Virginia Agricultural Experiment Station **Bulletin 83-5**
Virginia Polytechnic Institute and State University

Sediment Detachment and Transport Functions to Simulate Soil Loss from Reclaimed Mine Soils

M. L. Wolfe, V. O. Shanholtz, L. L. Rice, and B. B. Ross

James R. Nichols, Dean and Director
College of Agriculture and Life Sciences
Virginia Agricultural Experiment Station
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

The Virginia Agricultural and Mechanical College came into being in 1872 upon acceptance by the Commonwealth of the provisions of the Morrill Act of 1862 "to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life." Research and investigations were first authorized at Virginia's land-grant college when the Virginia Agricultural Experiment Station was established by the Virginia General Assembly in 1886.

The Virginia Agricultural Experiment Station received its first allotment upon passage of the Hatch Act by the United States Congress in 1887. Other related Acts followed, and all were consolidated in 1955 under the Amended Hatch Act which states "It shall be the object and duty of the State agricultural experiment stations . . . to conduct original and other researches, investigations and experiments bearing directly on and contributing to the establishment and maintenance of a permanent and effective agricultural industry of the United States, including the researches basic to the problems of agriculture and its broadest aspects and such investigations as have for their purpose the development and improvement of the rural home and rural life and the maximum contributions by agriculture to the welfare of the consumer . . . ."

In 1962, Congress passed the McIntire-Stennis Cooperative Forestry Research Act to encourage and assist the states in carrying on a program of forestry research, including reforestation, land management, watershed management, rangeland management, wildlife habitat improvement, outdoor recreation, harvesting and marketing of forest products, and "such other studies as may be necessary to obtain the fullest and most effective use of forest resources."

In 1966, the Virginia General Assembly "established within the Virginia Polytechnic Institute a division to be known as the Research Division . . . which shall encompass the now existing Virginia Agricultural Experiment Station . . . ."

Sediment Detachment and Transport Functions to Simulate Soil Loss from Reclaimed Mine Soils

M. L. Wolfe, V. O. Shanholtz, L. L. Rice and B. B. Ross

Department of Agricultural Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Virginia Agricultural Experiment Station
Bulletin 83-5 August 1983

Sediment Detachment and Transport Functions to Simulate Soil Loss from Reclaimed Mine Soils

Abstract

The Finite Element Storm Hydrograph Model (FESHM), a distributed parameter model developed in the Department of Agricultural Engineering at Virginia Polytechnic Institute and State University, was modified to predict sediment yield from surface-mined areas. Separate functions were included to define interrill detachment, rill detachment, and transport capacity of overland flow. Data from rainfall simulator studies, which were conducted at two surface mine sites in southern West Virginia, were used for field verification of the model.

A comparison of simulated and recorded hydrographs showed good agreement. The model, however, consistently overpredicted sediment yield. Two factors, aggregate stability and armoring, were shown to contribute to the biased predictions.

Acknowledgments

Special thanks are extended J.N. Jones, Jr., Dan Amos, John McKay, Barry Wolfe, Basil Sweeny, Jim White and Roger Steele for taking the time from other responsibilities to provide technical assistance to the authors. Contributions from Chanchai Tiyamani, Jan Carr, Dexter Davis, Louise Howard, Kara Hurst and Phillip McClellan are greatfully appreciated.

The work upon which this report is based was supported in part by funds provided by the United States Department of Interior, Office of Surface Mining under Grant No. G1106007.

Table of Contents

List of Tables

List of Figures

Figure Page

INTRODUCTION

Over four billion tons of sediment are delivered annually into streams and rivers of the conterminous United States (Novotny and Chesters, 1981). The major sources of this sediment are the land-disturbing activities associated with mining, construction, agriculture and silviculture. Agricultural activities, particularly cropland, yield fifty percent or more of the sediment deposited in streams and lakes (EPA, 1976). Surface mining and construction activities, though not as widespread as farming, also have the potential of generating large quantities of sediment. Table 1 lists representative rates of erosion from various land uses. It is apparent that, on the basis of equal areas of disturbance, active surface mining and construction operations have the highest rates of erosion. Sediment has a two-fold effect: it depletes the land resource

Table 1. Representative rates of erosion from various land uses (EPA, 1976).

Land use	Metric tons per km^2 per year	Tons per mi^2 per year	Relative to forest = 1
Forest	8.5	24	1
Grassland	85.0	240	10
Abandoned Surface Mines	850.0	2400	100
Cropland	1700.0	4800	200
Harvested Forest	4250.0	12000	500
Active Surface Mines	17000.0	48000	2000
Construction	17000.0	48000	2000

from which it is delivered, and it degrades the quality of the water resource in which it is entrained and deposited (Robinson, 1970). Some of the adverse effects of sediment include: loss of storage capacity in reservoirs; changes in aquatic communities and their food supplies; destruction of aquatic habitat; increased water treatment costs; creation of turbidity that detracts from recreational use of water; and transportation of other pollutants such as plant nutrients, insecticides, herbicides and heavy metals (Robinson, 1970). As a result of increased environmental concern in recent years, legislation such as the Federal Water Pollution Control Act (PL 92-500, 1972) and its 1977 amendments (PL 95-217) has been passed. With specific regard to surface mining, the Surface Mining Control and Reclamation Act (PL 95-87, August 1977) regulates surface mining operations and the acquisition and reclamation of abandoned mines. The primary purpose of this act is to establish a nationwide protection program from the adverse effects, including erosion, of surface coal mining operations (Novotny and Chesters, 1981). To achieve this goal, stringent limits have been set for the allowable sediment export from surface-mined lands. Best-management sediment control alternatives are used to meet these limits. To be effective, their design must be based on reliable methods of predicting sediment yield.

Many methods of predicting soil loss and sediment yield, ranging from empirical equations to mathematical models based on erosion mechanics, have been developed for and applied to agricultural landuses. However, there has been limited application of these procedures to surface-mined areas and virtually no development of predictive procedures specifically for surface-mined areas. Consequently, sediment control practices usually consist of off-site detention ponds, designed from limited field data. On-site controls may be less expensive and/or more effective alternatives to off-site ponds. Reliable design criteria to give optimal combinations of these practices, however, are virtually non-existent. An accurate procedure to predict sediment yield from surface-mined areas on which alternative best management erosion control practices are used would be a useful tool for establishing these much-needed design criteria.

The purpose of this study was to develop a model that predicts sediment yield from surface-mined areas. Appropriate functions for describing the erosion process were chosen from the literature. An existing distributed-parameter watershed hydrology model, the Finite Element Storm Hydrograph Model (FESHM), was amended to include the sediment component. Field plot data from two surface-mine sites in West Virginia were used to verify the model.

LITERATURE REVIEW

Ellison (1947) defined erosion as a process of detachment and transport of soil material by erosive agents. Meyer and Wischmeier (1969) expanded this definition for erosion by water by separating the soil-erosion process into the following component processes:

1. detachment by rainfall
2. detachment by runoff
3. transport by rainfall
4. transport by runoff.

The relative importance of each of the four subprocesses varies greatly, depending on the conditions under which erosion occurs. Therefore, knowledge of the significance of each process for specific situations is essential for accurate prediction of sediment yields and for design of effective erosion-control practices (Meyer et al., 1975). Identification of the sources of sediment is also important in developing methods of erosion control and for developing a comprehensive soil-erosion model (Meyer et al., 1975).

This chapter summarizes some of the research reported on individual detachment and transport processes. Sources of sediment are also discussed. The final sections outline a number of methods of sediment yield prediction.

Detachment by Rainfall

Erosivity is a measure of the potential of rainfall to cause erosion. Meyer (1965) listed intensity, drop-size distribution, and drop-fall velocity as the main characteristics of natural rainfall that influence its erosivity. Many investigators (Ellison, 1947; Ekern, 1950; Mazurak and Mosher, 1968; Martinez et al., 1980) have found that the amount of soil splashed is directly related to rainfall intensity. Total mass or kinetic energy at impact also has been found to influence rainfall erosivity (Ekern, 1953; Mihara, 1951; Free, 1960; Kilinc and Richardson, 1973).

Nichols and Sexton (1932) showed that rain intensity was more important than rainfall amount in causing erosion. The effect of intensity (I) on erosion from research plots has been expressed as $I^{1.5}$ (Ekern, 1954), $I^{2.2}$ (Neal, 1938), and $I^{1.1}$ (Smith and Wischmeier, 1957).

Bubenzer and Jones (1971) investigated the importance of rainfall mass and impact velocity on the detachment and splash of soils. Soil splash was related to the kinetic energy of simulated rainfall through regression equations of the form:

$$ss = a(ke)^b \tag{1}$$

where:

ss = splash loss (g/cm^2)

ke = total kinetic energy applied ($joules/cm^2$)

a,b = empirically determined constants.

Correlation improved significantly when soil splash was related to both kinetic energy and rainfall intensity rather than to kinetic energy alone.

Free (1960) found that sand-splash loss correlated best with rainfall energy but that splash of aggregated soil was more closely correlated with the erosion index, EI (defined as the product of rainfall kinetic energy and maximum 30-minute intensity).

Bubenzer and Jones (1971) found that smaller drops produced significantly less splash than larger ones, even though the kinetic energy, total rainfall mass, and impact velocity were almost constant. As the energy level increased, the influence of drop size decreased.

Several investigators have attempted to relate various soil parameters to soil splash. Barnett and Rogers (1966) examined the relationship between 34 soil parameters and soil loss for 17 soils in the southeastern United States. Among the most significant variables in predicting soil loss were slope, moisture level at field capacity, depth of the A horizon, and various combinations of parameters from the mechanical analysis of the soils. Wischmeier and Mannering (1969) reported that in addition to the mechanical properties of the soil, such parameters as organic matter, pH, structure, bulk density of both the plow layer and the subsoil, steepness and shape of slope, the amount of air-filled pore space, the residual effects of sod crops, degree of aggregation, and parent material all contributed greatly to soil loss variance. Bubenzer and Jones (1971) also examined several soil parameters to relate soil type to detachment and splash. Terms describing particle size, aggregate index, organic matter, bulk density, moisture content, and percentage of clay were included in various combinations in regression equations. The only parameter that significantly improved correlation was percentage of clay.

Relationships have been proposed that relate detachment by rainfall to both rainfall and soil characteristics. Ellison (1944) developed the following equation:

$$E = Kv^{4.33}d^{1.07}I^{0.65} \tag{2}$$

where:

E = soil splashed during 30 minutes (grams)
K = soil constant
v = drop velocity (ft/sec)
d = diameter of drops (mm)
I = rainfall intensity (in/hr).

Based on Free's (1960) observation that soil splash is approximately proportional to the parameter EI, Meyer and Wischmeier (1969) suggested the following empirical relationship for detachment by rainfall:

$$D_R = S_{DR}A_i I^2 \tag{3}$$

where:

D_R = detachment by rainfall
S_{DR} = soil effect constant
A_i = area of detachment
I = rainfall intensity.

The detachment capacity of rainfall is influenced by the presence of overland flow. The amount of soil splashed can be either increased or reduced depending on the depth of the water (Palmer, 1965). Smith (1979) included the effect of surface water depth on soil splash as a coefficient in the following equation:

$$g_s = C_f r^2 C_h(h) \tag{4}$$

where:

g_s = splash erosion rate (l^2/t)
C_f = constant reflecting soil erodibility and cover conditions

r = rainfall intensity

$C_h(h)$ = coefficient attenuating splash erosion as a function of surface water depth.

Martinez et al. (1980) expressed soil detachment by rainfall under overland flow conditions as :

$$D_R = (66.67\pi a/b^2)C_i e^{-0.07h} \tag{5}$$

where:

D_R = detachment capacity by rainfall (g/m/sec)

a = coefficient

b = decay function with distance (cm^{-1})

C_i = detachment-transport factor

h = water depth (cm).

Detachment by Runoff

Detachment by overland flow is a function of the shear stress, or tractive force, on the soil boundary. Shear stress is defined by the surface slope and the velocity and depth of flow (Kilinc and Richardson, 1973).

Letting tractive force represent detachment by runoff, Meyer and Wischmeier (1969) derived the following empirical relationship:

$$D_F = S_{DF}A_i S^{2/3}Q^{2/3} \tag{6}$$

where:

D_F = detachment by runoff

S_{DF} = constant to express a soil's susceptibility to detachment by runoff

A_i = area of detachment
S = surface slope
Q = flow rate.

Meyer (1965) assumed that if tractive force is proportional to flow velocity squared (v^2), then detachment by runoff, also, would be proportional to v^2. Equation (6) was based on Meyer's expression for velocity, which can be presented as:

$$v = C_t S^a Q^b n^{-c} \quad (7)$$

where:

v = velocity of flow
S = slope
Q = flow rate
n = hydraulic roughness
C_t, a, b, c are constants.

The constant "a" varied from 0.30 for shallow, infinitely wide channels to 0.35 for wide, shallow, parabolic channels to 0.38 for wide, shallow, triangular channels. Therefore, v is approximately proportional to $S^{1/3}Q^{1/3}$, where the hydraulic roughness is constant, and detachment by runoff is assumed proportional to $S^{2/3}Q^{2/3}$. Consequently, D_F was assumed proportional to $S^{2/3}Q^{2/3}$. Soil effect was expressed as a constant since no information was available for expressing a soil's susceptibility to detachment by runoff as a function of its properties.

Foster and Meyer (1975) proposed the following equation to estimate detachment by runoff as a function of shear stress:

$$D_{RO} = C(\tau - \tau_c)^a \qquad (8)$$

where:

D_{RO} = detachment capacity by runoff

τ = average shear stress

τ_c = critical shear stress

C and a are constants.

Transport by Rainfall

The capacity of rainfall to transport soil by splashing is a function of slope steepness, amount of rain, soil properties, microtopography, and wind velocity (Meyer and Wischmeier, 1969). Meyer and Wischmeier (1969) expressed the function empirically as:

$$T_R = S_{TR}SI \qquad (9)$$

where:

T_R = transport by rainfall

S_{TR} = soil effect constant

S = slope

I = rainfall intensity

The effects of wind and microtopography were omitted because pertinent relationships were not available.

Ekern (1953) found that the percentage of total splashed soil that moved downslope equaled the percent slope plus fifty. Ellison (1945) reported that 75 percent of the splash moved downhill and 25 percent moved uphill on a 10 percent slope. Bubenzer and Jones (1971) found that the distribution of the splashed material in their study varied directly with slope. Farmer and Van Haveren (1971) proposed the following equation to relate the downslope component of soil splash to the slope:

$$S_d = \sin(x) + \cos(x/2) \tag{10}$$

where:

S_d = portion of total soil splash moving downhill

x = slope angle (degrees).

Martinez et al. (1980) stated that the amount of soil splashed is directly related to rainfall intensity. Meyer and Wischmeier (1969) expressed transport by rainfall as a function of slope and rainfall intensity. Soil effect was included as a constant.

Martinez et al. (1980) developed a model to predict soil transported by rainfall in sloping areas:

$$T = (2\pi a/b)((\sin(x)+\cos(x/2))-0.5) \tag{11}$$

where:

T = soil transported by rainfall (g/cm/unit of time)

a = coefficient

b = decay function with distance (cm^{-1})

x = slope angle (degrees).

Martinez et al. (1980) also presented an equation for predicting transport by rainfall when overland flow is present:

$$T_R = (66.67\pi a/b^2)C_t[(\sin(x) +0.5\cos(x))-0.5e^{-0.07h}] \tag{12}$$

where:

T_R = soil transportability by rainfall (g/m/sec)

a = parameter

b = decay function with distance (cm^{-1})

C_t = transportability factor

x = slope angle (degrees)

h = water depth.

The parameter "a" was estimated using multiple regression analysis. The prediction equation is:

$$a = [0.00848 + 0.0023 \ln(K)]I \qquad (13)$$

where:

a = model parameter

K = erodibility

I = rainfall intensity.

The transport capacity of rainfall by raindrop splash is usually negligible (Bennett, 1974). Research that separated erosion by splash from that by thin film runoff showed that rain intensity affected soil loss by runoff much more than splash loss (Moldenhauer and Long, 1964; Farmer and van Haveren, 1971). Harmon and Meyer (1978) found that doubling rain intensity slightly more than doubled sediment moved by splash but approximately quintupled sediment carried by runoff.

Transport by Runoff

Transport by runoff can be estimated as a function of water discharge, flow depth, flow velocity, rainfall effects, soil depth, and slope steepness (Martinez et al., 1980). Laursen (1958) found that the sediment-carrying capacity of flowing water is approximately proportional to the fifth power of the flow velocity.

Based on Laursen's (1958) work, Meyer and Wischmeier (1969) assumed that transport by runoff was proportional to v^5. They derived an empirical equation for transport by runoff based on an expression for flow velocity cited earlier (Equation 7). The expression is:

$$T_f = S_{tf} S^{5/3} Q^{5/3} \tag{14}$$

where:

T_f = transport capacity of runoff

S_{tf} = constant to account for the effect of particle size and density on the transportability of the soil

S = slope

Q = flow rate.

Source Areas of Sediment

The erosion process in upland areas can be divided into interrill erosion and rill erosion according to the source of the eroded sediment (Meyer et al., 1975). In general, runoff on erodible soil surfaces concentrates in many small definable channels, called rills (Foster, 1971). Rill erosion is that occurring in the rills, and interrill erosion occurs on the areas between the rills (Foster and Meyer, 1975).

Rill Erosion

The major subprocesses controlling rill erosion are detachment by runoff and transport by runoff (Foster and Meyer, 1975). Rill erosion begins when the eroding capacity of the flow at some point exceeds the ability of the soil particles to resist detachment by flow (Meyer et al., 1975). Once rilling begins, the concentrated flow tends to increase the detachment rate, and rilling progresses. Rill development often proceeds upslope as headcuts. The erosion at each headcut is very intense because of the erosive overfall condition. Where headcuts develop, they apparently contribute the major portion of the soil lost from the rill (Meyer et al., 1975). Rill erosion can occur without major headcuts as a relatively uniform increase in the erosion rate with distance along the rill (Meyer et al., 1975).

Rill erosion is most common in regions of rather intense precipitation and on soils of low absorptive capacity. Soils with a high silt content are especially vulnerable, although the process usually occurs during heavy rains on all areas where loose soil overlies dense subsoil. Rill erosion is characterized by long grooves, generally box-shaped, often extending from near the top of a cultivated field down the slope to the lower side of the field.

The extent of rilling and type of rill pattern that develops on sloping land depends on soil properties, slope steepness and other topographic characteristics, runoff rate and tillage (Meyer et al., 1975). Assuming that rill frequency and cross-sectional geometry can reach an equilibrium condition, Li et al. (1977) used information on stable channel and watershed geomorphology (Li et al., 1976) to derive the following equation to describe rill density:

$$D = 100(K_1 K_2 \nu / 8g)(i S_o^2 / d_{84}^3) \tag{15}$$

where:

D = rill density (percentage of area)

K_1 = parameter describing boundary roughness

K_2 = constant depending on angle of friction and lift-to-drag ratio of sediment particle

ν = kinematic viscosity

g = acceleration due to gravity

i = rainfall intensity

d_{84} = size of sediment on the bed, of which 84 percent is finer by weight

S_o = channel bed slope

Equation (15) agrees with the work of Meyer et al. (1975) that suggested that rill erosion could be expected to increase as slope steepness and runoff rate increase, and particle size decreases (soil erodibility increases). Li et al. (1977) stated that further study was necessary to validate Equation (15).

