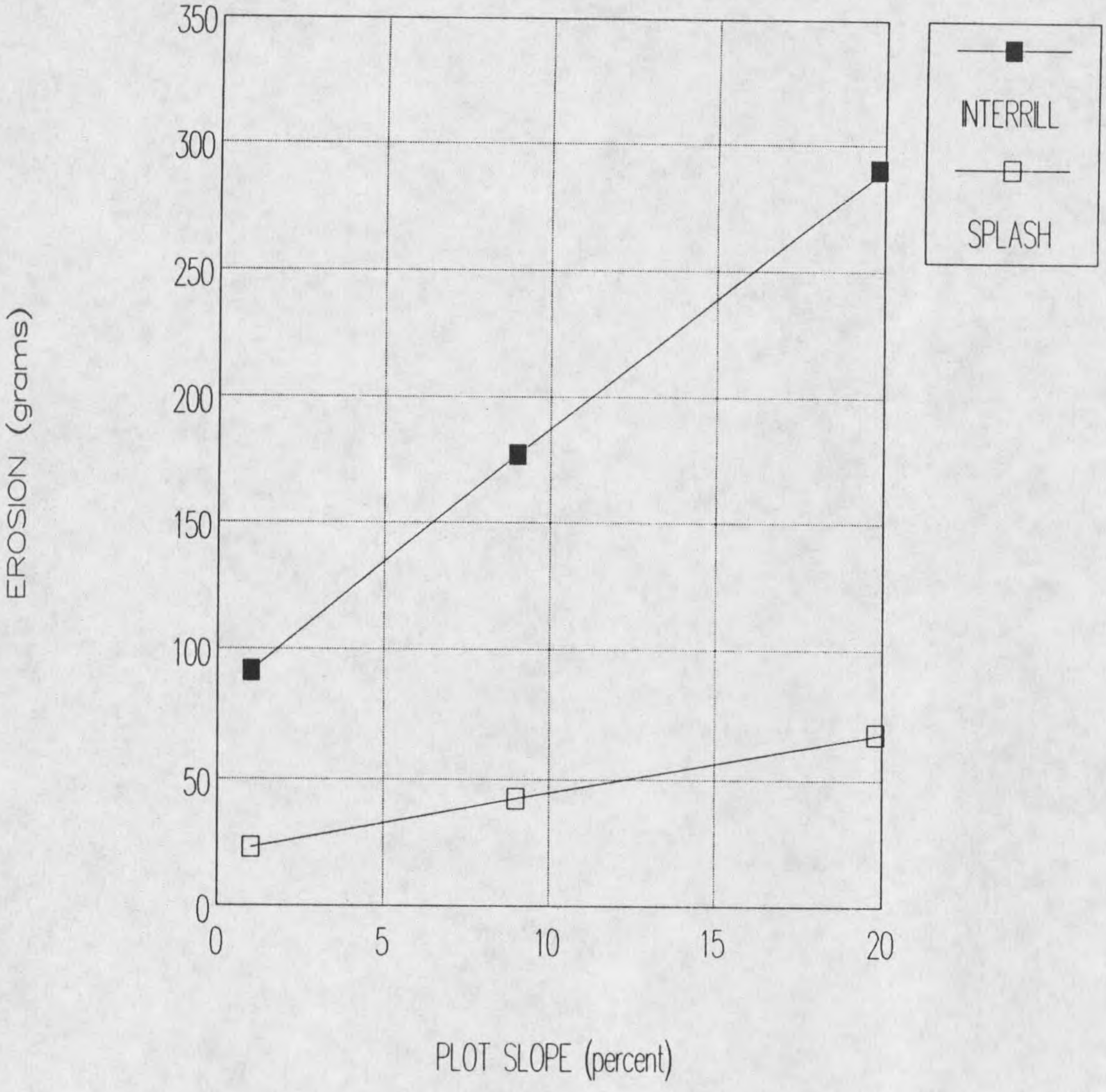


Figure 5. Average interrill erosion and splash erosion versus slope angle.

included in Table 2. Other soil interaction terms were not shown in Table 2, because the F-values for these interactions were not appreciably higher than those of the linear variables.

Variables Included

Table 2 shows that slope (SL) is the most important single variable and that LLXSL and SANDXSL are the only interaction terms with substantially higher F-values than slope alone. Of the linear variables, M (Wischmeier's M) has the second best correlation to interrill erosion. SILT was close to M as a predictor, but this was expected because these two variables are highly correlated. SAR and LL have the next best correlations and F-values with interrill erosion. INF and SAND are the only other single variables in Table 2 that show significant partial correlations with interrill erosion. The above variables should then comprise most of the variables which are in the regression models for interrill erosion.

An inspection of these variables showed that M was negatively correlated to interrill erosion, which indicates that erosion decreased as the percentage of silt increased. This is contrary to results of most other investigators. Wischmeier and others (1971) also found M to be the most important soil property for estimating K-values in their nomograph, but they found that M was positively related to soil erodibility. Lab procedures and calculations for M were carefully checked at this point to verify these results. Gradation curves for all soils were partitioned into ten size ranges so that the correlation between, percent-by-weight in each size range, and interrill erosion, could be determined. The partitions within the sand and clay particle sizes all had positive correlations with interrill erosion while those partitions in the silt sizes had negative correlations. Change of sign in the correlations occurred very close to the upper (0.10-mm) and lower (0.002-mm) silt sizes as defined by Wischmeier for calculating M. The correlations verified that the clay, silt, and sand groups were defined so that soil particles within each size group had similar effects on interrill erosion.

A possible explanation for the negative correlation between M and interrill erosion could be that the clay fraction of these soils was not erosion-resistant as is normally the case. Soils with high SAR values are often dispersible when exposed to water. This makes the clay fraction of the soil erodible, particularly with expansive clays such as smectite or montmorillinite, which are known to be present at two of the sites sampled. LL (Liquid Limit) is a measure of a clay soil's ability to absorb water, and high values of LL could indicate the presence of these expansive clays. Figure 6 shows that interrill erosion is