Foster et al. (1977a) reported microrelief data from three 10.7 meter erosion plots, one on a twenty percent slope and two on a six percent slope, which suggested that rill density and geometry, as expressed by total rill width, varied relatively little with distance beyond one meter downslope from the upper end of the plot. The data also indicated that the total rill width on highly erodible soils increases with slope steepness. Meyer et al. (1975) conducted a rainfall simulator study to determine the influence of rill frequency on erosion. Based on the data from four plots as given in Table 2, denser rilling resulted in greater erosion. Results similar to those in Table 2 were obtained in a similar study on an erodible Russell silt loam. Meyer et al. (1975) noted that soils that do not rill readily may not follow this trend because a broader distribution of flow may reduce the total amount of erosion.

Table 2. Effect of rill frequency on soil erosion (Meyer et al., 1975)

Plot	Downslope rills per 12 ft of width	Soil loss per 12 ft of width (lb)
M-1 (random rills)	3 - 5	686
M-3 (herringbone rills)	2	622
M-4 (herringbone rills)	2	609
M-2 (herringbone rills)	1	496

Interrill Erosion

Soil erosion on interrill areas combines the processes of soil detachment by raindrop impact, transport by splash, and transport by very thin flow (Meyer, 1980). Young and Wiersma (1973) concluded that rainfall energy, rather than surface-flow energy, was the major force initiating soil detachment on interrill areas. Meyer et al. (1975) agreed that thin flow on interrill areas has very little detachment capacity in the absence of raindrop impact. Martinez et al. (1980) stated that detachment by runoff on interrill areas may be minimal and neglected due to shallow depths and low flow rates occurring on those areas.

Soil particles are transported to rills partly by raindrop impact (Mutchler and Young, 1975; Meyer et al., 1975), but the primary means of transport to rills is very thin surface flow accelerated by raindrop impact splash velocities (Mutchler and Young, 1975; Meyer et al., 1975). Foster and Meyer (1975) estimated the transport capacity of runoff on interrill areas as:

$$T_{ro} = C_t S Q \tag{16}$$

where:

T_{ro} = transport capacity of interrill flow (g/m/sec)

C_t = soil transportability factor

S = slope steepness

Q = water discharge (cm^3/sec/m of width).

Meyer (1980) found that interrill erosion (E) was related to rain intensity (I) as the power equation, $E = c(I)^b$, for a wide range of soils and cropping conditions. The same type of relationship was found by Neal (1938) and Ekern (1954). This relationship also fits the soil loss data of Moldenhauer and Long (1964).

The exponent b varied from approximately 1.6 for soils with near 50 percent clay to near 2.0 for low-clay soil in Meyer's (1980) study. This result seemed to indicate that the influence of rainfall intensity on erosion was greater for low-clay soils than for those with higher clay contents. For the low-clay soils (silts, silt loams, loams and sandy loams), the power equation with b = 2 ($E = cI^2$) fit the data well, and the coefficient c then expressed the relative interrill erodibility of the different soils. When a certain soil was studied at different crop stages, c indicated the relative effect of different cropping conditions on interrill erosion.

Slope steepness is another factor influencing interrill detachment (Foster et al., 1977a). Data of Meyer et al. (1975) indicate that the relationship of interrill detachment to slope steepness is linear for slopes less than fifteen percent. On steep slopes, the detachment capacity of rainfall probably limits interrill erosion while, on flat slopes, the transport capacity of interrill flow may possibly limit sediment delivery (Foster and Meyer, 1975).

Interrill erosion is also a function of soil characteristics (Foster et al., 1977a). Primary particle size distribution, amount and type of clay, and clod size after tillage (Moldenhauer and Long, 1964; Bubenzer and Jones, 1971; Moldenhauer and Koswara, 1968) are some of the soil factors that influence interrill detachment. Different soils with different textures and cohesiveness may vary greatly in their susceptibility to rainfall detachment (Meyer, 1980).

Methods of Predicting Sediment Yield

Empirical Methods

One of the first empirical equations to predict the amount of soil loss per year by sheet erosion was developed by Musgrave (1947). Soil loss was defined as a function of erodibility, cover, degree and length of slope, and the maximum 30-minute amount of rainfall during a 2-year frequency event. The equation was limited to estimating long-term average soil losses for broad areas. It was most useful in the more humid areas of the country (EPA, 1973).

Perhaps the most widely used empirical equation is the Universal Soil Loss Equation (USLE) introduced by Wischmeier and Smith (1960):

$$A = RKLSCP \tag{17}$$

where:

A = annual soil loss (tons/acre)
R = rainfall factor
K = soil erodibility factor
LS = slope length and gradient factor
C = cropping management factor
P = erosion control practice factor.

This equation was developed from 10,000 plot years of data. It estimates the amount of soil moved per acre, but seldom gives a reliable estimate of the sediment yield to a channel because it does not account for deposition on the land.

The USLE can be used in conjunction with a delivery ratio to predict sediment yield. A delivery ratio is the sediment yield at any point along a channel divided by the source erosion above that point (Williams, 1975). Delivery ratios have been computed for only a small portion of the United States.

Williams (1975) modified the USLE by replacing the rainfall factor with a runoff factor (volume of runoff x peak runoff rate for a storm):

$$S = 95(Qq_p)^{0.56}KLSCP \tag{18}$$

where:

S = sediment yield (tons)
Q = volume of runoff (acre-feet)
q_p = peak flow rate (cfs)
K,L,S,C,P are as defined in the USLE.

Onstad and Foster (1975) and Williams (1975) concluded that introducing the runoff component improved individual storm predictions over the basic USLE. Because the runoff component is highly correlated with rainfall and also defines the quantity of runoff available, it describes the processes of detachment and transport better than does a rainfall factor alone.

The USLE has been applied in both the original and modified forms to surface mined areas. Haan and Barfield (1978) proposed guidelines for evaluating the USLE factors for surface-mined sites, but there is limited experimental data to validate these guidelines. Barfield et al. (1979) found the USLE superior to other empirical equations for surface-mined area applications. They concluded that the relative sediment yield calculated for alternative mining strategies and sediment control measures gives a reasonably reliable comparative evaluation of these strategies and measures.

Hockman (1981) concluded that the USLE did not accurately predict soil loss from the surface-mine site that he investigated. He noted that the predictions improved when measured soil loss exceeded three tons per acre.

Modifications of the USLE specifically related to surface mine applications include the Deposition Modified USLE (Haan and Barfield, 1978) to account for deposition in vegetation between erosion areas and established waterways on long steep slopes. Chen (1974) modified the CP factor to account for surface stabilization characteristics.

Various other empirical equations have been developed for different conditions. For example, Kilinc and Richardson (1973) developed an equation to predict soil loss from a single, short-duration storm. The equation is supported by statistical results from data collected on slopes up to 40 percent and rainfall intensities up to 4.6 inches per hour.

Mathematical Basis

Three differential equations form the mathematical basis for modeling sediment yield (Bennett, 1974). These equations describe the movement of suspended sediment particles in a one-dimensional, infinitely wide, free surface flow:

$$\partial h/\partial t + u\partial h/\partial x + h\partial u/\partial x = q \tag{19}$$

$$\partial u/\partial t+u\partial u/\partial x+g\partial h/\partial x=g(S_o-S_f)-qu/h \tag{20}$$

$$\partial(hc)/\partial t+(1-\lambda)\partial y/\partial t+\partial(hu_p c)/\partial x=\partial/\partial x h\varepsilon_p \partial c/\partial x \tag{21}$$

where:

- h = depth of flow
- t = time
- u = flow velocity
- x = distance in the direction of flow
- q = gravitational constant
- S_o = local bed slope
- S_f = friction slope
- c = sediment concentration
- λ = porosity of deposited sediment
- y = local bed elevation
- u_p = average velocity of sediment

ε_p = sediment particle mass transfer coefficient.

Equations (19) and (20) are, respectively, the conservation of mass and momentum equations for flow. Equation (21) is the conservation of mass equation for sediment. Equations (19)-(21) are equally applicable to sediment transport by overland flow and by channel flow, although in certain channel-flow situations the equations need to be modified to consider variations in cross-sectional shape and area with distance (Bennett, 1974).

Stream-erosion and sediment-transportation equations may be modified and used to predict land erosion because the mechanics of stream-channel erosion and land erosion are complementary (Kilinc and Richardson, 1973). Kilinc and Richardson (1973) stated that any bedload transport equation for alluvial channels using tractive force or stream-power methods may be modified for overland flow and used as a transport equation for land erosion. However, Smith (1979) expressed doubt that existing transport equations would be accurate when applied to shallow flows on steep watersheds with fine sediments.

Equation (21) differs from the conservation of mass equation for a dissolved substance in that the second term on the left accounts for deposition or erosion from the bed. The term on the right-hand side of Equation (21) accounts for dispersion of the material while it is suspended in the flow. In comparison with the effects of other processes embodied in Equation (21), dispersion is normally negligible (Bennett, 1974). Also, although it cannot necessarily be assumed that the transport velocity of suspended sediment is equal to the flow velocity, it is customary to make this assumption (Bennett, 1974).

Smith (1979) solved Equation (21), neglecting dispersion. He expressed the erosion-deposition term (second term on the left) as the sum of the splash erosion rate, g_s (Equation 4), and the hydraulic erosion rate, g_h:

$$g_h = C_g(C_s - C_{mx}) \tag{22}$$

where:

C_g = constant related to particle fall velocity when $C_s \geq C_{mx}$

C_s = steady flow maximum concentration

C_{mx} = steady flow transport capacity.

Almost all existent experimentally-based expressions for C_{mx} have been developed using uniform sand particles, for depths much greater than overland flow depths, and for slopes much lower than upland watershed slopes (Smith, 1979).

Foster and Meyer (1972a) presented Equation (21) as:

$$\partial G_F/\partial x = D_F + R_{DT} \tag{23}$$

where:

G_F = weight transport rate per per unit width

x = distance

D_F = net flow detachment rate (weight/unit time/unit area)

R_{DT} = net raindrop detachment rate (weight/unit time/unit area).

In deriving this equation, Foster and Meyer (1972a) implicitly assumed that the first term on the left side of equation (21) is negligible or, alternatively, that the flow is quasi steady state. This is a common assumption made in calculations concerning predictions of bed formation (e.g., Simons and Richardson, 1966).

Foster and Meyer (1972a) suggested the following relationship for determining the net flow detachment rate:

$$(D_F/D_C) + (G_F/T_C) = 1 \tag{24}$$

where:

D_F = net flow detachment rate (weight/unit time/unit area)

D_C = ultimate detachment capacity of the overland flow

T_C = ultimate transport capacity of the overland flow

G_F = weight transport rate per unit width.

This approach is equivalent to assuming that a particular flow carrying less than its transport capacity will fill this capacity according to the first-order reaction:

$$D_F = G(T_C - G_F) \tag{25}$$

where:

G = reaction rate coefficient.

Equation (25) was not experimentally verified when it was presented.

Computer Simulation Models

A number of approaches have been used to simulate the erosion and sediment yield processes with computer models. Both empirically-developed and theoretically-based equations have been used to define sediment detachment and transport.

One of the earliest models was developed by Negev (1967). He used a power-function relationship to calculate the sediment supply from impervious surfaces. If overland flow occurred, all the loosened material was transported. The rate of rill and gully erosion was also computed using power functions.

David and Beer (1974) attempted to simulate erosion by water using power functions to define the detachment and transport processes. They recognized some major problems but still concluded that their model formed a sound and workable foundation for erosion simulation. One significant drawback was the amount of time needed to calibrate the parameters included in the power-function relationships.

Onstad and Foster (1975) moved away from power functions and used modifications of the USLE to define the detachment and transport processes. The model computed and compared detachment and transport potentials to determine sediment yield and deposition. Williams and Berndt (1977) used the modified universal soil loss equation (Equation 18) in a model designed to predict sediment yield from ungaged watersheds.

Foster and Meyer (1975) presented a model based on the sediment continuity equation, assuming quasi-steady flow (Equation 21) and the relationship defined by Equation (23). They considered both interrill and rill erosion in predicting sediment loads and erosion or deposition rates for all locations within an upland area at all times during an erosion event.

Another model (Kuh and Reddell, 1977) which predicts the location of sediment deposition was described by Sweeten and Reddell (1976). It is a two-dimensional model that predicts both the total amount of erosion from a watershed and the areal distribution of erosion and sediment deposition. The model includes procedures for calculating the rainfall detachment capacity, runoff detachment capacity, transport capacity, effective rainfall width, and effective runoff width. These values were used in a closed-form soil loss equation.

Barfield et al. (1979) found no continuous simulation models developed specifically for surface-mine applications; however, other models have been applied to various mining situations. Jennings et al. (1980) described several watershed models with particular emphasis on their sediment computations. They indicated that these models will be applied to surface-mine conditions in future studies.

Overton and Crosby (1980) simulated the effects of contour coal strip mining on runoff and pollutant yields with ERODE-I, a model developed at the University of Tennessee. The erosion mechanics component of ERODE-I is a modification of the soil loss model developed by Foster and Meyer (1972b). A conservation of sediment mass and a diffusive type relation between detached particles and sediment transported is included in the model.

Warner et al. (1981) determined the relative sediment yield expected from alternative surface mining methods using a model called SEDIMOT, a distributed parameter model developed at the University of Kentucky. In this model the Modified Universal Soil Loss Equation (MUSLE) predicts erosion from relatively homogeneous subareas. Sediment routing is performed on a particle size basis using Williams' (1975) routing equation.

Smith (1979) described KINEROS, an extension of a model KINGEN by Rovey et al. (1977). KINEROS simplifies a watershed geometrically into a network assembly of rectangular planes, channels, and storage elements. Sediment detachment is calculated by Equations (4) and (22). A choice of equations is included for the transport process. The equations are those of: a) Bagnold (Kilinc and Richardson, 1973); b) Yang (1973); c) Yalin (1963); d) Ackers and White (1973); and e) Engelund and Hansen (1967).

Smith (1979) studied a 22-ha watershed, established on a reclaimed portion of a stripmine area in western Colorado. The reshaped spoil had been covered with 15 to 30 cm of clay loam topsoil. The watershed had mean surface slopes ranging from 12 to 15 percent and channel slopes as high as 20 percent. Application of the model indicated a need for more data on median particle size and particle-size distribution of sediment in the runoff water (Smith, 1979). Also, comparison with snowmelt runoff data indicated that more appropriate sediment-transport relationships need to be developed for steep watersheds with fine sediment.

KINEROS can be used to study the effectiveness of various surface treatments that can impede runoff velocity. Some surface treatments that involve artificial roughening in the form of mulching or harrowing require translation into hydraulic roughness changes, so that any simulation would be no better than the estimated change in roughness coefficient. Treatments such as intercepting terraces, however, can be simulated directly by KINEROS.

Smith (1979) simulated the effects of slope length. Shorter slopes limit velocity, depth of flow, and other variables affecting erosion. Smith found that, although runoff was unaffected, sediment production from the system (including terraces, where deposition occurs) was almost proportional to terrace interval. Sediment loss from the surface, before the effects of the terrace channels, was approximately proportional to terrace length raised to the 1.4 power. As surface cover increases, the erosive force of rain is reduced and surface flow resistance is increased, slowing the flowing water. The decrease in erosion caused by increased cover can be simulated in KINEROS by reducing the parameter C_F in the expression that defines detachment. Unfortunately, Smith (1979) had not produced an empirical relationship between C_F and any field measure of plant density or cover interception.

DISTRIBUTED PARAMETER MODEL STRUCTURE

Two basic approaches have been used in the development of computer models that predict the hydrologic response of watersheds. Many of the models are lumped parameter models in which non-uniform parameters, such as rainfall and topographic characteristics, are weighted to obtain representative values for the entire drainage basin (Ross et al., 1979). The output from this type of model is the quantity and quality (for some models) of runoff at a single point, generally the watershed outlet (Ross et al., 1980).

The second type of model is based on a distributed parameter structure in which the spatial variation of watershed characteristics is maintained. A watershed is divided into a number of sub-areas, each selected to be as hydrologically homogeneous as possible. This kind of model yields more comprehensive information than the lumped parameter type. Consequently, a major advantage of a spatially-responsive model is the ability to identify critical influencing areas, whether flow quantity or sediment yield is being simulated (Ross et al., 1980). Each model structure has both advantages and disadvantages. The intended application of the model, then, should be the deciding factor in selecting one of the two approaches.

A major objective of predicting sediment yield from surface-mined areas is to demonstrate the relative effectiveness of different erosion control practices, both individually and in various combinations. Many activities and, therefore, different landuses occur simultaneously in a surface-mined watershed. A distributed parameter model allows the prediction of sediment yield from each area of the watershed and leads to the identification of the critical areas.

The model used in this study is the distributed parameter Finite Element Storm Hydrograph Model (FESHM) developed in the Agricultural Engineering Department at VPI&SU to predict the hydrologic response of ungaged areas. The model consists of two major components: a precipitation excess generator and a flood routing algorithm. All model parameters are based on readily definable watershed and climatic properties, so calibration and optimization are not required. Model documentation and concepts are discussed extensively by Judah (1973), Judah et al. (1975), Li (1975), Ross (1975; 1978), Ross et al. (1978), Heatwole (1979), Heatwole et al. (1982), and Shanholtz et al. (1981a).

Processes such as infiltration, canopy interception, seasonal growth of vegetation, and depression storage are described in the FESHM. Ross et al. (1980) demonstrated how these capabilities, together with the spatial detail and responsiveness of the model, allow a ready adaptation of the model to provide for the prediction of sediment yield.

The version of the FESHM used for this study was developed by Heatwole et al. (1982). The original model was modified to account for transmission losses from the overland flow plane. Heatwole (1979) explained the desirability of including this capability in the model. First, the model would be a more accurate representation of the physical system. Also it should lead to improved runoff predictions for low intensity storms and for conditions where great spatial variability exists in the soils of a hillside. Ultimately, this model should provide more accurate simulations of the transport of nonpoint source pollutants such as sediment, other suspended particles, and dissolved compounds. Ross et al. (1978) stated that the ability to simulate sediment transport will be one of the more important uses of the FESHM.

SELECTION OF DETACHMENT AND TRANSPORT RELATIONSHIPS

Relationships to describe the detachment and transport processes were chosen from the literature. First, it was assumed that transport by rainfall is negligible, an assumption supported by Bennett (1974).

The main criteria for selecting detachment and transport relationships were: a) the equations should be based on erosion mechanics; b) there should be no coefficients that require calibration (i.e., all coefficients should be determined from watershed characteristics); c) there should be separate equations for rill and interrill erosion.

Derivation of Detachment Equations

The equations chosen to define interrill and rill detachment on the overland flow elements were adapted from Foster et al. (1980). The two equations were presented as:

$$DI = 0.210\ EI(s+0.014)KCP(q_p/V_u) \tag{26}$$

$$DR = 37983mV_u q_p^{1/3}(x/72.6)^{m-1}s^2KCP(q_p/V_u) \tag{27}$$

where:

DI = interrill detachment rate (lb/sq.ft/sec)

DR = rill detachment capacity rate (lb/sq.ft/sec)

EI = Wischmeier's rainfall erosivity (energy x 30-minute intensity) [(100(ft-tons/acre)(in/hr)]

x = length of the overland flow element (ft)

s = sine of the slope angle

m = slope length exponent

K = USLE soil erodibility factor [(tons/acre)(acre/100 ft-tons)(hr/in)]

C = USLE cover management factor

q_p = peak runoff rate (ft/sec)

V_u = runoff volume (ft).

Equations (26) and (27) meet the criteria listed above. The factors K, C, and P are from the Universal Soil Loss Equation (USLE) and have been evaluated extensively for agricultural land uses. Work is currently in progress to determine soil erodibility factors for mine soils in surface-mined areas.

The detachment equations are based on the concept of dividing the erosion process into rill and interrill erosion according to the source of the eroded sediment (Meyer et al., 1975; Foster and Meyer, 1975). All sediment detached from interrill areas is assumed to move laterally to the rills. Flow in the rills transports this sediment, as well as the sediment detached from the rills. The equations were derived from the equation of continuity for sediment transport (Bennett, 1974), incorporating expressions to describe rill and interrill erosion (Foster et al., 1977a). The following derivation follows work reported by Foster et al. (1977a), Foster et al. (1977b), and Foster and Meyer (1972a).

Assuming negligible dispersion and quasi-steady flow, Foster and Meyer (1972a) wrote the continuity equation for sediment as:

$$\partial G/\partial x = D_r + D_i \tag{28}$$

where:

G = sediment load (mass/unit width)
x = distance downslope (length)
D_r = rill detachment (mass/unit area)
D_i = interrill detachment (mass/unit area).

An expression defining detachment on interrill areas as a function of raindrop impact, soil characteristics, and slope steepness is:

$$D_i = K_i I(bS + c) \tag{29}$$

where:

K_i = soil erodibility factor for interrill erosion (mass/unit area/erosivity)
I = rainfall erosivity factor (erosivity units)
b = coefficient for slope effect on interrill erosion
S = slope of land surface
c = constant for slope effect on interill erosion.

Detachment on rill areas depends on the shear stress of rill flow and can be expressed as:

$$D_R = a_s(\tau_e - \tau_{cr})^{\xi} \tag{30}$$

where:

a_s = coefficient
τ_e = effective shear stress of flow
τ_{cr} = critical shear stress of flow
ξ = exponent

Assuming $\tau_{cr} = 0$ and $\xi = 3/2$ (from data of Partheniades, 1965), Equation (30) becomes:

$$D_R = a_s \tau_e^{3/2} \qquad (31)$$

Assuming effective shear stress is proportional to average overland flow depth and slope steepness, effective shear stress can be defined as:

$$\tau_e = C_\tau \gamma y S \qquad (32)$$

where:

$C_\tau = \tau_e/\tau_a$

$\tau_a = \gamma y S$ = average stress

γ = weight density of the flow

y = overland flow depth

S = land slope.

Overland flow depth is usually expressed by a uniform flow equation, such as the Darcy-Weisbach form (Foster et al., 1968):

$$y = (f_c/8gS_e)^{1/3} q^{2/3} \qquad (33)$$

where:

f_c = coefficient of friction

g = acceleration due to gravity

S_e = slope of the energy gradeline

q = flow rate.

Assuming steady-state conditions, $q = \sigma x$, where σ = excess rainfall rate (rainfall rate - infiltration rate). Also, S_e is usually assumed equal to the land slope, or $S_e = S$. Incorporating these assumptions and Equation (33) into Equation (32) yields:

$$\tau_e = C_\tau (f_c/8g)^{1/3} S^{2/3} (\sigma x)^{2/3} \qquad (34)$$

Substituting Equation (34) in Equation (31) yields:

$$D_R = a_s C_\tau^{3/2} \gamma^{3/2} (f_c/8g)^{1/2} S\sigma x \qquad (35)$$

The coefficient of friction, f_c, is assumed constant with respect to location, Reynolds number, and slope steepness, but it is assumed to vary with soil properties (Foster, 1971). The factor, C_τ, is a function of rill density and cross-section geometry, and, consequently, it is a function of soil properties and probably slope steepness, but is independent of location (Foster et al., 1977a). Equation (35) can be rewritten as:

$$D_R = 2K_r(aS^e)\sigma x \qquad (36)$$

where:

$2Kr$ = the product of $a_s \gamma^{3/2}(f_c/8g)^{1/2}$ and the portion of $C_\tau^{3/2}$ that is a function of soil properties

aS^e = the portion of $C_\tau^{3/2}$ that is a function of slope combined with S, where a and e are functions of the tillage pattern, soil roughness, and other factors that interact with the slope steepness to influence rill pattern.

Substituting Equations (29) and (36) into Equation (28) yields:

$$\partial G/\partial x = 2K_r(aS^e)\sigma x + K_i I(bS + c) \qquad (37)$$

Integrating Equation (37) with respect to time (to estimate soil loss for a storm event) yields:

$$G_T = x^2 \int_0^{T'} K_r(aS^e)\sigma dt + \int_0^{T''} K_i(bS + c)Idt \qquad (38)$$

where:

G_T = total sediment loss for a storm event (mass/unit width)

T' = time runoff ends

T'' = time rainfall ends

T = 0 is time runoff begins.

Clearly, variables such as σ and I are time-dependent functions. Soil factors such as K_r as well as K_i and exponents and coefficients such as a, b, c, and e depend on the extent of erosion and, therefore, are time dependent also. Unfortunately, very little information exists to indicate how these variables change with erosion amounts or time. Assuming that all factors except σ and I are independent of time, Equation (38) becomes:

$$G_T = x^2K_r(aS^e)F_t + xK_i(bS + c)I_t \qquad (39)$$

where:

$F_t = \int \sigma dt$ = runoff erosivity (erosivity units)

$I_t = \int Idt$ = rainfall erosivity (erosivity units).

Foster et al. (1977a) felt that storm EI (product of total energy and maximum 30-minute intensity) is a good approximation of rainfall erosivity. This approximation is supported by the research cited earlier in the general discussion of detachment by rainfall. Volume of runoff, as indicated by $\int \sigma dt$, is a variable which could be used as a measure of runoff erosivity. However, a factor including both runoff volume and peak discharge seems to represent runoff erosivity better than a term including only runoff volume (Williams, 1975). Also a factor giving more weight to runoff volume than to peak discharge might be more desirable because runoff volume can probably be predicted more accurately than peak discharge. A term for runoff erosivity that meets these criteria is $aV\sigma_p^{1/3}$.

The coefficient "a" was evaluated using data collected from 20 Indiana and Minnesota soils as part of a soil erodibility study (Wischmeier and Mannering, 1969). The data included 55 rainfall sumulator runs on both freshly tilled and eroded soil surfaces. The average value of "a" was 15 $EI/cm(cm/hr)^{1/3}$ (or 12541 $EI/ft(ft/sec)^{1/3}$), and "a" was not significantly affected by soil type or by previous erosion. This runoff erosivity factor has been used successfully with the USLE to estimate watershed erosion (Onstad and Foster, 1975).

Substituting these expressions for rainfall and runoff erosivity, Equation (39) becomes:

$$G_T = x^2 K_r (aS^e)(12541 V\sigma_p^{1/3}) + xK_i(bS + c)EI \qquad (40)$$

Foster et al. (1977a) included factors from the USLE to describe the effects of cropping, management, and contouring practices on erosion and sediment yield. The coefficients a, b, and c and the exponent e in Equation (40) define the relationship between soil loss and slope steepness. Equation (40) is similar to the USLE if a = 430/6.574; b = 30/6.574; c = 0.43/6.574; e = 2; and the slope is expressed as the sine of the slope angle (Foster et al., 1977b). Rewriting Equation (40) including these factors and values and solving for sediment load per unit area yields:

$$A = 430xK_r s^2 V\sigma_p{}^{1/3} C_r P_r/\lambda_u 6.574 \\ + K_i(30s + 0.43)EIC_i P_i/6.574 \qquad (41)$$

where:

A = sediment load (mass/unit area)

λ_u = length of the unit plot (22.1 m or 72.6 ft) from the USLE.

The factors C_r and C_i are not necessarily equal. For example, for erosion control by mulch, C_r has been related to the reduction in flow velocity by mulch, and C_i has been related to the percent of the soil surface that the mulch protects from direct raindrop impact (Foster and Meyer, 1975).

Sediment load is expressed as the sum of rill and interrill detachment in Equation (41). Including units conversions and solving for detachment per unit time, Equation (41) yields the equations (Equations 26 and 27) chosen to define rill and interrill detachment.

Selection of Transport Equation

No widely accepted transport formula has been developed for the transport of aggregates and very fine primary particles by overland flows (Alonso et al., 1981). Most existing transport theories have been developed for streamflows. Vast differences exist between the hydraulics of shallow flows in upland areas and deeper channel flows (Foster and Meyer, 1972b), making the application of existing transport theories to overland flow seem questionable in principle, at least (Alonso et al., 1981). For example, shallow flows undulate considerably, resulting in flow regime changes, and rainfall drastically alters the turbulence structure of the flow (Barfield, 1968). Also, in the range of relative roughness, surface tension may affect the flow characteristics, and surface-wave effects become as significant as viscous effects. However, because there are also important similarities between streamflow and shallow flow concentrated into small channels, several researchers have investigated the possibility of applying sediment transport equations for streamflow to transport by overland flow.

Alonso et al. (1981) evaluated a number of sediment transport formulas suitable for watershed modeling with the hope of using the results to restrict the use of each formula to conditions for which it gives satisfactory results.

The formulas were selected for evaluation based on three criteria: a) ease of use in digital applications; b) requirement for information only on the hydraulic parameters of the transporting flow; and c) reliable estimation of the sediment load when applied to flows and sediments within the range of interest.

The formulas chosen for evaluation in Alonso et al.'s (1981) study were the total-load formulas of Ackers and White (1973), Engelund and Hansen (1967), Yang (1973), Einstein (1950), and Laursen (1958); and the bed-load formulas of Meyer-Peter and Muller (1948), Bagnold (1956), and Yalin (1963).

Predictions of the nine equations were compared with flume and field data, including 40 field measurements, 523 flume experiments, and 176 tests on concave slopes, with sediments ranging from coarse sands to very fine soil particles. As expected, no formula satisfactorily represented the entire spectrum of sediment and flow characteristics. The results indicated that three of the tested formulas may give satisfactory estimates of transport capacity over different subsets of the data range.

Alonso et al. (1981) concluded that the Yalin formula can be used to compute sediment transport capacities for overland flows. It gave satisfactory results for the range of sizes and densities characteristic of field situations, and can also be used with confidence to predict transport rates of light materials in streamflows.

Alonso et al. (1981) cautioned that their recommendations should be viewed in a statistical sense, and only within the scope of the data used in their study. As a broader data base and better sediment transport theories become available, their conclusions will have to be reviewed and modified accordingly.

Foster and Meyer (1972b) also chose the Yalin equation over other sediment transport equations to evaluate soil transport by shallow flow. The choice was based on the equation's theoretical soundness for shallow flow. The Yalin equation assumes that sediment motion begins when the lift force of flow exceeds a critical lift force (Foster and Meyer, 1972b). Once a particle is lifted from the bed, the drag force of the flow carries the particle downstream until the particle weight forces it out of the flow and back to the bed. Observations of the erosion process on natural soils during simulated rainstorms indicated that a large fraction of the transported soil moves by saltation and by a rolling fashion along the bottom of the small flow channels. Such soil is detached and transported in the form of aggregates having larger diameters but lower densities than primary particles (Moldenhauer and Koswara, 1968). When the flow slows, as in ponded areas, these aggregates readily deposit. These observations indicate that once aggregates are detached from cohesive agricultural soils, their transport is very similar to that of noncohesive grains, the type of particles for which the Yalin equation was developed.

Foster and Meyer (1972b) also cited the simplicity of the equation and its excellent fit to observed data as reasons for selecting it. The Yalin equation requires only two common-flow parameters: hydraulic radius, and the slope of the energy gradeline. The transportability of a soil is described by particle density, particle diameter, and the critical lift force, which is given by the extended Shields' diagram (Mantz, 1977).

Foster and Meyer (1972b) compared observed rates of transport of sediment from a bed of glass spheres of mixed sizes (Kramer and Meyer, 1969) to rates predicted by the Yalin equation. Predicted transport rates were most accurate for slopes of seven and ten percent and slope lengths of 70 and 100 feet. Flow concentration due to increased rilling is greater at these higher slopes and slope lengths, resulting in deeper flow. The increased depths increase the ratios of flow depth to particle diameter to magnitudes more in agreement with Yalin's assumption. The increased depths also reduce the surface tension effects that can occur with very low erosion rates where there is little rilling and the sheetflow is broader and more shallow.

Predicted particle size distributions were good at the higher erosion rates. For the lower erosion rates, availability of sufficient particles of a given size to meet the transport capacity may have been restricted due to armoring by the larger particles. Little armoring took place when the erosion rate was high because the dynamic rill movement continually exposed new bed material.

Based on these investigations by Foster and Meyer (1972b) and Alonso et al. (1981), the Yalin (1963) equation was selected to calculate the transport capacity of overland flow.

Foster and Meyer (1972b) presented the Yalin equation as:

$$W_s/[(S_g)\rho_w dV_* g] = 0.635\delta(1-1/\sigma \ln(1 + \sigma)) \qquad (42)$$

where:

σ = $A*\delta$

δ = $Y/Y_{CR}-1$ (where $Y \leq Y_{CR} = 0$)

A = $2.45(S_g)^{-0.4}(Y_{CR})^{0.5}$

Y = $V_*^{2}/(S_g-1.0)gd$

V = $(gRS_f)^{1/2}$

V_* = shear velocity

g = acceleration of gravity

ρ_w = mass density of the fluid

W_s = transport capacity (mass/unit width/unit time

d = particle diameter

Y_{CR} = critical lift force given by the Shields' diagram

R = hydraulic radius

S_f = slope of the energy gradeline

S_g = particle specific gravity.

In the derivation of the equation, the constant 0.635 is the only empirically derived factor other than the critical lift force from the Shields' diagram.

The Yalin equation was developed for particles of uniform size. Foster and Meyer (1972b) modified the equation to predict transport rates of mixtures. The basis of the Yalin derivation was that the sediment transport rate is equal to the number of particles in transport over a unit area times the weight and velocity of each particle. To modify the equation, a mixture of sizes was assumed to reduce the number, but not the velocity, of particles of a given size in transport. Yalin assumed the number of particles in transport to be proportional to δ, the dimensionless excess of the tractive force. For a mixture, the number of particles of a given size i was assumed to be proportional to δ_i. Values of δ_i for each particle size group in a mixture were calculated and summed to a give a total:

$$T = \sum_{i=1}^{n} \delta_i \qquad (43)$$

where n is the number of size groups. The number of transported particles of size i in a mixture was taken as:

$$(N_e)_i = N_i(\delta_i/T) \qquad (44)$$

where N_i is the number of particles transported in sediment of uniform size i for a δ_i.

As derived by Yalin, the left side of Equation (42) is proportional to the number of particles in transport. Let the left side of Equation (42) equal P, the non-dimensional transport. Then,

$$(P_e)_i = (P_i\delta_i/T) \qquad (45)$$

where:

$(P_e)_i$ = effective P for particle size i in a mixture

P_i = P calculated for uniform material of size i.

The actual transport rate W_{si} of each particle size in a mixture was then expressed by:

$$W_{si} = (P_e)_i(Sg)\rho_w gdV_* \qquad (46)$$

MODIFICATIONS OF THE FESHM

A simplified flow chart for the FESHM is given in Figure 1, and a listing of the complete program is given in Appendix A. The sections of the model that were modified are identified with an asterisk. Minor changes were made in other sections of the model. These changes involved coding for entering input parameters required by the sediment calculations and coding to provide access to the subroutines that execute the sediment calculations (SEDCAL, DETACH, TRANS).

A flow chart of the sediment calculations coordinated by subroutine SEDCAL is shown in Figure 2. Sediment yield and deposition are determined for each element during each overland flow-routing increment.

Interrill and rill detachment are calculated in subroutine DETACH, using Equations (26) and (27). Potential interrill detachment is computed when the transport capacity exceeds the sediment load entering the element. Potential rill detachment is computed when the transport capacity exceeds the sum of the sediment entering the element and the sediment from interrill detachment. The total amount of detachment is limited to the amount that will just satisfy the transport capacity when the potential for detachment exceeds the transport capacity. This assumption ignores internal exchanges of soil particles by detachment and deposition in each element. This assumption was justified because virtually no data exist to verify spatiotemporal variation of detachment and/or deposition within an element.