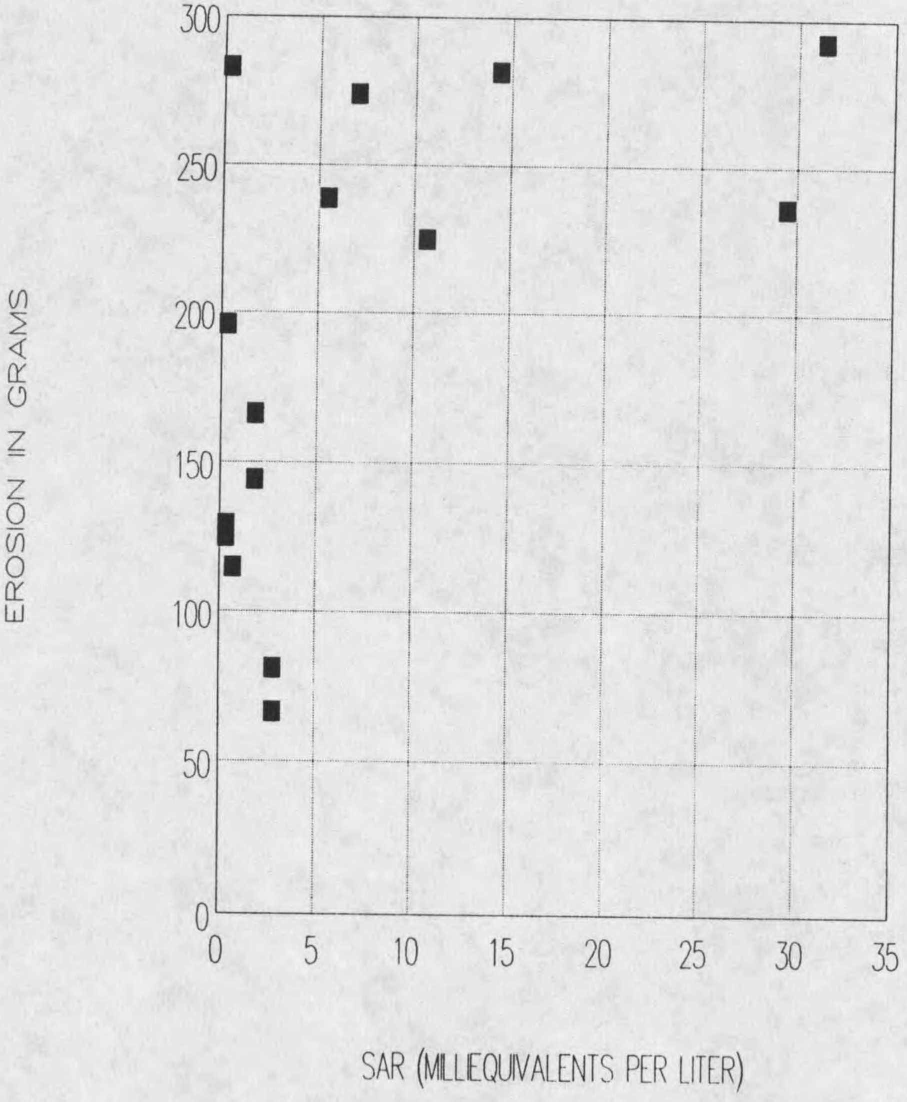


Figure 6. Interrill erosion versus SAR (average values for 1-, 9-, and 20-percent tests).

very high for all soils with a SAR value greater than about four. This indicates the existence of a threshold level of SAR beyond which these clays will disperse. This threshold apparently will vary in magnitude, depending on the clay minerals present. Results of Tanji and others (1978) and Sherard and others (1973) also indicate that some soils exhibit this dispersible behavior when measures of soil sodium exceed a threshold level.

Interrill Erosion Equations

The data were partitioned into two groups--SAR less than 4.0 and SAR greater than 4.0--and then analyzed as two separate groups. The 18 observations with SAR greater than 4.0 yielded a regression equation:

$$EI = 114.5 + 14.35\ SL$$

with an R-squared value of 84.2 percent. None of the other parameters for these soils were found to be significant estimators of runoff erosion when SAR exceeded a value of 4.0; slope alone explains over 84 percent of the variation in the response (EI) for these soils. For the 30 observations with SAR values less than 4.0, the interaction term, SANDXSL, was by far the most significant variable in the regression. Other soil parameters, PH and INFXSAND, are also in the equation but are barely significant at the 5-percent probability level:

$$EI = 510.3 + 0.31\ SANDXSL - 54.46\ PH - 1.231\ INFXSAND$$

has an R-squared value of 80.7 percent for soils with SAR values less than 4.0. The importance of SANDXSL interaction is probably due to the influence of the downslope component of gravity acting on the larger sand-sized grains when they are impacted by raindrops on this size plot. It seems logical that sand-sized particles could be detached more easily on steeper slopes and moved the short distance to the plot boundary by saltation due to raindrop impact in the sheet flow.

An overall regression equation for all values of SAR was developed by coding the data. Values of SAR less than 4.0 were given a value of zero, and values greater than 4.0 were given a value of 1. The resulting regression equation has an R-squared value of 82.4 percent,

$$EI = 49.7 + 88.44\ SAR + 0.142\ LLXSL + 0.240\ SANDXSL$$

where SAR = 0 when the soil has a Sodium Adsorption Ratio of less than 4.0, and SAR = 1.0 when the soil has a Sodium Adsorption Ratio greater than 4.0.

Stepwise regression analyses were also made on the data in Table 1 without special partitioning of SAR. Table 3 shows different combinations of the linear independent variables found to be important for predicting interrill erosion. The R-squared and regression coefficients are given for each combination of the linear variables. Equation 4, Table 3, has the highest R-squared, 69.5 percent, for the linear variables:

$$EI = 193.30 + 10.43\ SL - 0.037\ M + 1.49\ LL$$

Linear variables found to be important in the step-wise analysis are SL, M, and LL. Regression equations with combinations of these variables are given in Equations 1 through 4 of the table.

Stepwise regression analyses on slope-interaction terms are shown in Table 4. Equation (3) has the highest R-squared, 75.2 percent for the slope-interaction variables:

$$EI = 83.4 + 0.293\ LLXSL + 0.191\ SANDXSL - 0.001\ MXSL.$$

Regression coefficients and R-squared values are also given for other combinations of these variables in Equations 1 and 2 of Table 4.

Table 5 presents the best stepwise equations for any combination of linear, quadratic, and slope-interaction variables. Equation (3);

$$EI = 137.3 + 0.240\ LLXSL - .00000297\ MSQ + 0.136\ SANDXSL$$

has the highest R-squared, 77.9 percent. The R-squared values and regression coefficients are also presented in the table for other steps in the analysis.

None of the equations given in Tables 3, 4, or 5 have R-squared values as high as the SAR partitioned equations for interrill erosion. It was felt that the limited number of soils used in this experiment precludes a recommendation for a general interrill erosion equation. Judgments can be made by the reader on the usefulness of a particular equation. This may be a function of which soil properties

Table 3.--Interrill erosion regression coefficients and R-squared for the independent variables in their linear form.

Equation number	Stepwise regression variables			R-squared	Coefficients			
					Constant	SL	M	LL
(1)	SL			0.455	81.9	10.43		
(2)	SL	M		0.682	263.7	10.43	-.044	
(3)	SL		LL	0.575	-28.3	10.43		3.79
(4)	SL	M	LL	0.695	193.3	10.43	-.037	1.49

Table 4.--Interrill erosion regression coefficients and R-squared for the independent variables in their slope interaction form.