Interrill detachment is dependent on rainfall erosivity, expressed as EI (energy times maximum 30 minute

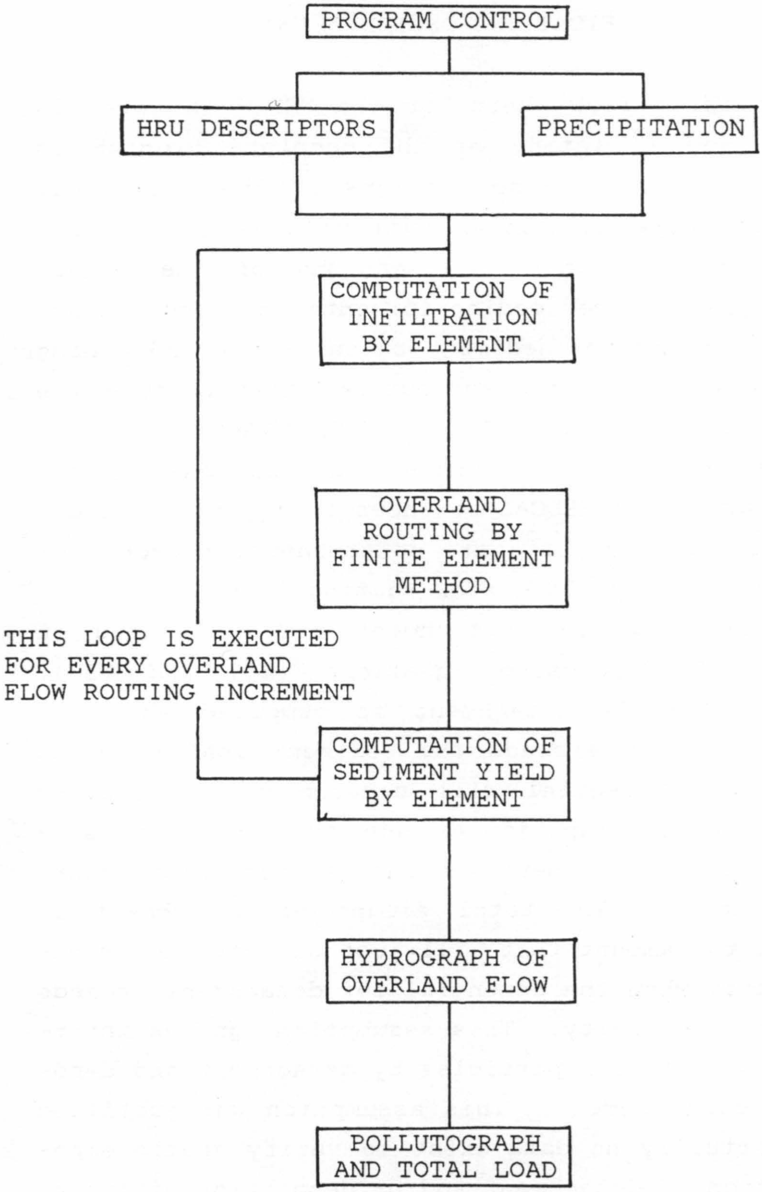

Figure 1. Computational sequence of modified FESHM

KEY:

DEP = AMOUNT OF DEPOSITION
DI = INTERRILL DETACHMENT
DR = RILL DETACHMENT
ISED = SEDIMENT FROM UPSLOPE ELEMENT
PSL = POTENTIAL SEDIMENT LOAD
Q = DISCHARGE AT DOWNSLOPE NODE
QSED = SEDIMENT LEAVING THE ELEMENT
TC = TRANSPORT CAPACITY OF FLOW

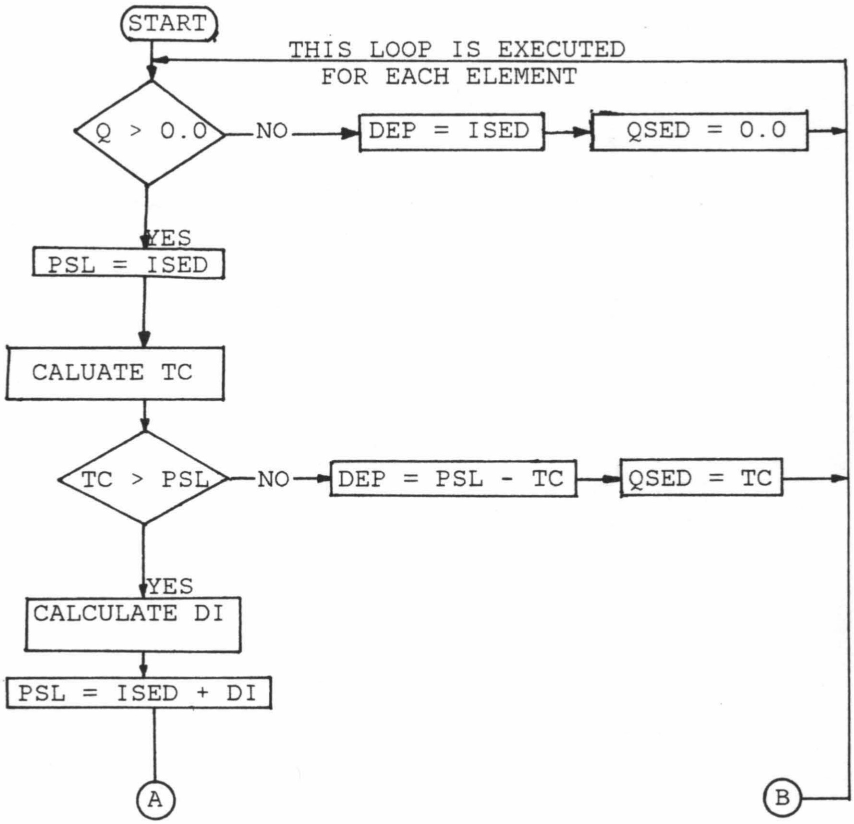

Figure 2. Flow chart of subroutine SEDCAL.

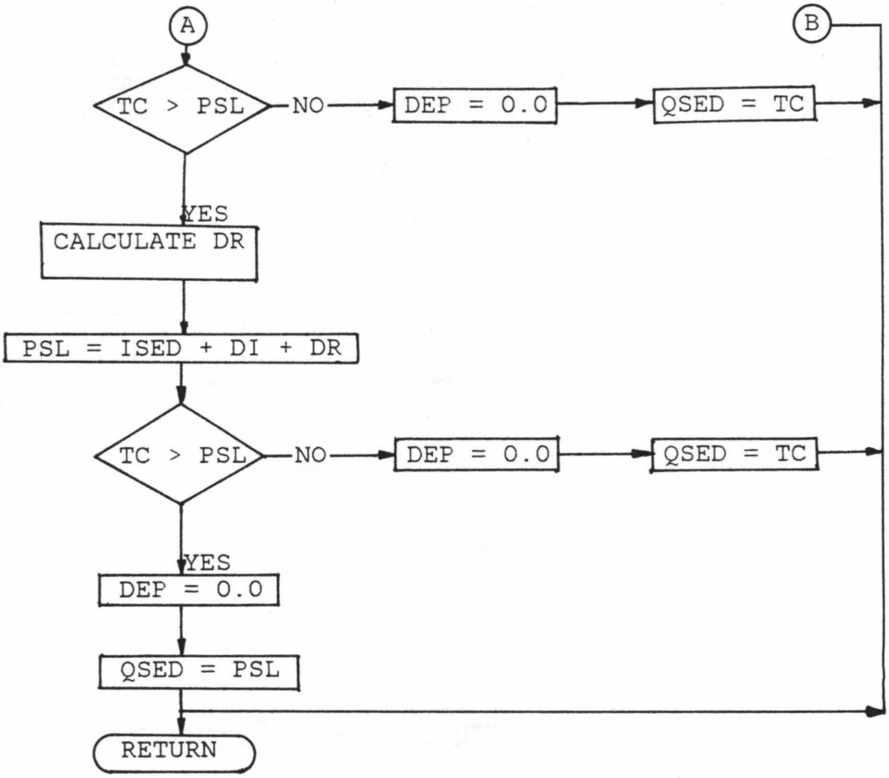

Figure 2. (continued)

intensity) in Equation (26). Energy for each rainfall increment is calculated as (Wischmeier and Smith 1958):

$$e = 916 + 331 \log_{10} i \qquad (47)$$

where:

e = rainfall energy per unit of rainfall (ft-tons/acre-in)

i = rainfall intensity (in/hr).

The maximum thirty-minute intensity of the storm is calculated in subroutine INTENS.

The volume of flow available for rill detachment during each time-routing increment is computed as:

$$Q_i = (Q_{u,t-1} + Q_{u,t} + Q_{l,t-1} + Q_{l,t})/4 \qquad (48)$$

where:

Q_i = volume of flow for element i for overland flow routing increment

$Q_{u,t}$ = volume of flow at upper node at time t

$Q_{l,t}$ = volume of flow at lower node at time t.

The slope length exponent in Equation (27) is set equal to 2.0 for slopes less than 150 feet. However, to prevent excessive erosion for very long slopes, the exponent is limited by:

$$m = 1.0 + (5.011/\ln(x)) \qquad (49)$$

where:

m = slope length exponent, and

x = slope length

The transport capacity of overland flow is calculated in subroutine TRANS according to Yalin's equation modified for mixtures, as expressed by Equations (42) through (46). The transport capacity is determined for each particle type with Equation (46). Excess transport capacity is distributed among the particle types as suggested by Foster et al. (1980) and shown in Figure 3.

The Yalin equation requires two flow parameters: the hydraulic radius and the slope of the energy gradeline. Assuming a wide, shallow channel, the hydraulic radius is expressed as the area of flow divided by the width of the flow element. The slope of the energy gradeline is assumed equal to the slope of the element. Particle density, particle diameter, and critical lift force define the transportability of a soil. Particle density and diameter are input parameters of the model. Critical lift force is obtained from the extended Shields' diagram (Mantz, 1977) which defines critical lift force as a function of the particle Reynolds' number.

In subroutine TRANS, the nondimensional particle Reynolds' number is calculated as (Graf, 1971):

$$R = (dV_*)/\nu \tag{50}$$

where:

R = particle Reynolds' number

d = particle diameter (ft)

V_* = shear velocity (ft/sec)

ν = kinematic viscosity (ft^2/sec).

The kinematic viscosity is assumed to be 1.06 x 10^{-5}

For Reynolds' numbers less than one, the critical

KEY:

DELTA(i) = EXCESS TRACTIVE FORCE FOR PARTICLE TYPE i

PSL(i) = POTENTIAL SEDIMENT LOAD FOR PARTICLE TYPE i

TC(i) = TRANSPORT CAPACITY FOR PARTICLE TYPE i

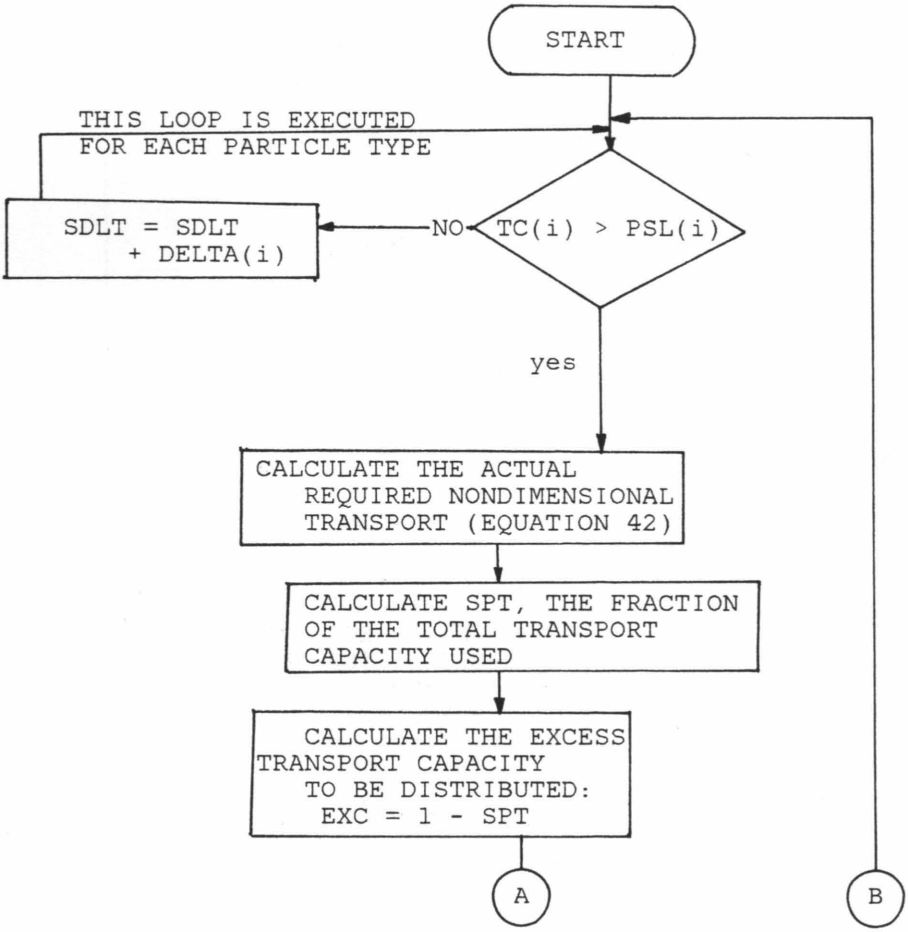

Figure 3. Distribution of excess transport capacity.

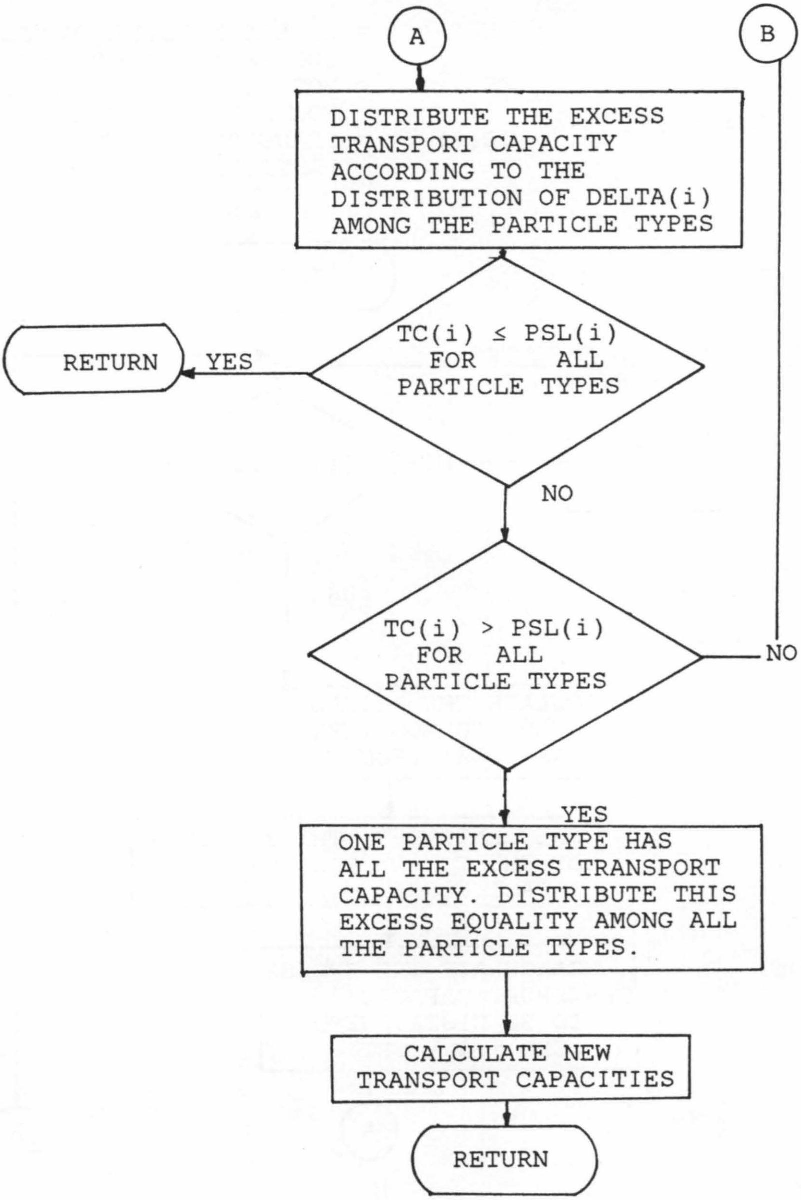

Figure 3. (continued)

lift force is defined as (Mantz, 1977):

$$Y_{cr} = 0.10R^{-0.03} \tag{51}$$

where:

Y_{cr} = critical lift force
R = Reynolds' number.

When the Reynolds' number is greater than or equal to one, the critical shear stress is obtained by interpolation from the Shields' diagram, represented in TRANS as a table of coordinate points.

To minimize computational errors, particle diameters are expressed in millimeters for calculations, then the resulting quantities are converted from millimeters to feet.

MODEL VERIFICATION

Data Base

Field data collected at two surface-mine sites in southern West Virginia were used to verify the model. Three adjacent plots, each measuring 36.3 feet long by 13.3 feet wide, were constructed at each site. Rainfall, runoff, and sediment quantities were collected for each plot for a series of tests. Each test consisted of three rainfall applications using a rainfall simulator (Shanholtz et al., 1981b). The three-run sequence included a) a 60-minute dry run; b) a 60-minute wet run (24 hours after run 1); and c) a 30-minute very wet run (1 hour after run 2). A detailed description of the data collection procedures is included in Rice (1982).

Input Data for Model

The first step in compiling an input data set for the model is discretizing the drainage area. The FESHM calls for the discretization of a drainage area into hydrologic response units (HRU's) and flow elements. An HRU map is obtained by overlaying the soils map and the land use map of the watershed (Li, 1975). Each unique combination of land use and soil type is defined as an HRU.

Each plot was divided into three elements, each 12.1 feet long by 13.3 feet wide (Figure 4). Each element consists of a single HRU. In this application, then, an element and an HRU are identical. This discretization scheme was chosen to facilitate full use of

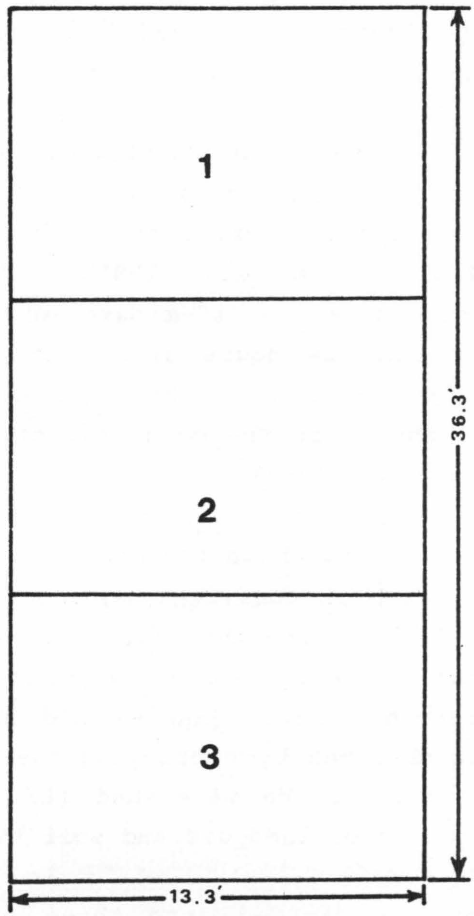

Figure 4. Discretization scheme of plots.

the available data. Information such as amount of rainfall and soil moisture was collected for the top, middle, and bottom areas of the plots, corresponding to the three elements.

The majority of the input parameters can be measured directly or determined from measurable characteristics of the plots. The remaining inputs include geometric parameters that are defined by the discretization of the plot. All of the model variables are defined in Appendix B, with the input variables so designated.

The input data set for one field plot (QB2, Run 1) is given in Table 3 and contains the following four basic types of data:

1. description of rainfall event
2. description of HRU's
3. description of elements
4. description of soils

Description of Rainfall Event

The variables in this group include: the number of raingages, the hours of rainfall, the time interval for entering precipitation records, the date of the storm, and the amount of rainfall for each raingage for each input time increment. This information was recorded for each plot during each run of the rainfall simulator. Because the amount of rainfall was measured on each element, the number of raingages was set equal to three, and the appropriate raingage was specified for each element.

Table 3. Input Data for Plot QB2 for Run 1.

Group 1. Description of Rainfall Event

Number of raingages = 3
Hours of rainfall = 1
Precipitation interval = 3600 sec
Date of event = 8/25/81

RAINGAGE	RAINFALL
1	1.85 in.
2	1.89 in.
3	2.05 in.

Group 2. Description of HRU's

HRU NO.	HOLTAN 'a'	DEPRESSION STORAGE	ROUGHNESS COEFFICIENT
1	1.05	0.0	0.05
2	1.05	0.0	0.05
3	1.05	0.0	0.05

HRU NO.	PLANT AVAILABLE WATER	GRAVITATIONAL WATER	FINAL INFILTRATION RATE	INITIAL SOIL MOISTURE
1	0.2974	0.0494	0.007	0.83
2	0.1867	0.0288	0.007	0.79
3	0.2255	0.0144	0.007	0.75

Table 3. (continued)

Group 3. Description of Elements

ELEMENT NO.	LENGTH (FT)	RELIEF (FT)	AREA (AC)	TOP WIDTH (FT)
1	12.1	1.8876	0.0037	13.3
2	12.1	1.8876	0.0037	13.3
3	12.1	1.8876	0.0037	13.3

Group 4. Description of Soils

DIAMETER (mm)	SPECIFIC GRAVITY	PARTICLE SIZE DISTRIBUTION SOIL 1	SOIL 2	SOIL 3
0.001	2.65	0.2835	0.196	0.1855
0.026	2.65	0.4830	0.520	0.4855
0.075	2.65	0.1555	0.178	0.2145
0.175	2.65	0.0255	0.031	0.0315

soil depth = 4.0 in.
soil erodibility = 0.464

Description of HRU'S

The first set of parameters in this group defines the soil moisture characteristics of each HRU, including the potential plant-available water, the potential gravitational water, the final infiltration rate, and the initial soil moisture content for the rainfall event. The potential plant-available water is defined as the volumetric moisture content of the soil between 1/3 and 15 atmospheres of tension. Gravitational water is the volumetric moisture content between zero and 1/3 atmospheres of tension.

Values of plant-available and gravitational water for the Sullivan site were determined from data obtained from Jones (1980). Values for the Glen Jean site were estimated according to guidelines suggested by Li (1975) based on soil type.

Data collected before each rainfall application included the moisture content of the soil samples from the top and bottom areas of each plot. The initial moisture content of the middle element was assumed to be an average of the two measured values.

The second set of parameters describes the surface and vegetative conditions of each HRU. The inputs include the roughness coefficient used in Manning's flow equation, the potential depression storage, and the vegetative index "a" for the Holtan infiltration equation. The USLE cover-management factor, C, and the USLE contouring factor, P, are also specified.

The potential depression storage and roughness coefficients were estimated using criteria suggested by Ross et al. (1978). The C factor for all the HRU's was equal to one because the plots were bare and tilled up and down the slope. The contouring factor did not apply in this case; therefore, it was set equal to one for all HRU's.

Holtan's "a" is difficult to determine for surface mine conditions because traditional methods used to estimate this parameter do not apply. Wolfe et al. (1981) described the following procedure which can be used when measured infiltration curves are available for the site. Analysis of data from Hockman's (1981) ring infiltrometer tests on the Sullivan site showed that, in general, the following expression adequately described the infiltration rate at that site:

$$f_r = a_1 T^{-b} \tag{52}$$

where:

f_r = measured infiltration rate (inches/hour)

T = accumulated time (hours)

a_1 and b are constants.

The Holtan equation can be expressed as:

$$f_h = aS^C + f_c \tag{53}$$

where:

f_h = predicted infiltration rate (inches/hour)

a = vegetative cover index

S = unfilled pore space between 0 and 15 atmospheres of tension

C = ratio of potential gravitational soil water content to potential plant-available soil water content

f_c = final infiltration rate (inches/hour).

Equating Equations (52) and (53) and solving for "a" yields:

$$a = (a_1 - T_i^{\ b} f_c)/(T_i^{\ b} S^C) \quad (54)$$

where:

i = current time step.

A numerical solution of Equation (54) gives the functional relationship between Holtan's "a" and accumulated time nesessary to match the measured infiltration function (Equation 52). An example of this relationship is shown in Figure 5. Note that "a" becomes relatively constant after approximately one-half hour and remains constant for some time. These data suggest that "a" is reasonably constant during the mid-range of the infiltration cycle, providing a useful index of cover effects for a given storm. The high initial rates also support the findings of some investigators (e.g., Idike et al., 1980) who have shown that Holtan's equation gives good estimates of surface runoff during the middle stages of a given storm event.

The constants in Equation (52) were determined from hydrograph analyses of data collected at the Sullivan and Glen Jean sites. Curves similar to Figure 5 were determined for each site. The value of Holtan's "a" during steady state flow conditions was used for each plot.

Description of Elements

The geometric properties of the elements are described by the input variables in this section. These properties include length, relief, area, and

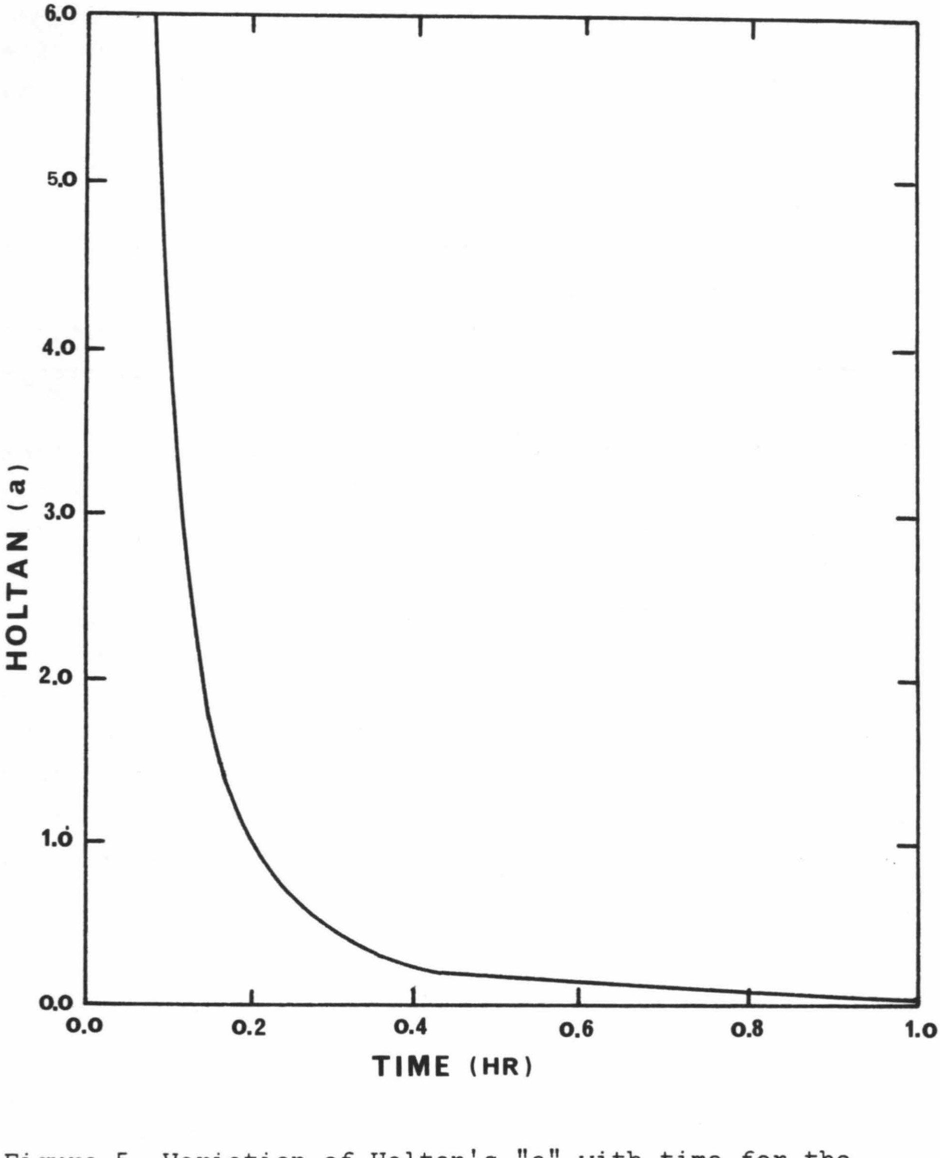

Figure 5. Variation of Holtan's "a" with time for the Sullivan site.

width. As stated earlier, the elements were each 12.1 feet long and 13.3 feet wide. The slope of each plot was determined from surveys made after plot construction. The slope of the plots at the Sullivan site ranged from 15.5 to 16.5 percent. The Glen Jean plots had a nine-percent slope.

Description of Soils

The required soils information includes the particle size distribution of each soil in the watershed, and the diameter and specific gravity of each particle type. Additional inputs include the depth and erodibility of each soil.

Particle size distributions were determined from soil samples taken from the top, middle, and bottom elements of each plot before the first rainfall application. The diameter of each particle type was estimated as the average diameter of that particle type according to the USDA scale (Novotny and Chesters, 1981). The specific gravity of each particle type was assumed to be 2.65. The soil depth was estimated to be equal to the depth of tillage, approximately four inches on all plots. The soil erodibility factors were determined from Wischmeier et al.'s (1971) nomograph using soils data obtained from the sites.

Results

The model was tested for a set of three runs on each plot. Predicted and observed values of both runoff and sediment yield were compared. Figures 6-11 represent typical comparisons of recorded and predicted hydrographs. The results for Plot QB2 (Sullivan) are illustrated in Figures 6-8 for the three successive runs. Figures 9-11 show similar results for plot QZ4 (Glen Jean).

The predicted and observed volumes of runoff for each plot for each run are presented in Table 4 and compared graphically in Figure 12.

Predicted and observed total sediment yields are presented in Table 5 and Figure 13. Total yields were compared because deposition in the flume resulted in errors in the suspended sediment loads. The total yield was determined by adding the sediment deposited in the flume and the suspended load (Rice, 1982).

Discussion of Results

Runoff

Close agreement between the steady state peaks and between the recessions of the predicted and observed hydrographs is illustrated in Figures 7 through 12. The rising limbs of the hydrographs do not match well for the dry run on each plot. These results were common to all the plots.

Note from the series of hydrographs in Figures 7 through 9 and Figures 10 through 12 that the discrepancy between the rising limbs of the hydrographs decreased as the initial moisture content increased. These results can be attributed to the value of the "a" coefficient in the Holtan infiltration equation. The choice of "a" becomes critical in modeling response from small plots because spatial variability of micro-relief and infiltration can become dominant factors.

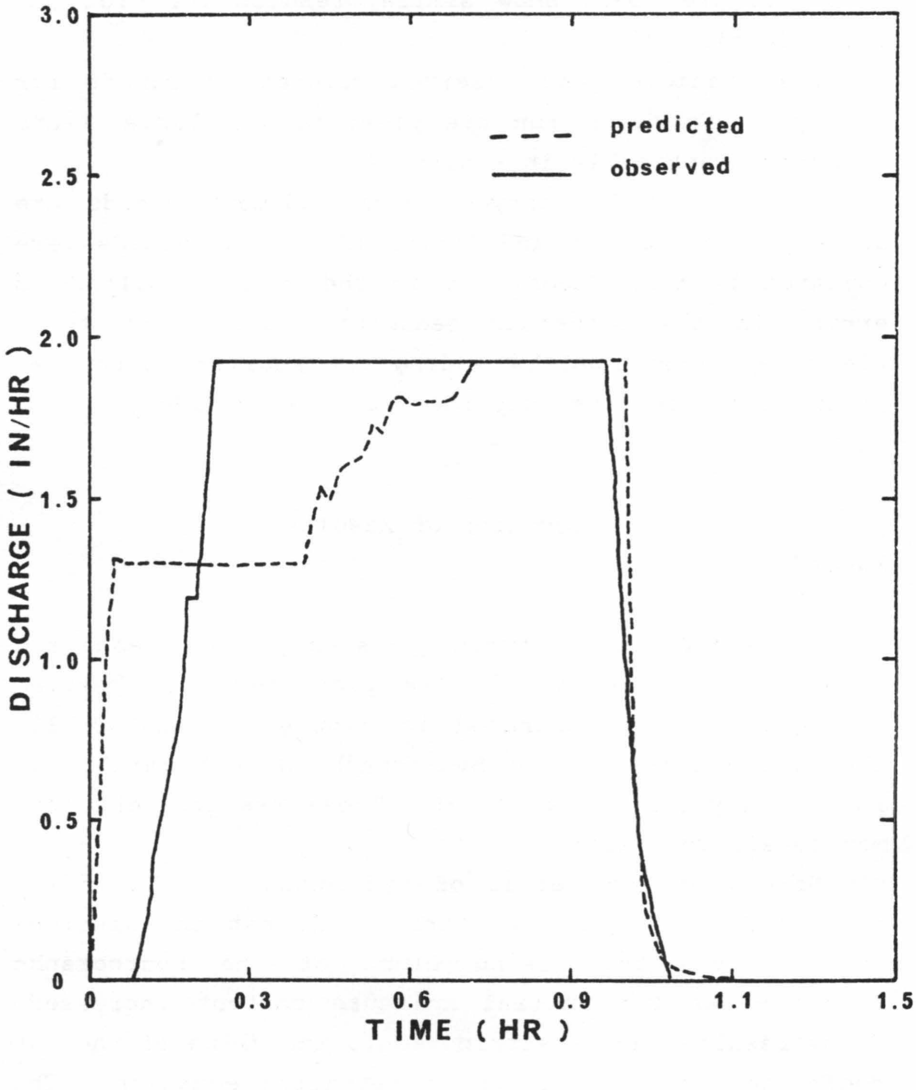

Figure 6. Comparison of observed and predicted discharge for Run 1 (dry condition) on Plot QB2.

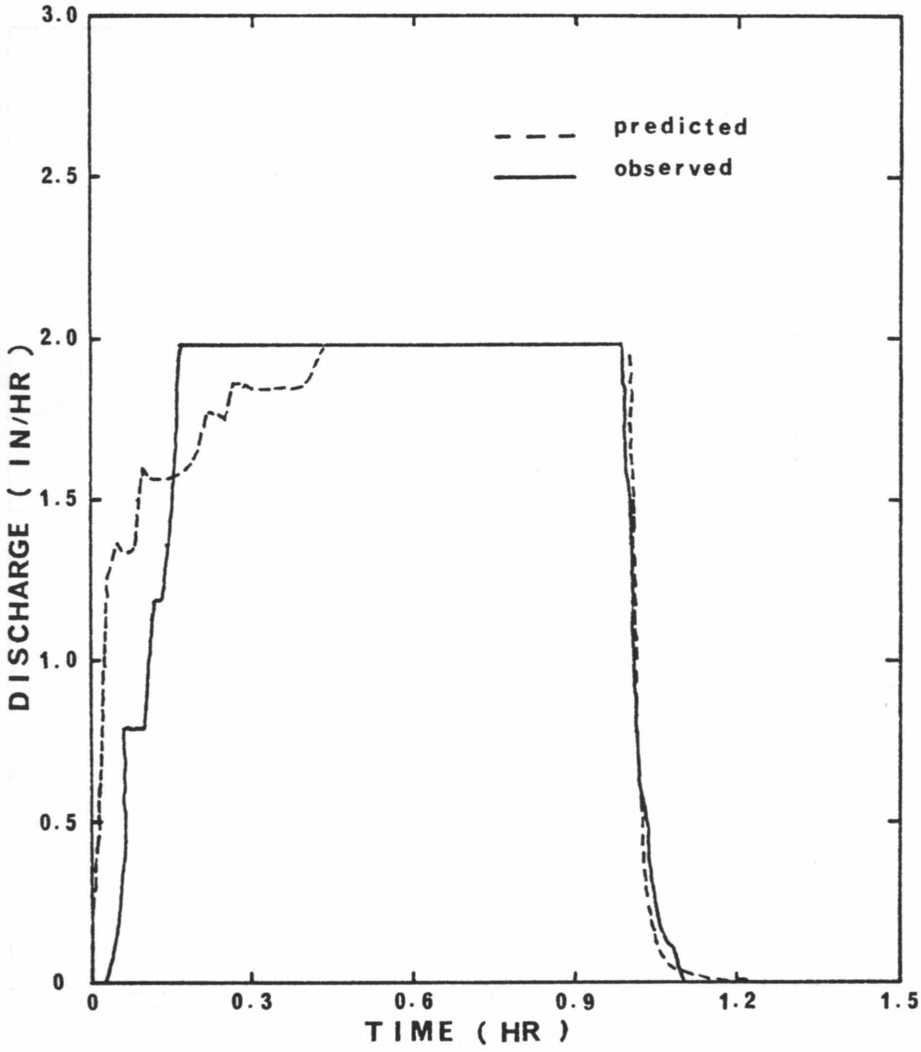

Figure 7. Comparison of observed and predicted discharge for Run 2 (wet condition) on Plot QB2.

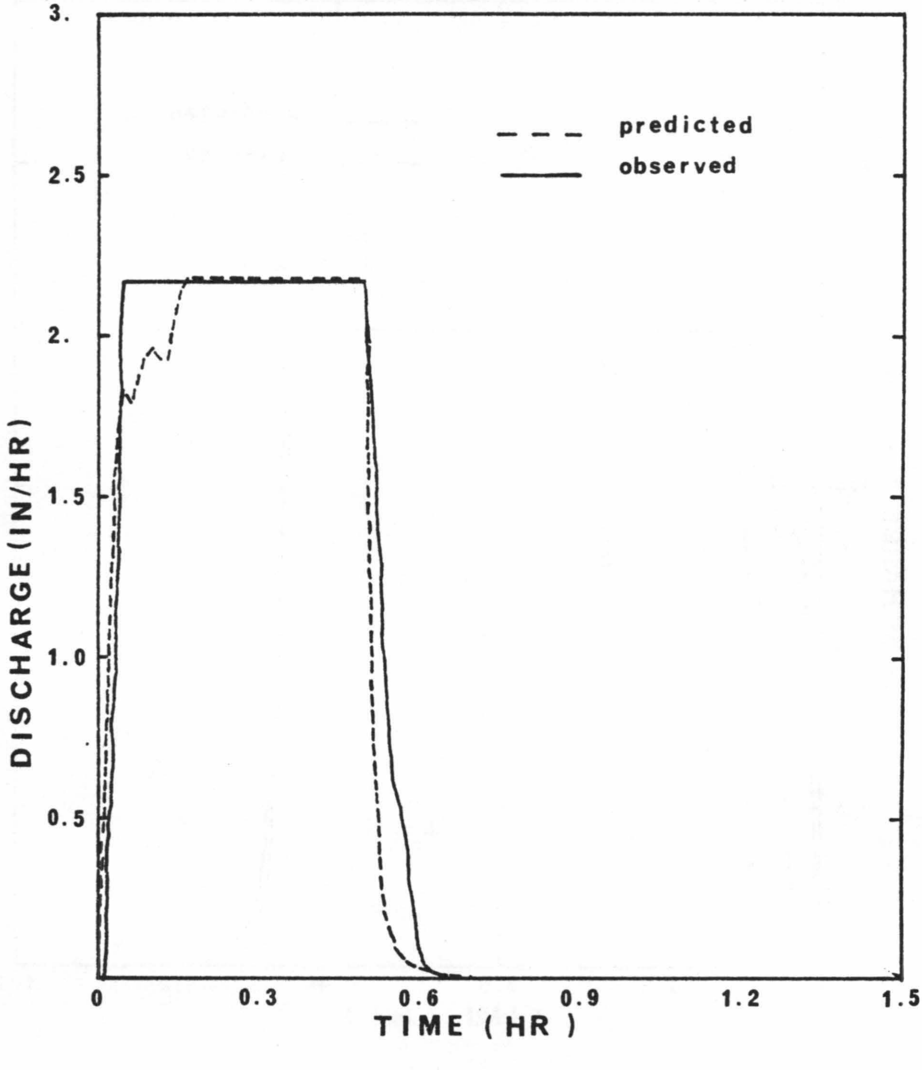

Figure 8. Comparison of observed and predicted discharge for Run 3 (very wet condition) on Plot QB2.