Equation number	Stepwise regression variables			R-squared	Coefficients			
					Constant	LLXSL	SANDXSL	MXSL
(1)	LLXSL			0.609	83.5	0.353		
(2)	LLXSL	SANDXSL		0.720	71.1	0.228	0.188	
(3)	LLXSL	SANDXSL	MXSL	0.752	83.4	0.293	0.191	-0.001

Table 5.--Interrill erosion regression coefficients and R-squared for the independent variables in any combination (linear, quadratic, interaction)

Equation number	Stepwise regression variables			R-squared	Coefficients			
					Constant	LLXSL	MSQ(10^{-6})	SANDXSL
(1)	LLXSL			0.609	83.5	0.353		
(2)	LLXSL	MSQ		0.728	166.9	0.322	-3.94	
(3)	LLXSL	MSQ	SANDXSL	0.779	137.3	0.240	-2.97	0.136

are known. The various equations will be especially helpful to researchers wishing to determine important variables to be considered for future studies of interrill erosion.

Splash Erosion Analysis

Table 6 lists the F-values and the partial correlations between the independent variables and splash erosion (ES). Independent variables in the table are in three forms: linear, quadratic, and slope-interaction. The partial correlations showed that the linear form of the variables would generally be better predictors of splash erosion than their squared transformations.

Importance of Slope

Slope is by far the most significant single variable in Table 6. Organic content, electrical conductivity of the soil, specific gravity, and several other soil-grain-size criterion (SAND, SILT, M, FMWD, and LT61) showed some correlation with the response but were at least an order of magnitude less than the F-value for slope. The linear form for slope is in agreement with Figure 5, which shows that at 1-, 9-, and 20-percent slope angles the average splash erosion graph is a straight-line relationship.

Table 6. Independent variables, partial correlations, and F-to-enter values at the zero step of the splash erosion regression analysis (linear, squared, and slope interaction forms of the variables are shown).

VARIABLE TRANSFORMATION	VARIABLE	PARTIAL CORR.	F TO ENTER
LINEAR :	SL	0.72392	50.65
	INF	.07064	.23
	LT61	-.15900	1.19
	MWD	.12707	.76
	FMWD	-.20561	2.03
	BD	.02791	.04
	SAR	-.01557	.01
	EC	-.23739	2.75
	OC	.30753	4.81
	LL	.03250	.05
	PH	-.02322	.03
	SG	-.19577	1.83
	SILT	-.22749	2.51
	SAND	.26471	3.47
	M	-.20678	2.06
SQUARED : (QUADRATIC)	SLSQ	0.70000	44.20
	INFSQ	.04850	.11
	LT61SQ	-.12147	.69
	MWDSQ	.09523	.42
	FMWDSQ	-.18389	1.61
	BDSQ	.02786	.04
	SARSQ	-.00918	.00
	ECSQ	-.17695	1.49
	OCSQ	.27642	3.81
	LLSQ	.01520	.01
	PHSQ	-.02376	.03
	SGSQ	-.19392	1.80
	SILTSQ	-.24033	2.82
	SANDSQ	.28537	4.08
	MSQ	-.23683	2.73
SLOPE : INTERACTIONS	INFXSL	0.56157	21.19
	LT61XSL	.63549	31.16
	MWDXSL	.61840	28.48
	FMWDXSL	.42695	10.25
	BDXSL	.72174	50.20
	SARXSL	.20457	2.01
	ECXSL	.21102	2.14
	OCXSL	.67892	39.33
	LLXSL	.59758	25.55
	PHXSL	.72282	50.33
	SGXSL	.70712	46.00
	SILTXSL	.58992	24.55
	SANDXSL	.69204	42.28
	MXSL	.58576	24.03

Variables Included

Graphs of splash erosion versus slope for the individual soils also showed that most of the soils had a linear association between erosion and slope angle. All of the soils exhibited a positive relationship between splash erosion and plot slope. The steepness of the relationships varied but not as much as for the runoff erosion. The varying steepness for some soils indicated the possibility of slope interacting with one or more of the soil properties, so these values were included in Table 6. Inspection of the values in Table 6 reveals that none of the slope-soil property interactions have F-values higher than the F-value for slope alone, therefore a separate model for slope interactions is not given. The statistics and plots of the data indicate that SAR does not affect splash erosion, as was found in the runoff erosion model.

Splash Erosion Equations

Table 7 presents the results of step-wise regression analyses on the linear independent variables versus splash erosion. Variables found to be important at each step, along with the coefficients and the R-squared, are included in the table. Equation (4), Table 7:

$$ES = 238.7 + 2.35\ SL + 6.63\ OC - 88.53\ SG + 0.427\ LL$$

has an R-squared of 72.2 percent, which is the highest of the linear splash erosion models. Liquid limit, the last variable entered in the regression, is only marginally significant at the 5-percent probability level. Organic content is a common parameter used for estimating erosion, and here it is shown to be related to the splash erosion component. Specific gravity of the soil grains has a negative coefficient which indicates that as specific gravity increases, splash erosion decreases as would be expected. Slope is the dominant variable and explains 52.4 percent of the variation in splash erosion by itself.

Table 8 gives the best stepwise regression equations for any combination of the variables (linear, quadratic, and interaction). Equation (4), Table 8:

$$ES = -12.56 + 1.66\ SL - 0.002\ ECXM + .395\ OCXSL + .744\ PHSQ$$

has an R-squared of 76.9 percent. As might be expected from the linear model results, slope and an organic content-slope interaction are in this combination model. Wischmeier's M multiplied by the electrical conductivity of the soil formed a strong interaction term with a negative partial correlation with splash erosion. The square of PH was also found to be significant, probably due to the relationship of PH to soil structure.

Table 7.--Splash erosion regression coefficients and R-squared for the independent variables in their linear form.

Equation number	Stepwise regression variables				R-squared	Coefficients				
						Constant	SL	OC	SG	LL
(1)	SL				0.524	21.0	2.35			
(2)	SL	OC			0.619	12.1	2.35	5.14		
(3)	SL	OC	SG		0.693	200.0	2.35	6.20	-69.5	
(4)	SL	OC	SG	LL	0.722	238.7	2.35	6.63	-88.5	0.427

Table 8.--Splash erosion regression coefficients and R-squared for the independent variables in any combination (linear, quadratic, interaction).

Equation number	Stepwise regression variables				R-squared	Coefficients				
						Constant	SL	ECXM	OCXSL	PHSQ
(1)	SL				0.524	21.0	2.35			
(2)	SL	ECXM			0.672	34.3	2.35	-.002		
(3)	SL	ECXM	OCXSL		0.735	32.6	1.76	-.001	0.337	
(4)	SL	ECXM	OCXSL	PHSQ	0.769	-12.6	1.66	-.002	0.395	0.744

DISCUSSION OF INTERRILL AND SPLASH EROSION ANALYSIS

Comparison of Interrill and Splash Equations

The models for interrill erosion (partitioned SAR equations and Tables 3, 4, and 5) and splash erosion (Tables 7 and 8) can be used to estimate downslope erosion in grams produced from a 55.25 cm x 55.25 cm wet soil plot subjected to a 30-minute simulated rainstorm with an intensity of 76.2 mm per hour. The sum of the two components of sheet erosion, interrill and splash, provides an estimate of the total sheet erosion. When models from this erosion experiment are compared to the rill plus sheet erosion model provided by the U.S.L.E., similarities and differences are evident.