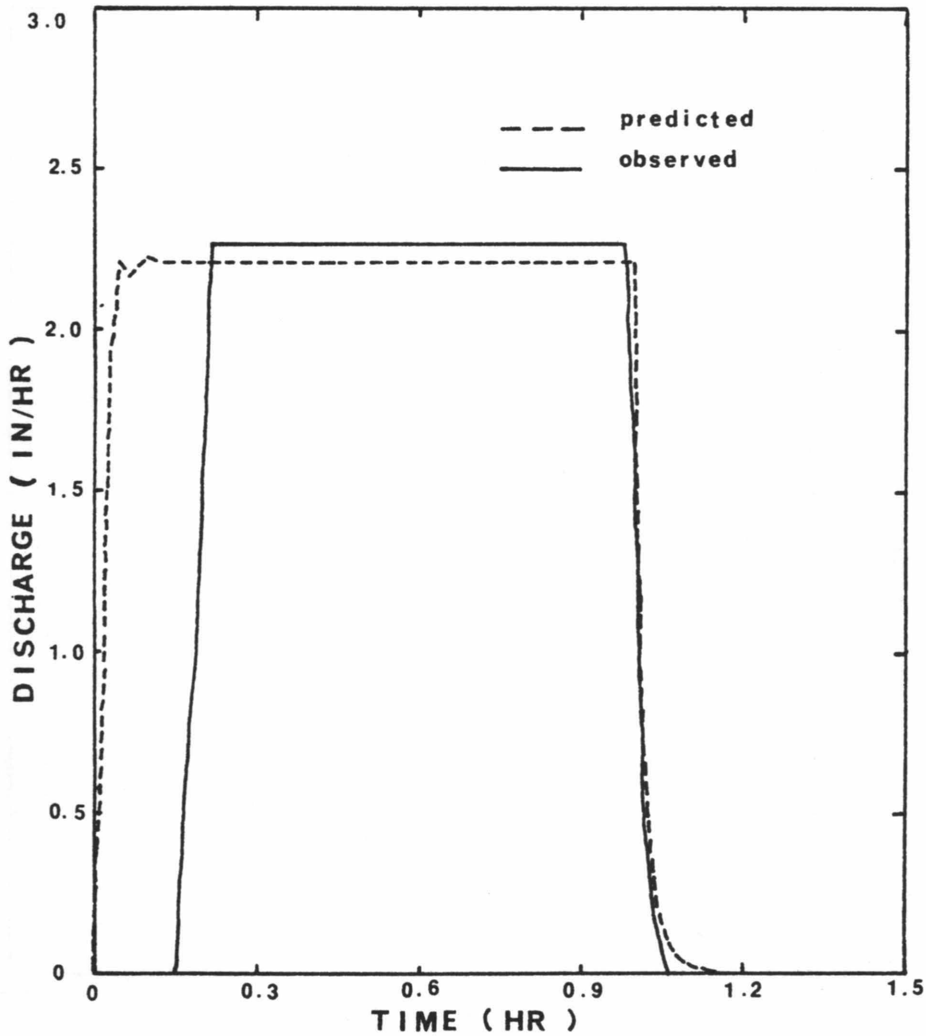

Figure 9. Comparison of observed and predicted discharge for Run 1 (dry condition) on Plot QZ4.

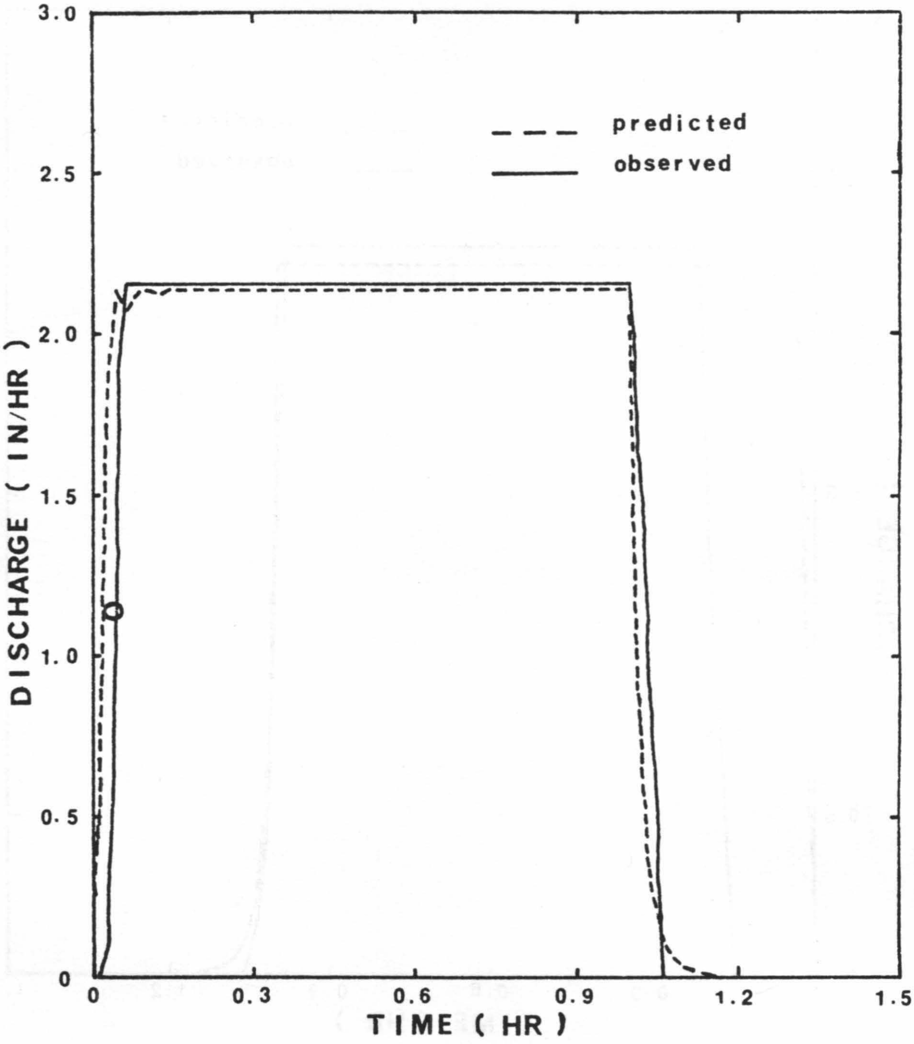

Figure 10. Comparison of observed and predicted discharge for Run 2 (wet condition) on Plot QZ4.

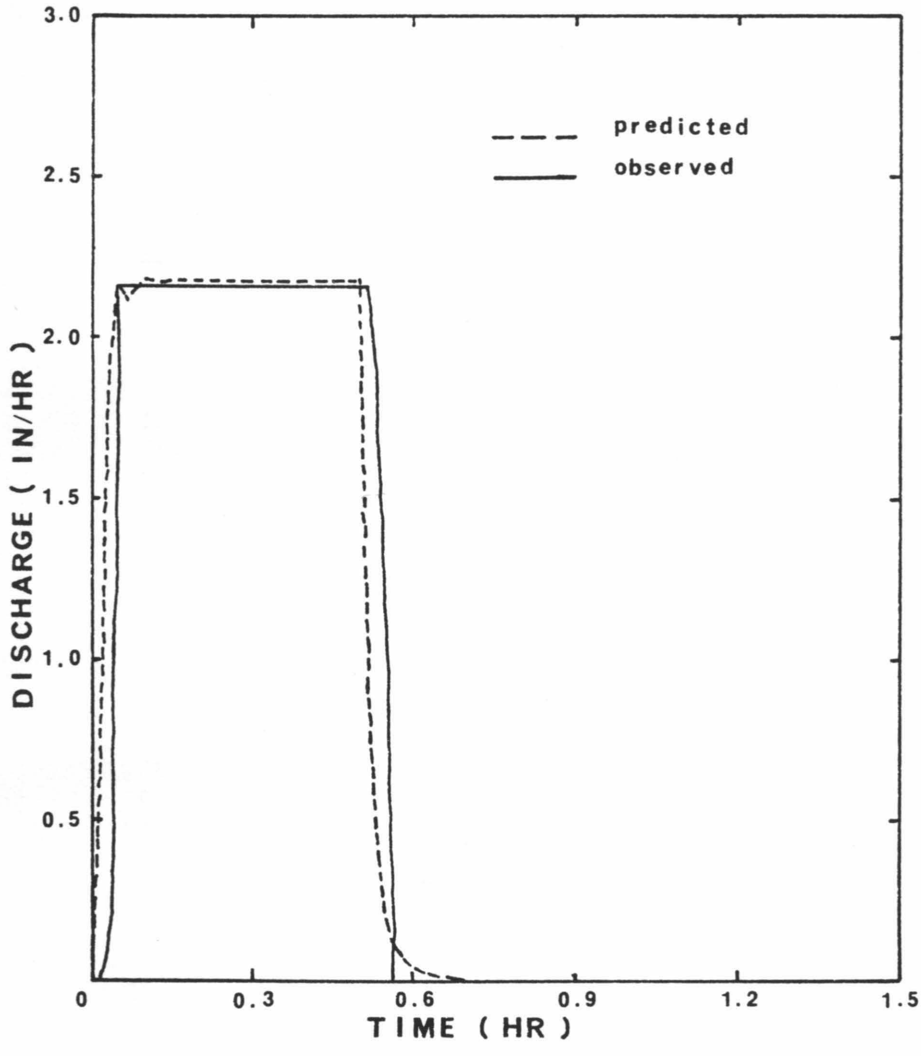

Figure 11. Comparison of observed and predicted discharge for Run 3 (very wet condition) on Plot QZ4.

Table 4. Observed and predicted runoff volume for all plots.

PLOT	TEST	RUN	RUNOFF VOLUME	
			RECORDED (IN)	PREDICTED (IN)
QB2	3	1	1.608	1.609
		2	1.804	1.849
		3	1.097	1.044
QB3	3	1	1.484	1.522
		2	1.932	1.874
		3	1.107	0.923
QB4	3	1	1.586	1.601
		2	1.944	1.985
		3	1.193	1.204
QZ2	3	1	2.007	2.318
		2	2.142	2.172
		3	1.084	1.127
QZ3	3	1	1.950	2.321
		2	2.230	2.218
		3	1.128	1.134
QZ4	3	1	1.869	2.207
		2	2.132	2.135
		3	1.091	1.084

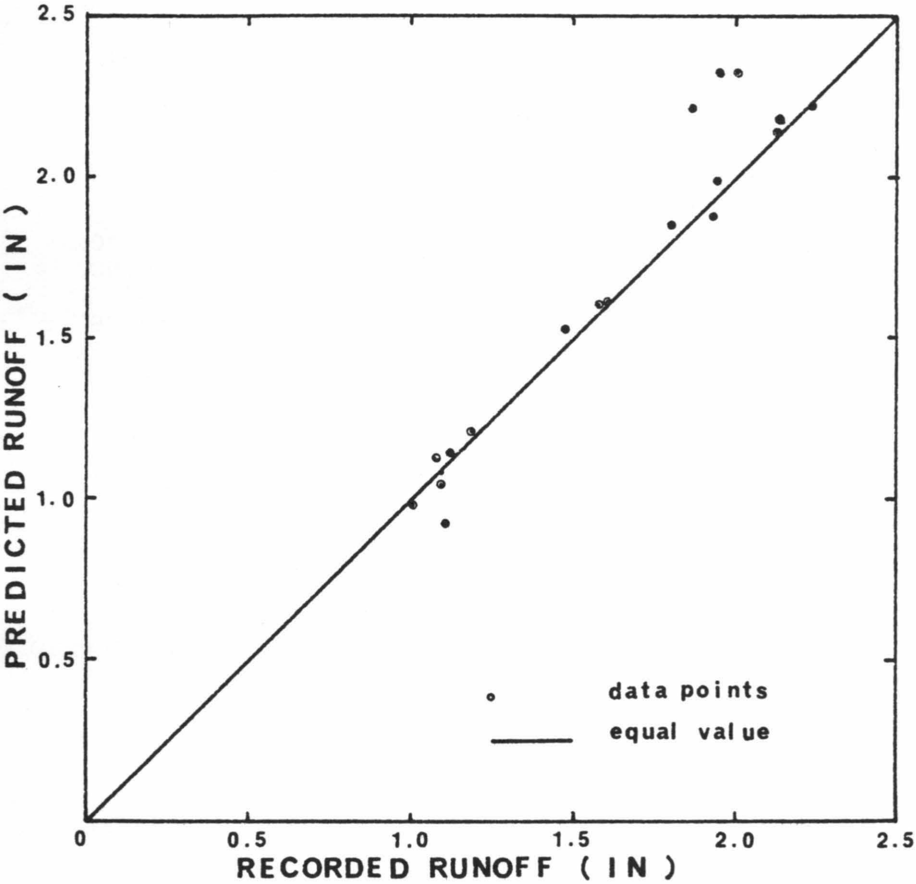

Figure 12. Observed vs. predicted runoff volume for all plots.

Table 5. Observed and predicted sediment yield for all plots.

PLOT	TEST	RUN	SEDIMENT YIELD RECORDED (LBS)	SEDIMENT YIELD PREDICTED (LBS)
QB2	3	1	249.17	366.06
		2	173.44	390.40
		3	73.34	240.24
QB3	3	1	187.09	359.02
		2	161.02	455.70
		3	65.78	250.90
QB4	3	1	234.36	382.78
		2	182.68	479.59
		3	68.45	299.29
QZ2	3	1	167.77	251.67
		2	143.83	220.82
		3	58.04	116.15
QZ3	3	1	151.19	269.33
		2	113.38	241.72
		3	55.82	128.39
QZ4	3	1	117.80	243.66
		2	96.56	227.52
		3	59.00	116.23

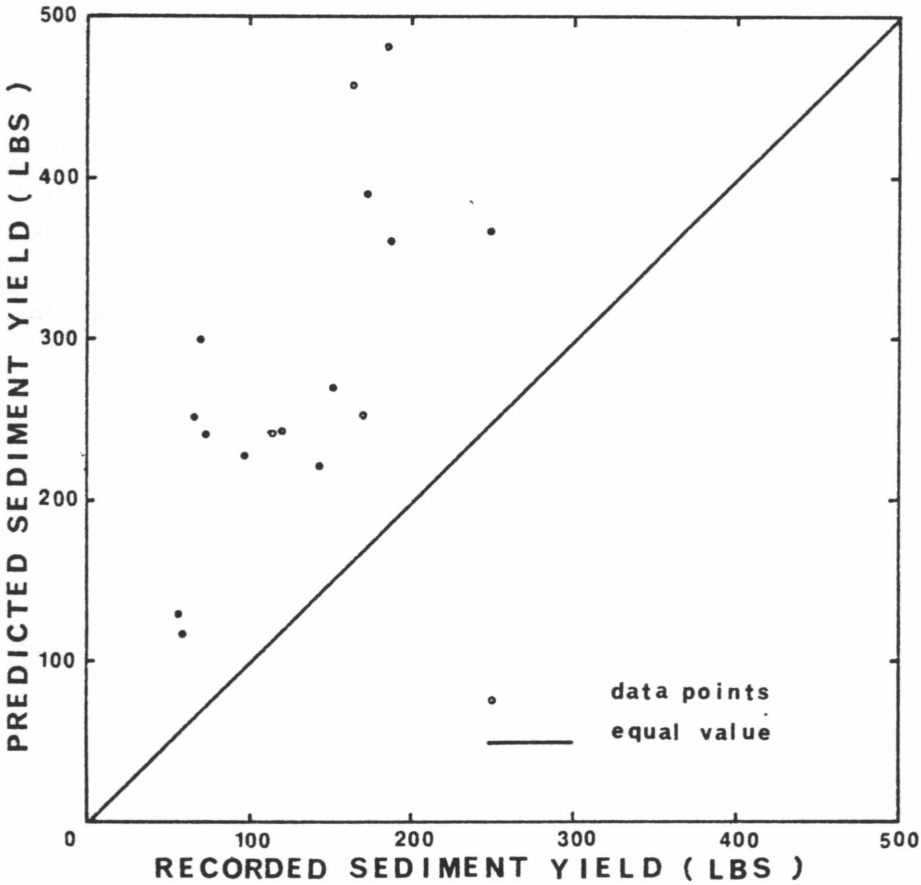

Figure 13. Observed vs. predicted sediment yield for all plots.

The "a" value selected was the value corresponding to the beginning of steady state conditions. Because the discrepancy between the hydrographs occurred in the early stages of the storm, an "a" value more representative of this time segment should yield better predictions.

To illustrate the effect of the Holtan "a" value, an average "a" value occurring during the time between the initiation of runoff and the beginning of steady-state was chosen. This change affected the rising limbs of the predicted hydrographs significantly, as shown in Figure 14. The effect of the "a" value approaches zero as the moisture content increases (unfilled pore space equals zero) because infiltration decreases.

These results indicate that a better method of estimating Holtan "a" values is needed. A function expressing the variation of "a" with time during a storm event would be useful. Also, for this model, it is desirable to estimate "a" from measurable characteristics of the watershed.

Sediment Yield

The comparison of observed and predicted sediment yield shows that the predicted value was always greater than the observed value. This pattern indicates a bias in the prediction procedure. Several factors could contribute to this bias.

One assumption that was expected to cause overprediction concerned the particle size distribution of the sediment. Because particle size-distribution data had not been analyzed for the sediment from these plots, it

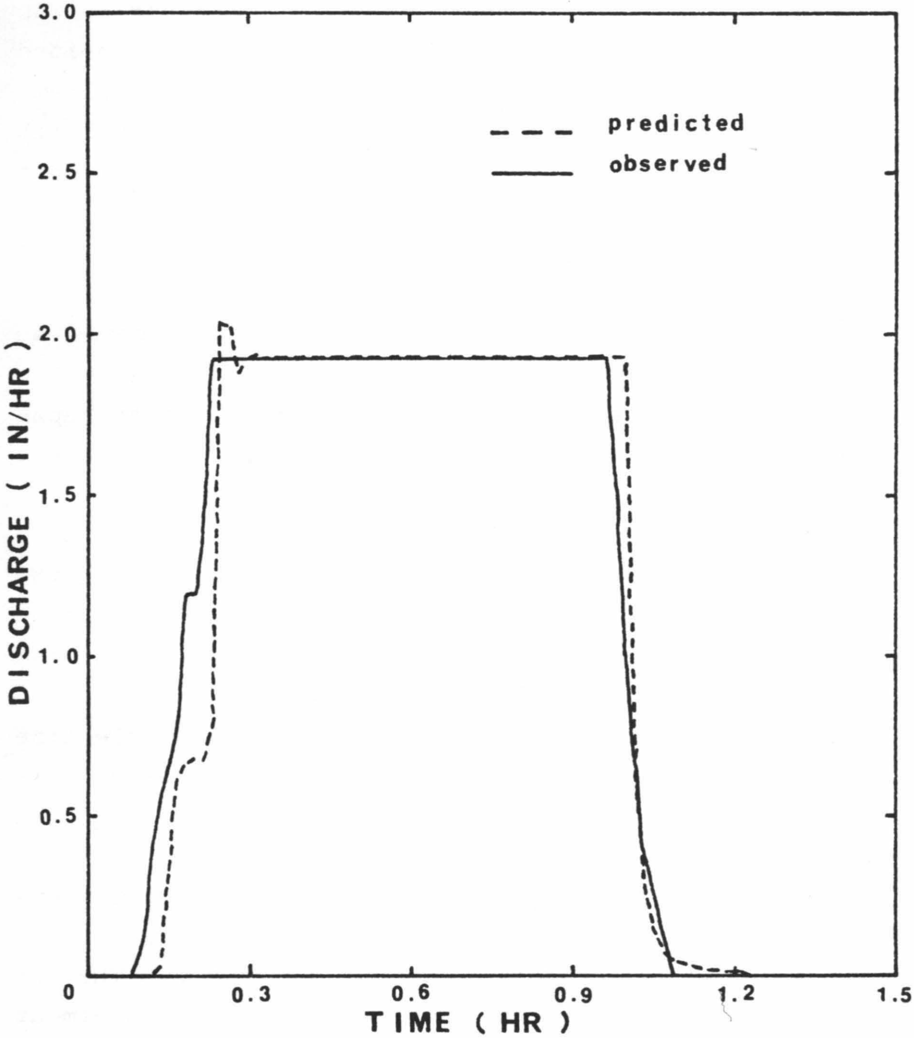

Figure 14. Effect of Holtan's "a" on hydrograph prediction, Plot QB2 Run 1 (dry condition).

was assumed that the particle size distribution of the sediment was the same as that of the soil on the plot before rainfall. Gilley et al. (1976), though, found substantial changes in the particle size distribution of eroded material from tilled plots. They examined three soil textures, including sandy loam, clay loam, and silty clay loam on a re-shaped mine spoil in North Dakota. The percentage of sand was less in sediment from the tilled plots, while the percentage of clay was substantially increased. This trend was found for all three soil textures.

Also, soil tends to be detached in aggregates as well as individual particles. Because the specific gravity of these aggregates is lower than that of separate particles, the sediment yield would be different for the two types of particle distributions.

Foster et al. (1980) proposed a relationship between the particle size distribution of a soil in the field and the resulting sediment. Because the relationship is based on data from midwestern silt-loam soils, it is not applicable to surface-mine soils. However, it was used to develop modified particle-size distributions to illustrate the effect of these distributions on the amount of sediment predicted by the model.

Modified soil distributions were estimated for one plot from each site. Sediment yield predictions were made for each of the three runs on both plots. The two predicted values and the observed value of sediment yield for each run are compared in Figures 15 and 16. The comparisons show a reduction in predicted sediment yield when the modified particle-size distributions were used.

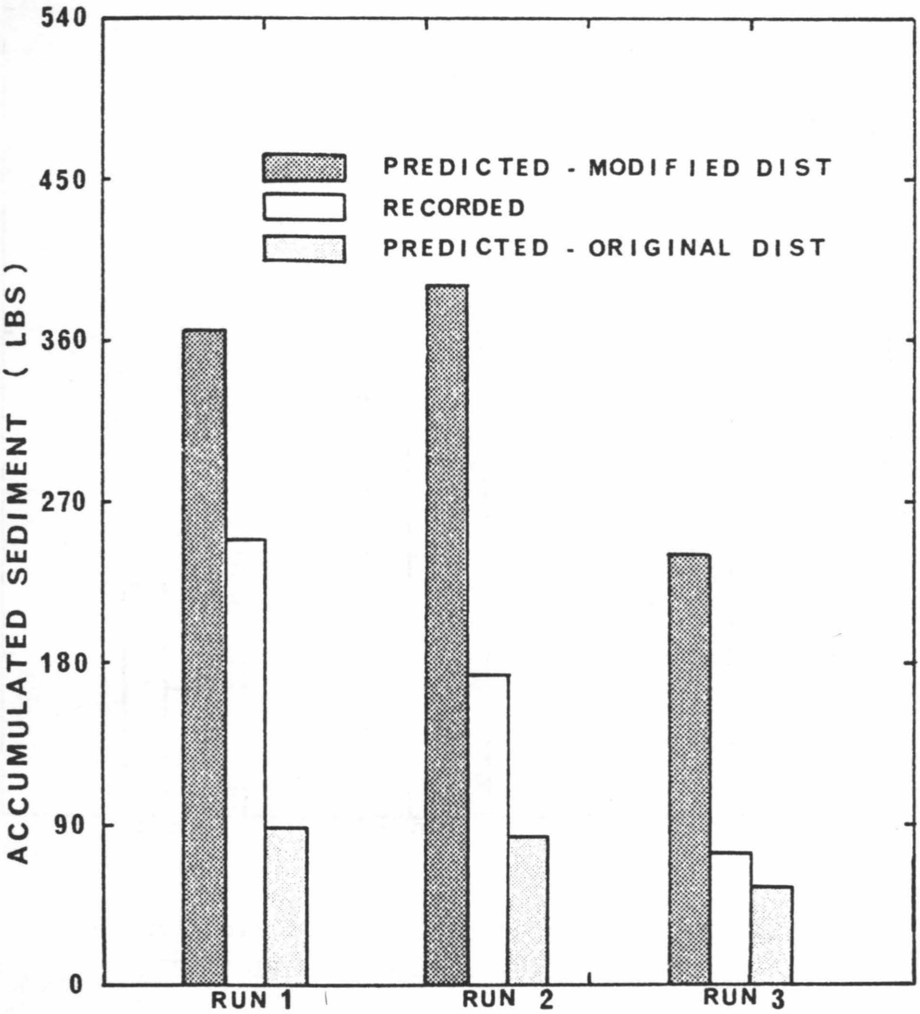

Figure 15. Effect of particle size distribution on sediment yield prediction, Plot QB2.

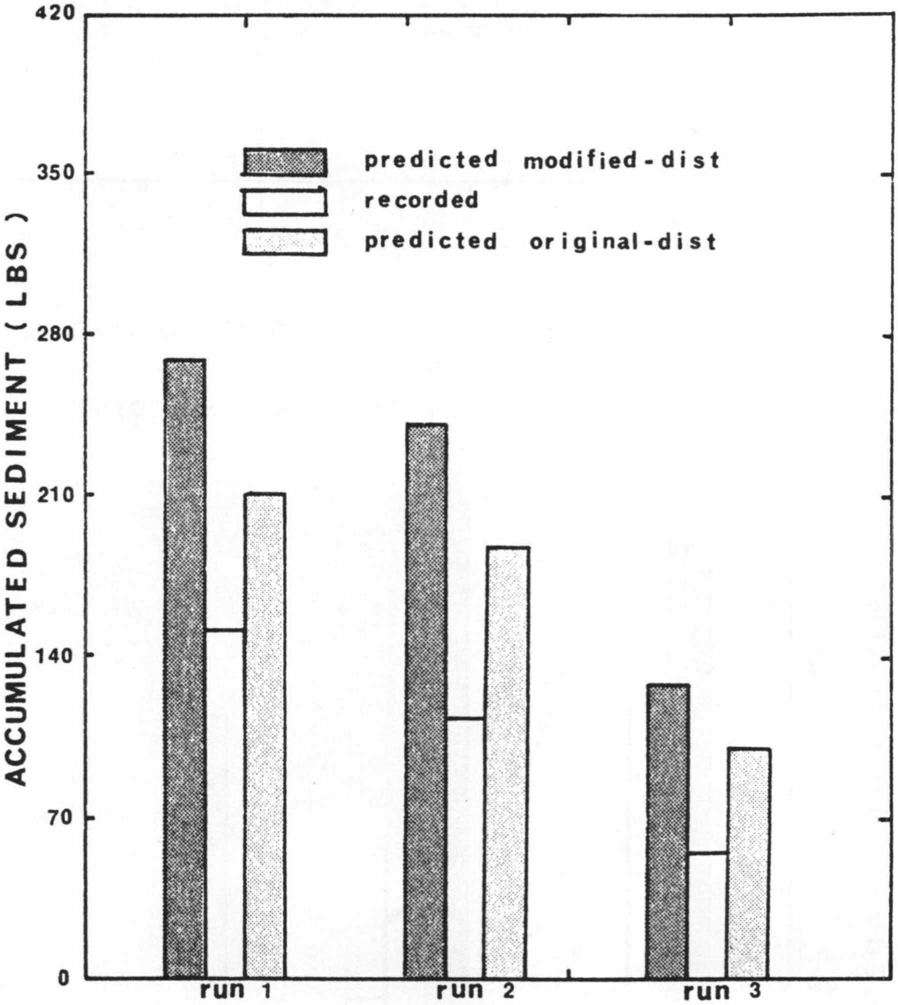

Figure 16. Effect of particle size distribution on sediment yield prediction, Plot QZ3.

A second factor that could cause higher predicted sediment values is the cropping-management factor, C, used in the detachment equations. As explained earlier, this factor was set equal to one for all runs. Observations in the field indicated that many of the finer soil particles were eroded during the first run, leaving a rock mulch consisting of coarser particles and fragments (Figure 17). Analysis of samples taken before and after the first run showed a 30 percent increase of coarse fragments during the run. There could be a compaction effect as well as an armoring effect after the first run.

The C factor was reduced to 0.7 to simulate the effect of armoring for the third run on each of the plots at the Sullivan site. The predicted values with C equal to 0.7 are compared to the predicted yields with C equal to one and the observed yields in Figure 18. The predicted sediment yield was decreased 30 percent, corresponding to the decreased C factor. Detachment is a direct function of the C factor, and, in this case, it appears that all of the detached sediment was transported from the plots.

The preceding discussion has described the sensitivity of the model's sediment calculations to particle-size distribution and the cover-management factor. Another factor that greatly affects sediment yield is slope, both length and degree.

Many on-site erosion control practices in surface-mined areas are aimed at reducing slope length or the degree of slope. Therefore, it is necessary to be able to predict the effect of slope on sediment yield to evaluate different combinations of best management practices.

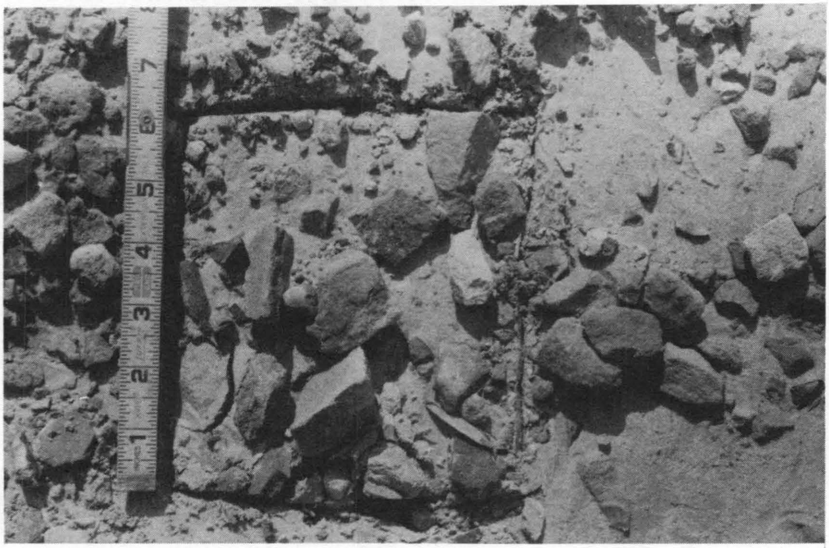

Figure 17. Soil surface after Run 1.

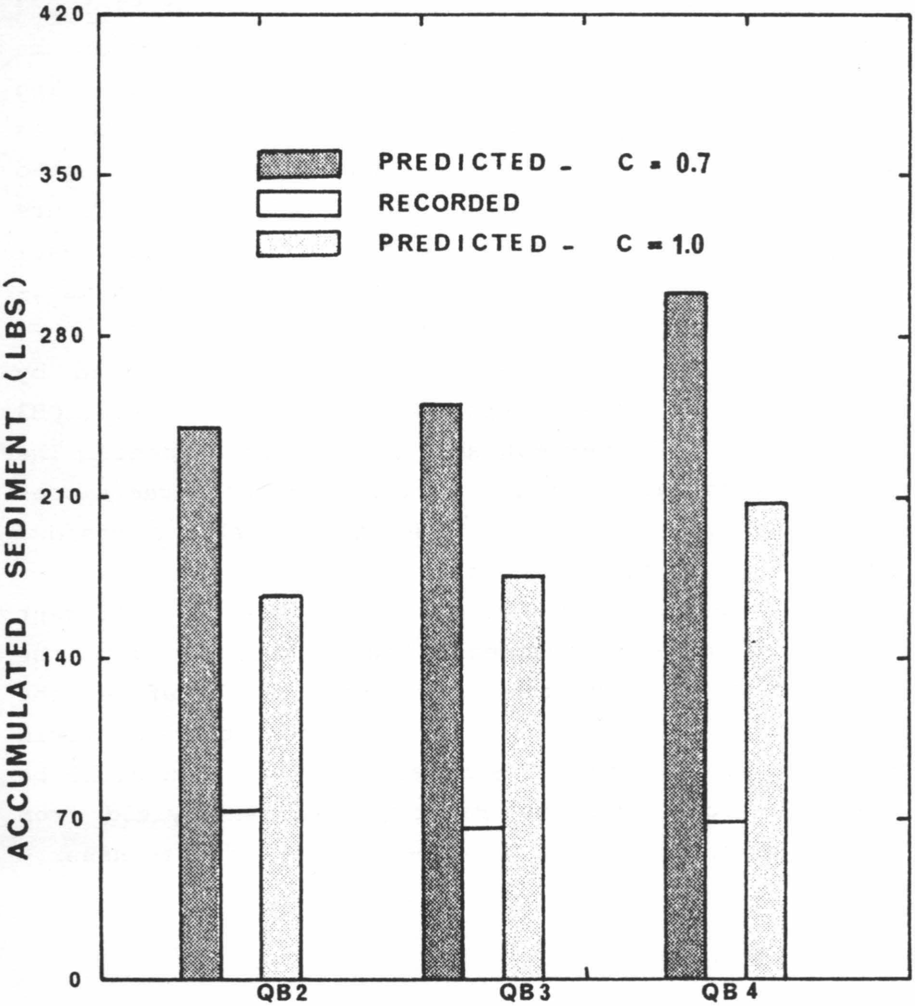

Figure 18. Effect of C factor on sediment yield prediction, Sullivan plots Run 3.

To demonstrate the effect of slope length on predicted sediment yield, the input data set for Plot QZ2 (Glen Jean) was modified to simulate an increase in the slope length to 100 feet and then to 200 feet. The predicted sediment yield for each of these lengths is compared in Figure 19 with the sediment yield predicted for the actual plot slope length of 36.3 feet. Figure 20 shows that the sediment yield increased for increasing slope length, following the trend reported by various researchers cited in the literature review.

The effect of slope steepness was simulated by increasing the actual slope of 16.3 percent on Plot QB3 (Sullivan) to 25 percent and then to 50 percent. The predicted values of sediment yield for the three slopes are shown in Figure 20. The steeper slopes yielded increasing amounts of sediment.

There were no recorded data available for different slope lengths and steepnesses for comparison with the sediment yield predicted by the model. Therefore, the accuracy of the values of predicted sediment yield could not be judged. The model, however, can still be used for comparing the relative sediment yield from different combinations of slope length and steepness.

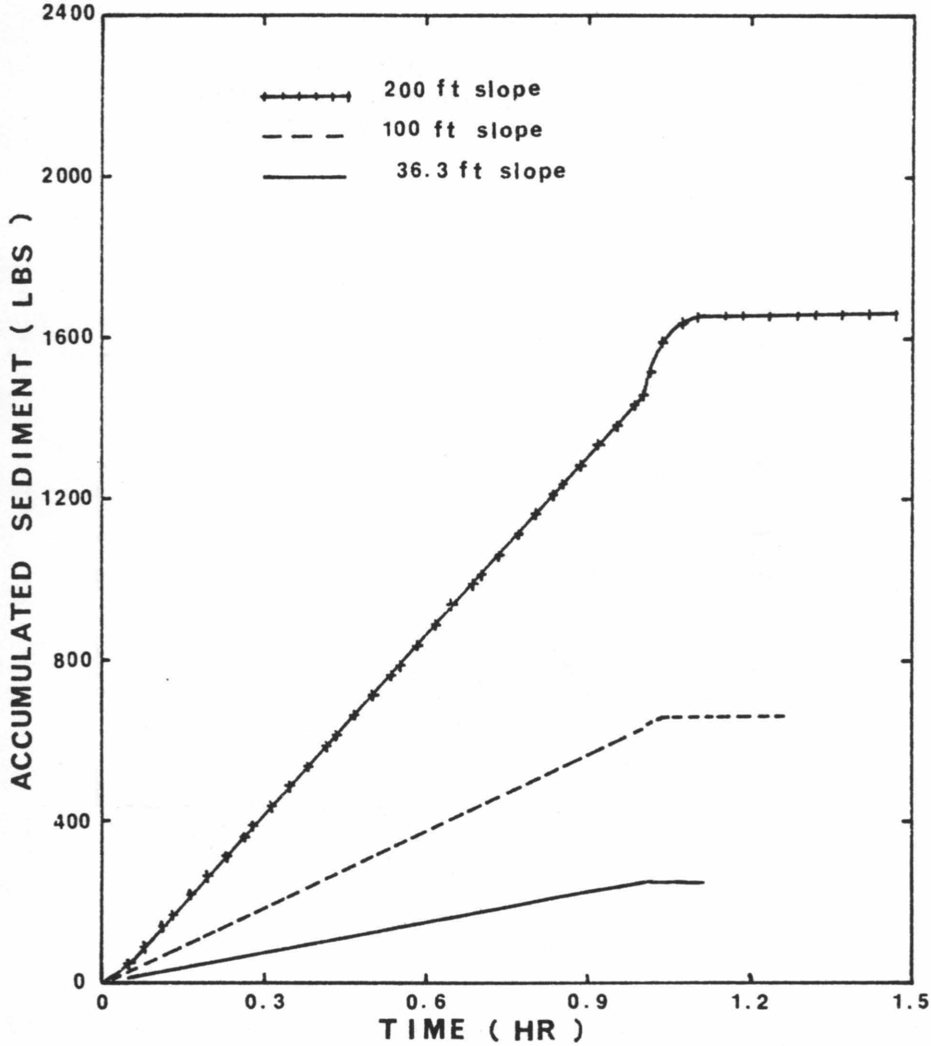

Figure 19. Effect of slope length on sediment yield prediction, Plot QZ2.

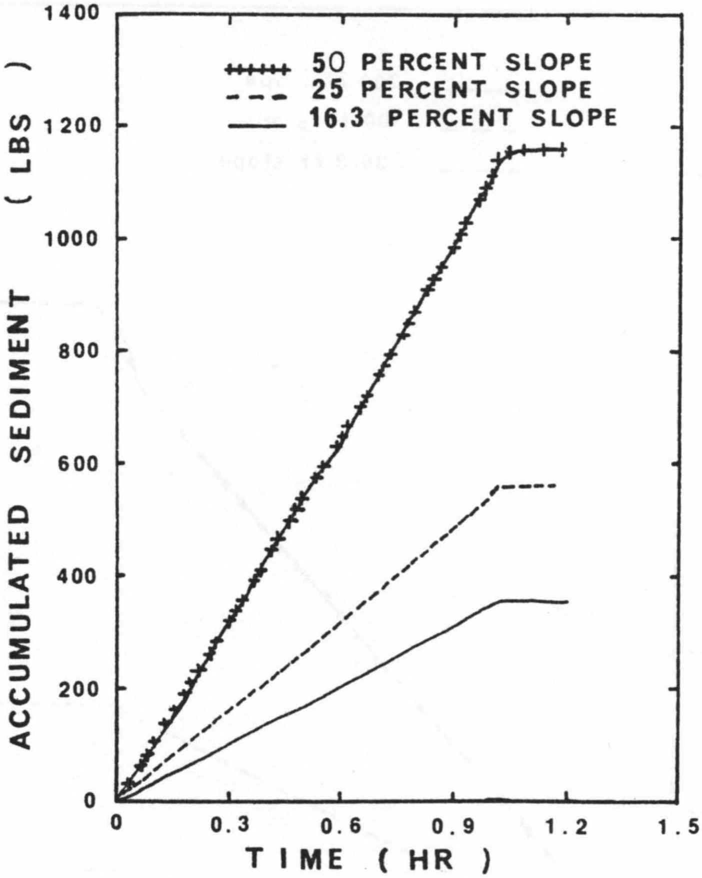

Figure 20. Effect of slope steepness on sediment yield prediction, Plot QB3.