Comparison of Equations to USLE

Applying the U.S.L.E. (A = RKLSCP) to the conditions of this experiment results in a simplified form of the equation because the rainfall factor (R) is constant, length of slope (L) is constant, and factors C and P are constants, each with a value of about 1. The resulting form of the equation then is:

$$A = BKS$$

where B = RLCP is constant for this experiment. Based on the U.S.L.E., for the conditions of this experiment, erosion is a function of the product of soil erodibility and slope. The K-factor for soil erodibility, as determined from Wischmeier's nomograph, is a function of the Wischmeier M, organic content, soil structure, and permeability. These same variables with the exception of permeability are in the models presented herein for predicting erosion. Infiltration (or permeability) is one of the soil properties measured during this experiment; however, the rainfall excess was so much larger than infiltration that no significant effect due to soil permeability was evident.

Interrill erosion models presented in Tables 3, 4, and 5 show similarities to the U.S.L.E. in that slope-soil property interactions, M, and SAND (which is a function of M) were found to be important. It must be noted, however, that M has a negative coefficient compared to a positive relationship in the U.S.L.E. nomograph. Other factors (SAR and LL), found important in the equations for interrill erosion, are probably related to chemical and physical properties of the clay fractions. SAR and LL are not among factors used in determining K-values with the U.S.L.E. nomograph.

Splash erosion models presented in Tables 7 and 8 contain all the parameters used in the U.S.L.E. nomographic solution for the soil erodibility factor K, except for permeability. M, organic content, and PH (related to structure) are all soil properties used in the nomographic solution.

These results indicate that only some of the important parameters used for estimating the U.S.L.E. soil erodibility K factor agree with those measured in the laboratory. Based on the results of these laboratory tests, caution should be used in determining soil erodibility from the Wischmeier nomograph for materials such as these mine soils. The negative correlation between Wischmeier's M and erodibility and the importance of SAR and Liquid Limit in the regression equations are reasons to question the use of the U.S.L.E. methods without field verification or modifications. Parallel studies, in the field and laboratory, are needed in order to determine how to apply the results of the laboratory tests. The goal, of comparisons between field studies and laboratory tests, would be to define a relative erodibility based on a model using results of these laboratory tests. This relative erodibility would be used as an alternate estimator of the K-value used in the U.S.L.E.

A more direct use of the models presented here would be in erosion process models currently under development. Results of this experiment may be particularly applicable to models where the interrill and rill components of erosion have been defined separately. The WEPP project, discussed earlier in the third chapter in the section on future of process models (page 13), is developing this type of model and is a likely process model to make use of these results.

Problems Related to Sample Variation

The regression equations presented for interrill and splash erosion explain a maximum of 82 percent of the sample variation. A model that explained 95 percent of the sample variation using soil properties and slope would have been desirable from a statistical standpoint to increase confidence in the findings. Samples with less variation in physical and chemical properties may have made it easier to characterize soil erodibility.

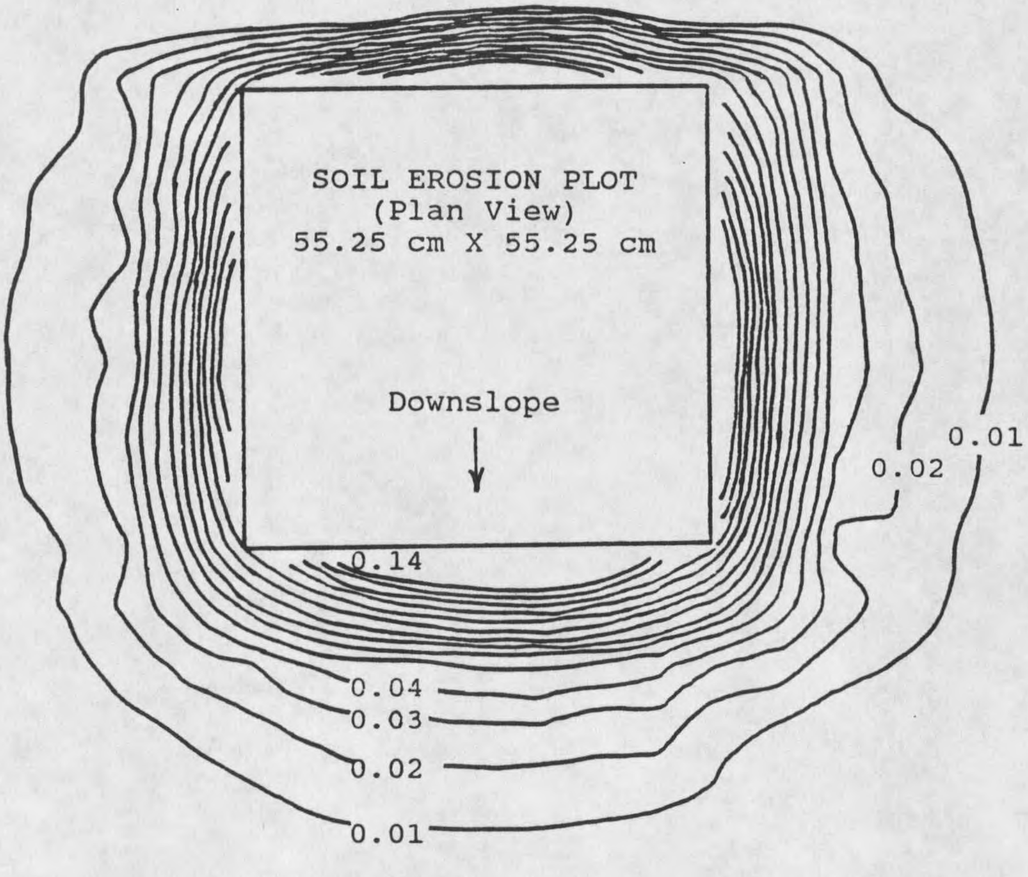
The basic problem is that physical and chemical properties of mine soil strata vary greatly with depth and lateral extent. Mining mixes the strata into a heterogeneous maze of soils with an infinite combination of properties as shown by Power and others (1975). This makes it difficult to characterize these nonhomogeneous soils without taking a large number of samples. A more logical approach may be to sample from specific strata of soil and rock wherein properties would be more homogeneous. This approach would, at least, provide information as to the range of erodibilities for overburden placement based on properties of the individual underlying strata. Mining and placement of the overburden by strata would then dictate the properties of the soil and its resulting erodibility. The feasibility of managing overburden to control mixing and subsequent placement to control erosion will ultimately depend on economics. Cost of overburden management versus cost of other methods of erosion control will be the deciding factor.

SPLASH DISTRIBUTION RESULTS

Erosion measurements made during this experiment were primarily concerned with soil moved past the lower boundary of the experimental plot. In an effort to contribute to our basic knowledge of the erosion process, additional data on splash in all directions was collected during the 30-minute runs of the experiment. This additional soil splash data was collected under the same conditions as described in the earlier chapter on "Equipment and Methods."