SUMMARY AND CONCLUSIONS

The Finite Element Storm Hydrograph Model (FESHM), a distributed parameter model developed in the Agricultural Engineering Department at VPI&SU, was modified to predict sediment yield from surface-mined areas. Separate functions were included to define interrill detachment, rill detachment, and transport capacity of overland flow.

Data from rainfall simulator studies conducted at two surface-mine sites in southern West Virginia were used for field verification of the model. A comparison of simulated and recorded hydrographs showed good agreement, with the exception of the dry run (Run 1 of the simulator test). The poor match was attributed to a faulty estimate of the Holtan infiltration factor "a". It was shown that Holtan's "a" varies significantly with time from initiation of runoff to steady-state flow. It was demonstrated that a nearly perfect match could be achieved with a coefficient that reflects this variation more accurately.

The model consistently overpredicted sediment yield. Two factors, aggregate stability and armoring, were shown to contribute to the biased predictions. Data for the distribution of water-stable aggregates were not available, so, for the initial simulation, the particle size distribution obtained from the field plots was assumed. Because it has been shown by a number of investigators that knowledge of the distribution of water-stable aggregates is important in predicting soil loss, the high predictions were expected. Modified particle size distributions including aggregates were used to demonstrate the effect of aggregate stability on sediment prediction. The predicted sediment yields were reduced approximately 78 percent when the aggregate distribution was included. The measured soil loss was bracketed by the predictions obtained using the two assumptions for particle distribution. The results indicated that data on water-stable aggregates for the field plots would have significantly improved simulation results.

During the dry run of each rainfall simulator test, a rock mulch was created by the erosion of the finer soil particles. The armoring effect was most noticeable at the end of the very wet run (Run 3). This effect was simulated by reducing the cover-management factor, C, for Runs 2 and 3. Approximately thirty percent of the area was estimated to be covered by rock mulching using photographic techniques. Simulations with this factor resulted in an approximate reduction of thirty percent in the soil-loss estimate.

With sensitivity analysis it was demonstrated that the model responds to factors known to affect sediment yield, such as armoring (defined by the cover-management factor), erodibility index K, slope length, and slope steepness.

The effect of slope length was demonstrated by increasing the slope length from 36.3 feet to lengths of 100 feet and 200 feet. The simulated soil loss was increased approximately 163 percent and 150 percent, respectively, when the slope length was increased from 36.3 feet to 100 feet and from 100 feet to 200 feet.

The effect of slope steepness was illustrated by increasing the actual slope of Plot QB3 from 16.3 percent to 25 percent and to 50 percent. The simulated soil loss was increased approximately 156 percent when the slope steepness was increased from 16.3 percent to 25 percent, and approximately 372 percent when the slope steepness was increased from 16.3 percent to 50 percent.

No field data were available to verify the accuracy of these sensitivity studies; however, the trends are consistent with those reported in the literature. The results show that accurate field data, particularly water-stable aggregate distribution and density, armoring, and soil infiltration characteristics, are essential to accurately quantify soil loss.

The simulations of discharge hydrographs and soil loss from field plots and the sensitivity analysis, however, show that the model should be a useful tool for evaluating alternate erosion control practices.

LITERATURE CITED

Ackers, P. and W.R. White. 1973. Sediment transport: new approach and analysis. Journal Hydraulics Division ASCE, 99(HY11): 2041-2060.

Alonso, C.V., W.H. Neibling, and G.R. Foster. 1981. Estimating sediment transport capacity in watershed modeling. Transactions of the ASAE, 24(5): 1211-1220, 1226.

Bagnold, R.A. 1956. The flow of cohesionless grains in fluids. Philosophical Transactions Royal Society London, Series A 249(964): 235-297.

Barfield, B.J. 1968. Studies of turbulence in shallow sediment laden flow with superimposed rainfall. Technical Report 11. Water Resources Institute, Texas A. & M. University, College Station, Texas.

Barfield, B.J., I.D. Moore, and R.G. Williams. 1979. Prediction of sediment yield from surface-mined watersheds. In Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. University of Kentucky, Lexington, Kentucky.

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

Bennett, J.P. 1974. Concepts of mathematical modeling of sediment yield. Water Resources Research, 10(3): 485-492.

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

Chen, C.N. 1974. Evaluation and control of soil erosion in urbanizing watersheds. National Symposium on Urban Rainfall and Runoff and Sediment Control, UK Bulletin 106, College of Engineering, University of Kentucky, Lexington, Kentucky, pp. 161-173.

David, W.P. and C.E. Beer. 1974. Simulation of soil erosion. Transactions of the ASAE, 18(1): 126-133.

Einstein, H.A. 1950. The bed-load function for sediment transportation in open channel flows. U.S. Department of Agriculture Technical Bulletin No. 1026, 71pp.

Ekern, P.C. 1950. Raindrop impact as the force initiating soil erosion. Soil Science Society America Proceedings, 15: 7-10.

Ekern, P.C. 1953. Problems of raindrop impact erosion. Agricultural Engineering 34: 23-25, 28.

Ekern, P.C. 1954. Rainfall intensity as a measure of storm erosivity. Soil Science Society America Proceedings. 18: 212-216.

Ellison, W.D. 1944. Studies of raindrop erosion. Agricultural Engineering 25(4): 131-136 and 25(5): 181-182.

Ellison, W.D., 1945. Some effects of raindrops and surface-flow on soil erosion and infiltration: Transactions American Geophysical Union, 26(3): 414-429.

Ellison, W.D. 1947. Soil erosion studies. Agricultural Engineering 28: 145-146, 197-201, 245-248, 297-300, 349-351, 402-405, 442-444.

Engelund, F. and E. Hansen. 1967. A monograph on sediment transport in alluvial streams. Teknisk Vorlag, Copenhagen.

EPA. 1973. Methods for identifying and evaluating the nature and extent of nonpoint sources of pollution. U.S. Environmental Protection Agency, Office of Air and Water Programs, Washington, D.C.

EPA. 1976. Erosion and sediment control for surface mining in the eastern U.S. United States Environmental Protection Agency, EPA-625/3-76-006.

Farmer, E.E. and B.P. Van Haveren. 1971. Soil erosion by overland flow and raindrop splash on three mountain soils. USDA-FS Research Paper INT-100, 14pp.

Foster, G.R. 1971. The overland flow process under natural conditions. In Monke, E. J. (ed.), Biological Effects in the Hydrological Cycle, pp. 173-185. Proceedings of the Third International Seminar for Hydrology Professors. Department of Agricultural Engineering, Purdue University, West Lafayette, Indiana

Foster, G.R., L.F. Huggins, and D.L. Meyer. 1968. Simulation of overland flow on short field plots. Water Resources Research 4(6): 1179-1187.

Foster, G.R. and L.D. Meyer. 1972a. A closed-form soil erosion equation for upland areas. Sedimentation Symposium to Honor Professor Hans Albert Einstein, H.W. Shen, ed., Colorado State University, Fort Collins, pp. 12-1 - 12-19.

Foster, G.R. and L.D. Meyer. 1972b. Transport of soil particles by shallow flow. Transactions of the ASAE, 15(1): 99-102.

Foster, G.R. and L.D. Meyer. 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. Present and Prospective Technology for Predicting Sediment Yields and Sources, ARS-S-40, pp. 190-206.

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

Foster, G.R., L.D. Meyer, and C.A. Onstad. 1977b. A runoff erosivity factor and variable slope length exponents for soil loss estimates. Transactions of the ASAE, 20(4): 683-687.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1980. A model to estimate sediment yield from field-sized areas: Development of model. In, CREAMS, a Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA-SEA Conservation Research Report No. 26, Vol. I: 36-64.

Free, G. R. 1960. Erosion characteristics of rainfall. Agricultural Engineering 41(7): 447-449, 455.

Gilley, J.E., G.W. Gee, and A. Bauer. 1976. Particle size distribution of eroded spoil materials. Farm Research, November-December, pp.35-36.

Graf, W.H. 1971. Hydraulics of sediment transport. New York: McGraw-Hill Book Co., Inc.

Haan, C.T. and B.J. Barfield. 1978. Hydrology and sedimentology of surface mined lands. University of Kentucky, College of Engineering, Lexington, Kentucky.

Harmon, W.C. and L.D. Meyer. 1978. Cover, slope, and rain intensity affect interrill erosion. Proceedings, Mississippi Water Resources Conference., p. 9-16.

Heatwole, C.D. 1979. A finite element hydrologic model to describe transmission losses from overland flow. M.S. Thesis, Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Heatwole, C.D., V.O. Shanholtz and B.B. Ross. 1982. Finite element model to describe overland flow on an infiltrating watershed. Transactions of the ASAE, 25(3): 630-637.

Hockman, E.L. 1981. Evaluation of the universal soil loss equation on a selected reclaimed eastern surface mine area. M.S. Thesis, Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Idike, F.I., C.L. Larson, D.C. Slack and R.A. Young. 1980. Experimental verification of two infiltration models. Transactions of the ASAE, 23(6): 1428-1433.

Jennings, M.E., W.P. Carey and D.W. Blevens. 1980. Field studies for verification of surface mining hydrologic models. In Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. University of Kentucky, Lexington, Kentucky.

Jones, J.N., Jr. 1980. Soil physical properties for mine soils. Unpublished data.

Judah, O.M. 1973. Simulation of runoff hydrographs from natural watersheds by finite element method. Ph.D. Dissertation, Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Judah, O.M., V.O. Shanholtz and D.N. Contractor. 1975. Finite element simulation of flood hydrographs. Transactions of the ASAE, 18(3): 518-522.

Kilinc, M. and E.V. Richardson. 1973. Mechanics of soil erosion from overland flow generated by simulated rainfall. Hydrology Paper No. 63, Colorado State University, Fort Collins, Colorado.

Kramer, L.A. and L.D. Meyer. 1969. Small amounts of surface mulch reduce soil erosion and runoff velocity. Transactions of the ASAE, 12(5): 638-641, 645.

Kuh, H.C. and D.L. Reddell. 1977. Two-dimensional model of watershed erosion. Technical Report 80, Texas Water Resources Research Institute, Texas A&M University, College Station, Texas.

Laursen, E. 1958. The total sediment load of streams. Journal Hydraulics Division ASCE, 54(HY1): Paper 1530. 36 p.

Li, E.A. 1975. A model to define hydrologic response units based on characteristics of the soil-vegetative complex within a drainage basin. M.S. Thesis, Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Li, R. M., D. B. Simons, and M. A. Stevens. 1976. Morphology of cobble streams in small watersheds. Journal Hydraulic Division ASCE, 102(HY8): 1101-1117.

Li, R. M., D. B. Simons, and D. R. Carter. 1977. Mathematical modeling of soil erosion by overland flow. Soil Erosion: Prediction and control. Special publication no. 21, SCSA, pp. 210-216.

Mantz, P.A. 1977. Incipient transport of fine grains and flakes by fluids - extended Shields diagram. Journal Hydraulic Division ASCE, 103(HY6): 601-615.

Martinez, M.R., M.M. Fogel, and L.J. Lane. 1980. Modeling for upland areas. Paper No. 80-2505, American Society of Agricultural Engineers, St. Joseph, Michigan.

Mazurak, A.P. and P.N. Mosher. 1968. Detachment of soil particles in simulated rainfall. Soil Science Society America Proceedings, 32: 716-719.

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

Meyer, L. D. 1980. How rain intensity affects interrill erosion. Paper No. 80-2503, American Society of Agricultural Engineers, St. Joseph, Michigan.

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

Meyer, L. D., G. R. Foster, and M. J. Romkens. 1975. Source of soil eroded from upland slopes. In, Present and Prospective Technology for Predicting Sediment Yields and Sources. Report No. ARS-S-40, ARS-USDA, pp. 177-189.

Meyer-Peter, E. and R. Muller. 1948. Formulas for bed load transport. Proceedings 2nd Congress of the International Association for Hydraulic Research, Stockholm: pp. 39-64.

Mihara, H. 1951. Raindrop and soil erosion. Bulletin National Institute Agricultural Science, Series A, No. 1.

Moldenhauer, W.C. and J.C. Koswara. 1968. Effect of initial clod size on characteristics of splash and wash erosion. Soil Science Society of America Proceedings, 32(6): 875-879.

Moldenhauer, W.C. and D.C. Long. 1964. Influence of rainfall intensity on soil loss and infiltration rates: I. Effect over a range of texture. Soil Science of America, 28(6): 813-817.

Musgrave, G.W. 1947. The quantitative evaluation of factors in watershed erosion. Journal of Soil and Water Conservation 2(3): 133-138.

Mutchler, C.K. and R.A. Young. 1975. Soil detachment by raindrops. In, Present and Prospective Technology for Predicting Sediment Yields and Sources. ARS-S-40, ARS-USDA, pp.113-117.

Neal, J.H. 1938. The effect of degree of slope and rainfall characteristics on runoff and soil erosion. Missouri Agricultural Experimental Station Research Bulletin, 280. 47pp.

Negev, N. 1967. A sediment model on a digital computer. Technical Report No. 76, Stanford University, Stanford, California.

Nichols, M.L. and H.D. Sexton. 1932. A method of studying soil erosion. Agricultural Engineering 13: 101-103.

Novotny, V. and G. Chesters. 1981. Handbook of nonpoint pollution: sources and management. VNR Environmental Engineering Series, ISBN 0-442-22563-6.

Onstad, C.A. and G.R. Foster. 1975. Erosion modeling on a watershed. Transactions of the ASAE, 18(2): 288-292.

Overton, D.E. and E.C. Crosby. 1980. Simulation of effects of contour coal strip mining on stormwater runoff and pollutant yields. In, Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. University of Kentucky, Lexington, Kentucky.

Palmer, R.S. 1965. Waterdrop impact forces. Transactions of the ASAE, 8(1): 69-70,72.

Partheniades, E. 1965. Erosion and deposition of cohesive soils. Journal Hydraulics Division ASCE, 91(HY1): 105-139.

Rice, L.R. 1982. Surface mine soil erodibility. M.S. Thesis. Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Robinson, A.R. 1970. Sediment, our greatest pollutant?. Paper No. 70-701. American Society of Agricultural Engineers, St. Joseph, Michigan.

Ross, B.B. 1975. A finite element model to determine the effect of land-use changes on flood hydrographs. M.S. Thesis, Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Ross, B.B. 1978. A spatially responsive catchment model for predicting stormwater runoff from ungaged watersheds. Ph.D. Dissertation, Department of Agricultural Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Ross,B.B., V.O. Shanholtz, D.N. Contractor and J.C. Carr. 1978. A model for evaluating the effect of land uses on flood flows. Bulletin 85, Virginia Water Resources Research Center, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Ross, B.B. D.N. Contractor and V.O. Shanholtz. 1979. A finite-element model of overland and channel flow for assessing the hydrologic impact of land-use change. Journal of Hydrology, 41: 11-30.

Ross, B.B., V.O. Shanholtz and D. N. Contractor. 1980. A spatially responsive hydrologic model to predict erosion and sediment transport. Water Resources Bulletin 16(3): 538-545.

Rovey, E.W., D.A. Woolhiser and R.E. Smith. 1977. A distributed kinematic model of upland watersheds. Hydrology Paper No. 93, Colorado State University, Fort Collins, Colorado.

Shanholtz, V.O., B.B. Ross and J.C. Carr. 1981a. Effect of spatial variability on the simulation of overland and channel flow. Transactions of the ASAE, 24(1): 124-138.

Shanholtz, V.O., M.D. Smolen, D.F. Amos and J.B. Burger. 1981b. Predicting soil loss from surface-mined areas - Equipment design. Completion Report to State Mining and Minerals Resources Research Institute, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Simons, D.B. and E.V. Richardson. 1966. Resistance to flow in alluvial channels. Professional Paper 422-J, U.S. Geological Society. 61 p.

Smith, D.D. and W.H. Wischmeier. 1957. Factors affecting sheet and rill erosion. Transactions American Geophysical Union 38(6): 889-896.

Smith, R.E. 1979. A kinematic model for surface mine sediment yield. ASAE Paper No. 79-2533, St. Joseph, Michigan.

Sweeten, J.M. and D.L. Reddell. 1976. Nonpoint sources: state-of-the-art overview. ASAE Paper No. 76-2563, St. Joseph, Michigan.

Warner, R.G., L.G. Wells, B.J. Barfield and I.D. Moore. 1981. Evaluating alternative surface mining methods using a distributed parameter approach. ASAE Paper No. SER 81-016, St. Joseph, Michigan.

Williams, J.R. 1975. Sediment-yield prediction with universal equation using runoff energy factor. In, Present and Prospective Technology for Predicting Sediment Yields and Sources, Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi, USDA, ARS-S-40 : 224-252.

Williams, J.R. and H.D. Berndt. 1977. Sediment yield predictions based on watershed hydrology. Transactions of the ASAE, 20(6): 1100-1104.

Wischmeier, W.H. and J.V. Mannering. 1969. Relation of soil properties to its erodibility. Soil Science Society America Proceedings, 33: 131-136.

Wischmeier, W.H. and D.D. Smith. 1958. Rainfall energy and its relationship to soil loss. Transactions of the American Geophysical Union 39: 285-291.

Wischmeier, W.H. and D.D. Smith. 1960. Predicting rainfall erosion losses- A guide to conservation planning. United States Department of Agriculture Science and Education Administration, Handbook 537.

Wischmeier, W.H., C.B. Johnson, and B.V. Cross. 1971. A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26(5): 193-198.

Wolfe, M.L. 1982. Sediment detachment and transport functions to simulate soil loss from reclaimed mine soils. Master of Science Thesis, Department of Agricultural Engineering, VPI&SU, Blacksburg, Virginia.

Wolfe, M.L., V.O. Shanholtz, M.D. Smolen, J.N. Jones, Jr., and B.B. Ross. 1981. Simulating sediment transport to evaluate sediment control practices in surface-mined areas. ASAE Paper No. 81-2041. American Society of Agricultural Engineers, St. Joseph, Michigan.

Yalin, M.S. 1963. An expression for bed load transportation. Journal Hydraulics Division ASCE, 89(HY3): 221-250.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal Hydraulics Division ASCE, 99(HY10): 1679-1704.

Young, R.A. and J.L. Wiersma. 1973. The role of rainfall impact in soil detachment and transport. Water Resource Research, 9(6): 1629-1636.

Virginia's Agricultural Experiment Stations

1—Blacksburg
Virginia Tech

2—Steeles Tavern
Shenandoah Valley Research Station

3—Orange
Piedmont Research Station

4—Winchester
Winchester Fruit Research Laboratory

5—Middleburg
Virginia Forage Research Station

6—Warsaw
Eastern Virginia Research Station

7—Suffolk
Tidewater Research and Continuing Education Center

8—Blackstone
Southern Piedmont Research and Continuing Education Center

9—Critz
Reynolds Homestead Research Center

10—Glade Spring
Southwest Virginia Research Station

11—Hampton
Seafood Processing Research and Extension Unit