Splash Intensity Contours

Dry weight of soil splashed using the blotter-paper method of catchment provided information on the spatial distribution of splashed soil. Figure 7 is a typical contour map of splashed soil (dry weight per unit-area) for one of the tested soils. Contour lines are labeled as to the intensity of splash, in grams per square inch. This map and other similar maps show that lines of constant splash intensity are rounded in the vicinity of the plot corners but are generally parallel to the plot sides. This observation is especially noticeable close to the plot boundary where most of the splashed soil was concentrated.



Sample - 1S1
Slope - 1%
Contour interval = 0.01 gm/in^2

Figure 7. Contour map of splashed soil weight per unit area (grams/square inch).

The splash intensity contours parallel to the plot boundary indicate that the plot was large enough to greatly reduce boundary effects if data are taken from the center portion of each side. This suggests that a small plot can probably be used to simulate soil splash behavior at the borders of field-sized plots if the data are properly interpreted.

Total Soil Splash

Models presented in the splash erosion analysis section were based on the dry weight of soil splashed over the downslope boundary of the erosion plot. This approach does not consider splash distance and direction. These added dimensions would give further insight into splash behavior. Figure 8 is a graph of the total dry weight of soil splashed off of the 55.25 x 55.25 cm soil plot in all directions as determined from the blotter-paper collection method. The graph shows total soil splash for spoils and topsoils from the four mine sites tested in both a wet and dry condition at 1-, 9-, and 20-percent slope angles. The main conclusion that can be drawn from the figure is that total splash increases with plot slope. Variation between the wet and dry runs does not have a consistent pattern. Variation among the different soils based on soil properties is explained by the equations for downslope splash presented in the "Data Analysis" chapter of this paper.

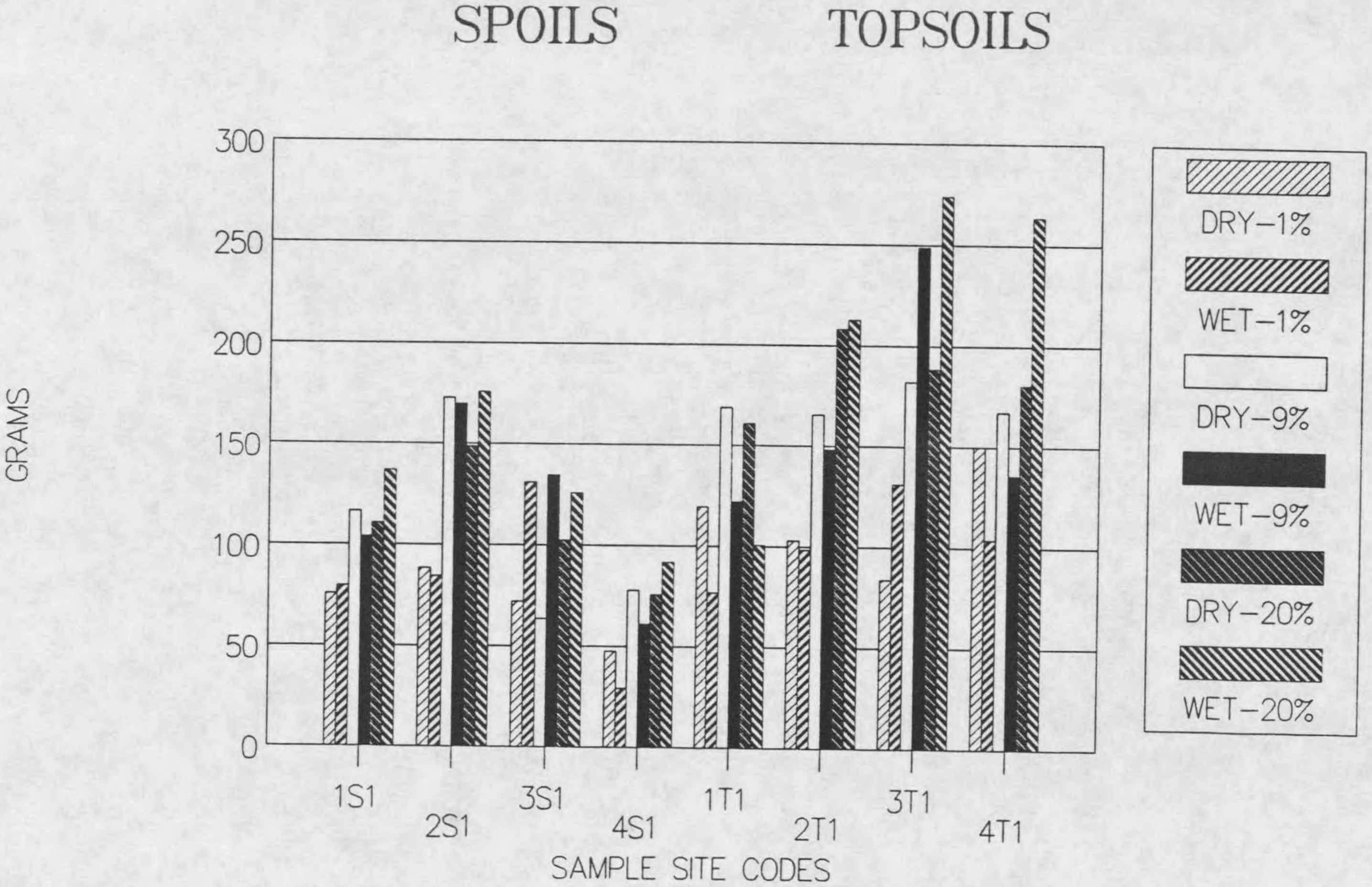


Figure 8. Total soil splashed off the soil plot for spoils and topsoils from four mine sites tested in a wet and dry condition at 1-, 9-, and 20-percent slope angles.

Splash Distance Versus Slope

Measuring the weight of soil splashed over a plot boundary does not completely quantify splash erosion. The distance soil is splashed is also an important factor. Splash erosion measurements should reflect this weight-distance relationship. Figure 9 shows the product of total weight of soil splashed off of the soil plot, multiplied by the average distance the soil was displaced downslope from the centerline of the plot. A horizontal line through the center of the plot was selected as the reference because it is the center of the source of splashed sediment when total splash is considered. When the plot slope is zero this reference line would yield an average splash distance of zero with downslope positive and upslope negative. As plot slope increases, the average downslope splash distance would be expected to increase using the centerline datum.

The total weight times splash distance was determined by multiplying the weight of soil collected on each blotter-paper times its perpendicular distance from the horizontal centerline of the plot and summing these products. The weighted average splash distance (or distance to the center of gravity of splashed soil) can be determined by dividing this weighted sum by the total soil splash weight. Figure 9 shows that slope has an even greater effect when the total weight of the soil off the plot and the distance it travels

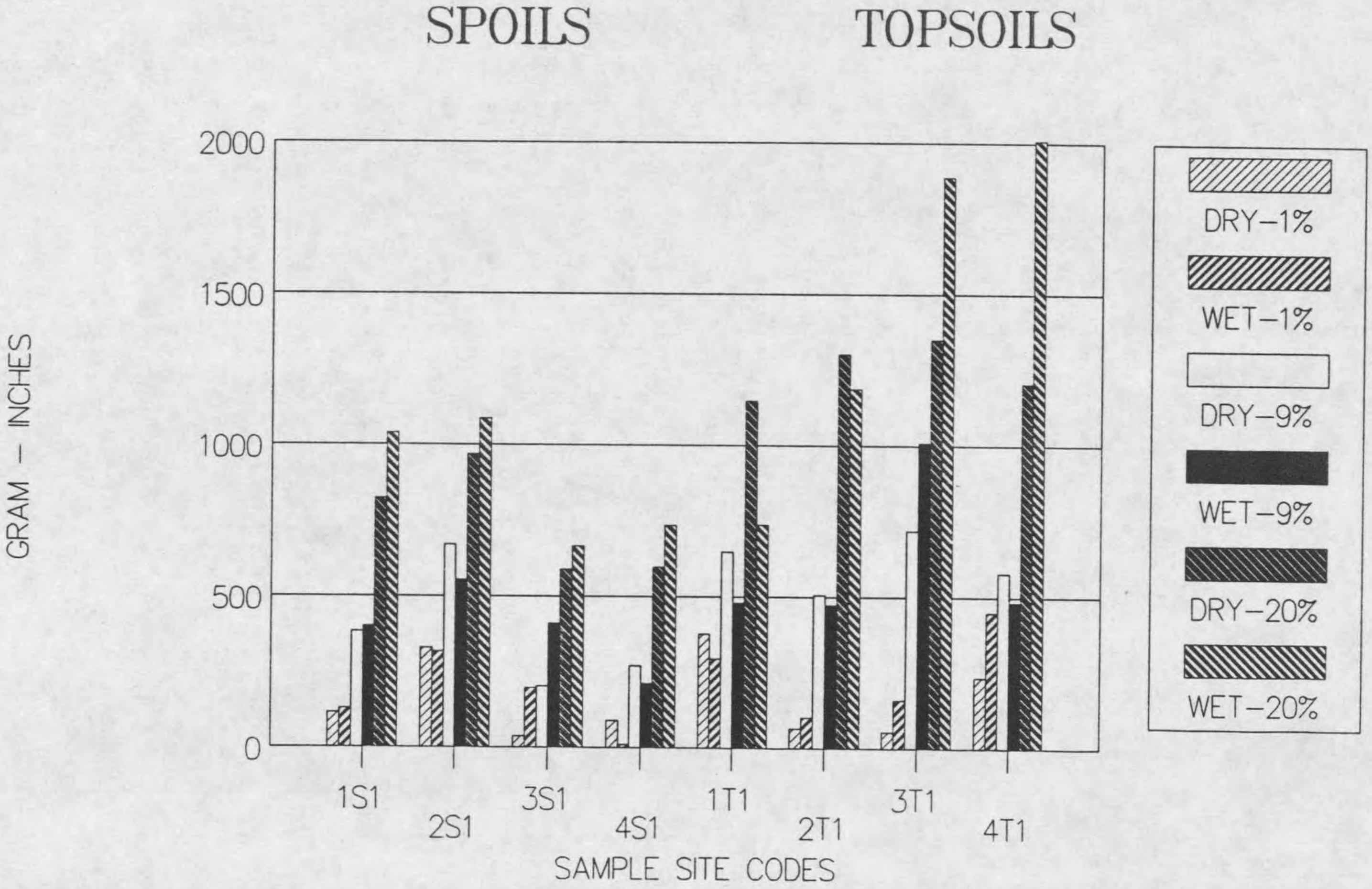


Figure 9. The product of total soil splashed and average splash distance downslope for spoils and topsoils from four mine sites tested in a dry and wet condition at 1-, 9-, and 20-percent slope angles.

is considered. This is logical because one would expect the quantity of splash and the distance it travels to increase as plot-slope increases.

Figures 8 and 9 represent splash behavior of the soil plot used in this experiment. Size and shape of the soil plot will affect the quantity of splashed soil due to the influence of the perimeter-to-area ratio of the soil plot. The perimeter provides a boundary across which splashed soil is measured and the area provides the source of soil for splash. As a given plot shape becomes smaller, the perimeter-to-area ratio will increase. Therefore, these data should not be extrapolated to different size plots without further experimentation as to the effects of plot size.

Directional Splash Distribution

The neoprene-nylon apron collection system provided data that was used to determine the proportional distribution of splash. Soil splash was collected on an apron extended out from the center foot of each side of the soil plot. This provided measurements of upslope, downslope, right, and left quantities of splash. As previously discussed, the contour maps indicate that the center 1-foot strip is largely free of edge or size effects of the plot. Figure 10 is a plot of the proportion of splash in each direction. Using the sum of the soil

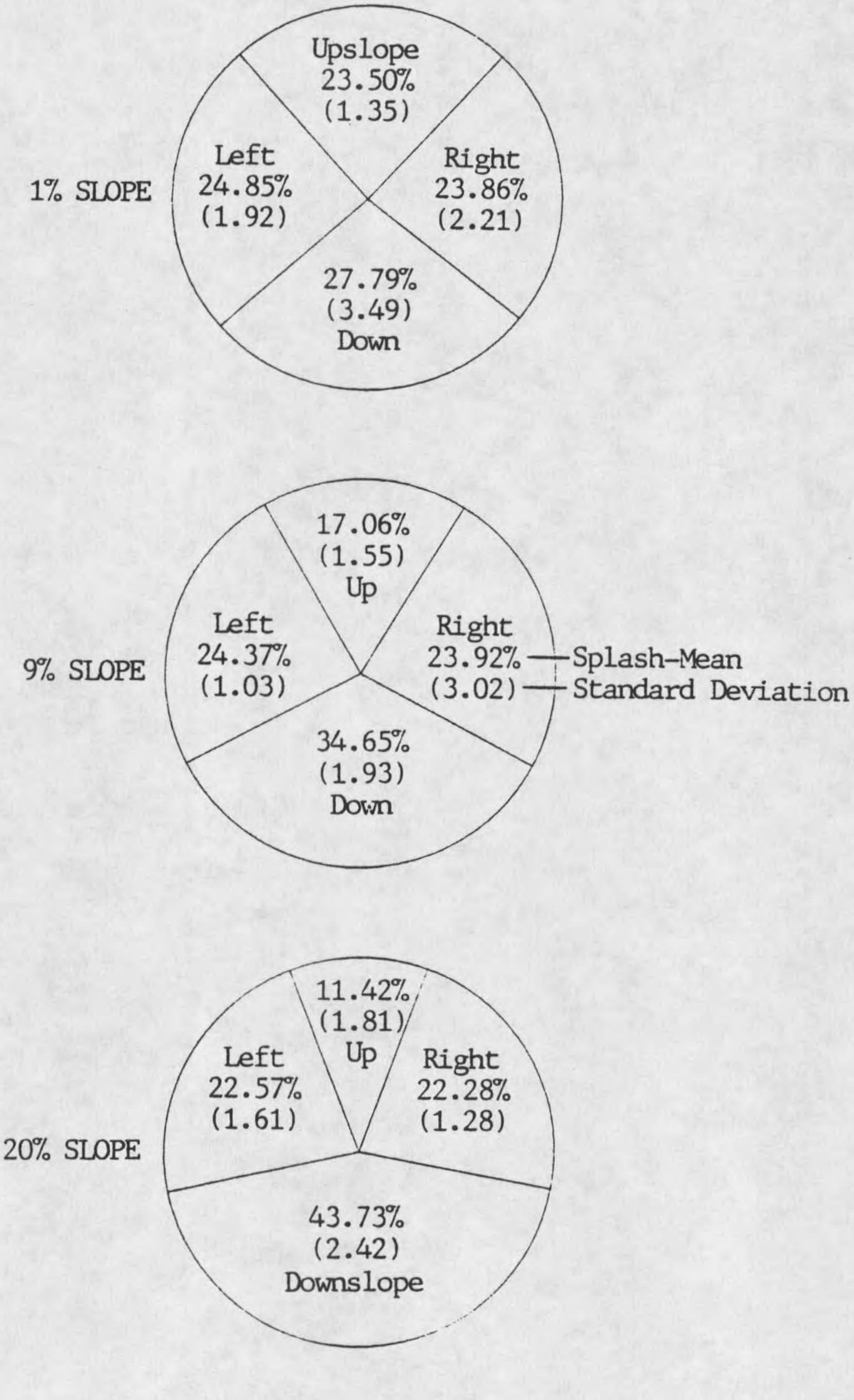


Figure 10. Proportion of splash by direction. (Average percentage of splash for all soils in the dry and wet condition at 1-, 9-, and 20-percent slopes).

splashed onto the four 1-foot-wide splash aprons as the basis, the percentage of soil splash in each direction was calculated for each soil. For a given plot slope, the percentage of soil splashed upslope varied little between the eight soils tested in both the wet and dry condition. This same small variation was found to be true for percentage of splash to the right, left, and downslope. Based on these observations, differences in soil properties and condition (wet or dry) apparently have little influence on the directional distribution of soil splash erosion. Figure 10 summarizes the results of percent soil splash in each direction for 1-, 9-, and 20-percent slopes. The pie charts depict the splash distribution and also show the average percent splash and standard deviation of the observations at each slope angle.

Figure 10 can be used to estimate the quantity of soil splashed to the right, left, or upslope from a soil plot. The splash erosion equations (ES) presented in this report are used to calculate the downslope splash erosion based on soil properties and slope. Figure 10 is then used to calculate the ratio of the percentage of splash in the desired direction to the percentage of splash downslope. This ratio multiplied by the downslope splash erosion (ES) provides an estimate of soil splash in the desired direction. As an example: suppose the calculated downslope splash erosion (using one of the "ES" equations) was 10 grams for a given soil on a 9-percent slope, and an estimate of the upslope splash erosion is needed. The upslope-to-downslope ratio is 17.06 percent divided by 34.65 percent which equals 0.492. The upslope splash erosion is found by multiplying this ratio, 0.492, times the downslope splash erosion, 10 grams. This yields an upslope splash erosion estimate of 4.92 grams.

This additional information on splash distribution provides insight into the total amount of sediment in motion due to raindrop impact. This may give an indication of soil splash available to be entrained into sheet flow or be transported directly by concentrated flow in rills and gullies. One limitation of the methods of measuring splash distribution used herein is that only soil that splashed off the erosion plot was measured. Ideally, the splash behavior on the plot should be known. This would yield measures of splash flux on the plot so that it could be related to the overall interrill and rill erosion processes. Varying the plot size and studying the effects of size on splashed sediment could provide data to predict splash flux on the plot. Measuring the splash flux on the plot with small samplers may provide a means of estimating the sheet erosion. This is based on the observation that splash erosion is a good predictor of interrill erosion since the two variables have a 73 percent correlation as observed during the data analysis.

CONCLUSION

The results of this erosion study on excavated soils provides 1) equations to predict interrill and splash erosion based on soil properties, 2) statistics that indicate SAR and liquid limit can be important soil erodibility parameters, 3) data showing that Wischmeier's M has an unexpected inverse correlation to erodibility, 4) splash erosion is highly correlated to interrill erosion, and therefore 5) splash erosion measurements may provide a method of predicting interrill erosion.

Data related to soil splash distribution provide additional information to aid in understanding erosion. The results also point out the complexity of the erosion problem and the need for further study.

Soil Erodibility Equations

The most direct application of the results of these laboratory experiments is to provide sheet erosion input to process-oriented erosion models. The regression equations for estimating the interrill and splash components of sheet erosion are functions of soil properties and slope. These equations quantify the effects of various factors which influence soil erodibility for the tested soils.

It would be valuable if erodibility of any soil could be related to commonly measured soil characteristics. However, this may not be practical for the widely varying soil characteristics possible in coal strip mines and other construction sites. It may turn out to be less expensive and more accurate to measure sheet erosion directly using a standard laboratory test similar to the one used in this experiment, when compared to testing each soil for all chemical and physical characteristics that may be related to soil erodibility. This observation is based upon some of the unforeseen results of this experiment relating to the negative coefficient on Wischmeier's M, and the significance of SAR and liquid limit. Results such as these on the limited number of samples tested indicate the complexity of relating soil erodibility to soil properties. Results of other scientists working on soil erodibility in the North Central and Western United States also show there are many complicating factors that influence soil erodibility. For example, Trott and Singer (1979) found various chemical compounds of iron, and aluminum to have a strong influence on soil erodibility. Much additional work is required to achieve a better understanding of erosion. The chapters on "Equipment and Methods" and "Data Analysis" should provide scientists with details helpful in future soil erodibility studies.

The factors which affect these laboratory erosion results reported here differ somewhat from the factors used in the U.S.L.E. nomographic solution for erodibility. This points out the possible need for additional factors to estimate soil erodibility. For this reason caution should be exercised when using the U.S.L.E. soil erodibility nomograph for mined or otherwise disturbed soils. On the positive side, the results presented in the "Data Analysis" chapter shows a linear association between slope and erosion which verifies work done by Foster and others (1977).

Splash Distribution

The chapter on "Splash Distribution" presents information which may aid in our basic understanding of the erosion process and provide information on the effects of plot size. Maps similar to the splash intensity contour map (Figure 7) indicate that the erosion plot was large enough to reduce boundary effects if data from the center portion of each side is used. Another observation is that total splash off the plot increases with slope but there was no consistent pattern of splash yield for soils which were initially in either the wet or dry condition. When the total weight of soil splashed off the plot times the distance it travels is considered, slope has an even greater influence as would be expected from the high partial correlations shown in Table 6 for slope interaction terms. The proportions of splash in each direction (Figure 10) were remarkably consistent at each slope angle (1%, 9%, and 20%), even though there were wide differences in the total splash off the plot.

Future Study Needs

These experiments revealed several phenomena worth future study. Further study is needed to determine if the relationships found for SAR and liquid limit are valid. This would require detailed studies relating the effects of the interaction of sodium and clay mineralogy to soil erodibility. Such a study might also explain in detail the negative correlation between erosion and Wischmeier's M. Studies are also needed to determine the effects of plot size, rainfall intensity, energy, momentum, and distribution. This would aid in adapting results of laboratory studies to field applications.

Another useful study would involve parallel studies on field sized plots and laboratory plots. This would be to determine if soil erodibility factors found important under laboratory conditions are also important under field conditions. This could provide a method to use laboratory tests to determine whether methods of estimating soil erodibility, such as the U.S.L.E. nomograph, include all the important soil erodibility factors for a particular soil.

A study of soil splash into small on-site samplers may provide a direct method of predicting sheet erodibility of the soil. This recommendation is based upon a 73 percent correlation between splash and interrill erosion observed during analysis of this data. If this proposed method of estimating erodibility using splash samplers proved feasible it would greatly simplify the prediction of sheet erosion.

LITERATURE CITED

Allison, L.E., J. W. Brown, H.E. Hayward, and others. 1969. Diagnosis and improvement of saline and alkali soils. Agriculture Handbook No. 60.

Dixon, W.J., ed. 1975. BMDP Biomedical Computer Programs. Health Sciences Computing Facility, Univ. of Calif.,Los Angeles, Calif.

Chow, Ven Te, and Terence E. Harbaugh. 1965. Raindrop production for laboratory watershed experimentation. J. Geophys. Res. 70(24): 6111-6119.

Curtis, Neville M., A.G. Durrach, and W.J. Sauerwein. 1977. Estimating sheet rill erosion and sediment yield on disturbed western forest and woodlands. U.S. Dept. of Agric., Tech. Notes-Woodland No. 10, West. Tech. Ctr., Portland, Oreg.

Farmer, Eugene E., and Bruce P. Van Haveren. 1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA For. Ser. Res. Pap. INT-100, 14 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

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

Knisel, Walter C., editor. 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, U.S. Dept. of Agric., Conservation Research Rep. No. 640 pp., illus.

Langbein, W.B. and S.A. Schumm. 1958. Yield of sediment in relation to mean annual precipitation. In EOS Trans. of Amer. Geophys. Union, 39, p. 1076-1084.

Laws, J. Otis. 1941. Measurements of the fall-velocities of waterdrops and raindrops. Trans. Amer. Geophys. Union 22:709-712. (Also mimeo. pub. USDA SCS-TP-145, Nov. 1941).

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

Malekuti, A., and G.F. Gifford. 1978. Natural vegetation as a source of diffuse salt within the Colorado River Basin. Water Resour. Bull. 14: 195-205.

Means, R.E., and J.V. Parcher. Physical Properties of Soils. Columbus, Ohio: Charles E. Merrill Books, Inc., 1963.

Meeuwig, R.O. 1971. Infiltration and water repellency in granitic soils. U.S.D.A. For. Serv. Res. Pap. INT-111, 20 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Meyer, L.D. 1974. Overview of urban erosion and sedimentation processes. In National Symposium on urban rainfall and runoff and sediment control. July 29-31, Lexington, KY, p. 15-21.

Meyer, L.D., G.R. Foster, and M.J.M. Romkins. 1972. Source of soil eroded by water from upland slopes. Proc. of Sed. Yield Workshop, November, USDA Agric. Res. Serv., Oxford, Miss.

Mulcher, C.K., and R.A. Young. 1972. Soil detachment by raindrops. Proc. of Sed. Yield Workshop, November, USDA Agric. Res. Serv., Oxford, Miss.

Power, J.F., and others. 1975. Progress report on research on reclamation of strip-mined land in the Northern Great Plains. A.R.S.(USDA) and North Dakota Agricultural Experiment Station, Mandan, N.D.

Rogoff, Marc Jay. 1978. Use of the universal soil loss equation in water quality assessment: an annotated bibliography. Counc. of Plan. Libr., Exchange Bibliogr. #1498, Michigan State University.

Sherard, J.L., R.S. Decker, N.L. Ryker. 1973. Hydraulic fracturing in low dams of dispersive clay. In Proceedings, Specialty Conference on Performance of Earth and Earth-Supported Structures. American Society of Civil Engineers 1(1): 653-681 and Vol. III, 1973.

Simons, D.B., R.M. Li, and L.Y. Shiao. 1976. Preliminary procedural guide for estimating water and sediment yield from roads in forests. Prepared for USDA F.S., Rocky Mtn. For. and Range Exp. Sta., Flagstaff, Ariz.

Sims, J.R., and V.A. Haby. 1970. Simplified colorimetric determination of soil organic matter. Journal Series, Pap. No. 186, Mont., Agric. Exp. Stat., Bozeman.

Tanji, K.K., M.J. Singer, D.W. Henderson, and others. 1978. Nonpoint sediment production in the COLUSA basin drainage area. First-year Ann. Prog. Rep. on EPA Grant No. R805462, Oct. 1977 through Sept. 1978. Water, Science, and Engineering Paper 4016, Dept. of Land, Air, and Water Resour., Univ. of Calif.

Trott, K.E., and M.F. Singer. 1979. The importance of Fe and Al in predicting soil erodibility. Agron. Abst. 1979 Annual Meetings, Amer. Soc. Agron., p. 211.

USDA, USDI, EPA, and States of Montana, Nebraska, North and South Dakota, and Wyoming as part of the Northern Great Plains Resources Program. April 1975. "Effects of Coal Development in the Northern Great Plains." 165 p.

USDA-Water Erosion Prediction Project, General Report, January 5,1987. (Letter from G.R. Foster).

U.S. Dept. of Agriculture, Soil Conservation Service and Environmental Protection Agency (EPA). 1977. Preliminary guidance for estimating erosion on areas disturbed by surface mining activities in the interior Western United States. Interim Final Rep., EPA-908/4-77-005, July, 26 p.

Veon, William J., and Arthur C. Miller. 1978. Soil properties that affect erosion. In Soil Taxonomy and Soil Properties. Transp. Res. Board Rec. Nat. Acad. Sci., Washington, D.C.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. Erodibility nomograph for farmland and construction sites. Jour. of Soils and Water Conserv. 16(5) 189-193.

Wischmeier, W.H., and L.D. Meyer. 1973. Soil erodibility on constructed areas. In Soil Erosion: causes and mechanisms, prevention and control. Highway Res. Board. Nat. Res. Counc., Washington, D.C., p. 20-29.

Wischmeier, Walter H., Dwight D. Smith. 1958. Rainfall energy and its relationship to soil loss. Trans. Amer. Geophys. Union 39(2) 285-291.

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