Interril Soil Erosion, Part I. Development of Model Equations

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ABSTRACT

EQUATIONS describing overland flow depth, rainfall induced soil detachment and sediment transport capacity on interrill areas were identified. The Darcy-Weisbach equation which included a parameter for predicting flow resistance caused by rainfall was used to calculate depth of overland flow. Soil detachment was determined from an equation incorporating raindrop induced, impact pressure estimates. The product of a soil transport factor, bottom shear stress and flow velocity was used to calculate sediment transport capacity. Nondimensional forms of the model equations were evaluated using existing experimental data.

INTRODUCTION

Interrill erosion takes place in the overland flow region between rills where raindrop impact is the primary soil detaching agent. Overland flow serves as the mechanism for transporting soil materials detached by raindrop impact. Thus, an understanding of the interrill soil erosion process requires knowledge of the mechanics of soil particle detachment by raindrop impact and transport by overland flow. In this study transport of soil particles by raindrop splash was assumed to be negligible.

Because of the complicated nature of soil detachment and transport mechanisms and the complexities involved in the routing of water and sediment, mathematical models have been developed to simulate soil erosion. Meyer and Wischmeier (1969) were among the first to mathematically model soil detachment and transport. Several other soil erosion models have been developed (Foster and Meyer, 1972 and 1975; David and Beer, 1975; Smith, 1976; Foster, Meyer and Onstad, 1977; Foster et al., 1981; and Park, Mitchell and Scarborough, 1982). Recently, modeling of splash erosion was examined by Park, Mitchell and Bubenzer (1982 and 1983) and parameters used for estimating soil detachment were examined by Al-Durrah and Bradford (1982). Alonso et al. (1981) evaluated several transport formulas against extensive laboratory and field data.

The purpose of this study was to evaluate model equations used to estimate interrill soil erosion. The equations developed in this investigation serve to complement existing erosion models. The accuracy of comprehensive erosion models can be improved if more reliable formulas for predicting overland flow depth, soil detachment and sediment transport capacity are identified.

DEVELOPMENT OF MODEL EQUATIONS

Water depth may play a significant role in soil detachment and transport on many interrill areas. In this study, an equation for determining overland flow depth was initially evaluated. Overland flow depth was then incorporated as a variable in soil detachment and transport capacity relations.

Overland Flow Depth

Rainfall may significantly affect the resistance and flow characteristics of shallow overland flow. The Darcy-Weisbach friction coefficient has been widely used to describe rainfall induced flow resistance. The friction slope obtained using the Darcy-Weisbach friction coefficient and the momentum approach as reported by Shen and Li (1973) is given as:

$$S_f = \frac{f\,V_f^2}{8\,g\,y} \qquad [1]$$

where S_f = friction slope; f = Darcy-Weisbach friction coefficient; V_f = average flow velocity; g = gravitational acceleration; and y = flow depth. If friction slope is assumed to equal channel bottom slope, S, (i.e. uniform flow) and equation [1] is solved for y, then:

$$y = \frac{f\,V_f^2}{8\,g\,S} \qquad [2]$$

The Darcy-Weisbach friction factor for laminar flow has been found to increase with increasing rainfall intensity and to decrease with increasing Reynolds number, R_n, which is defined as:

$$R_n = \frac{V_f\,y}{\nu} \qquad [3]$$

where ν = kinematic viscosity of water.

Shen and Li (1973) assumed f to be the sum of the friction coefficient due to rainfall, f_r, and f_w, the friction coefficient without rainfall:

$$f = f_r + f_w \qquad [4]$$

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If:

$$f_r = \frac{k_r}{R_n} \text{ and } f_w = \frac{k_w}{R_n} \quad [5]$$

then:

$$f = \frac{k_r}{R_n} + \frac{k_w}{R_n} \quad [6]$$

For laminar flow conditions, Shen and Li (1973) found that k_r could be determined from the equation:

$$k_r = b\, i^c \quad [7]$$

where i = rainfall intensity and b and c are regression constants. If equation [7] is substituted into equation [6] the following relation results:

$$f = \frac{b\, i^c + k_w}{R_n} \quad [8]$$

For laminar flow over smooth surfaces (Chow, 1959):

$$k_w = 24 \quad [9]$$

Under steady state conditions with no infiltration, the discharge per unit width, q, can be written as a function of x:

$$q = q_b + i\, x \quad [10]$$

where q = flow rate of combined flow per unit width q_b = base flow rate per unit width and x = distance in the main flow direction. If rainfall intensity and infiltration at any time are known, water depth can be estimated for other than the steady state case. By definition:

$$q = V_f\, y \quad [11]$$

If equation [10] and [11] are substituted into equation [2], the following relation is obtained:

$$y = \left[\frac{f(q_b + i\, x)^2}{8\, g\, S}\right]^{1/3} \quad [12]$$

The base flow can be assumed to equal zero without loss of generality. Substitution of equation [8] into equation [12] yields the following relation:

$$y = \left[\left(\frac{b\, i^c + k_w}{8\, g\, S}\right) \nu\, i\, x\right]^{1/3} \quad [13]$$

Equation [13] can be non-dimensionalized by defining the following normalizing quantities. Let L_o = length of the flow plane; and y_o = normal depth at x = L_o. Using the above quantities, normal depth is given as:

$$y_o = \left[\left(\frac{b\, i^c + k_w}{8\, g\, S}\right) \nu\, i\, L_o\right]^{1/3} \quad [14]$$

The following dimensionless variables can now be defined:

$$y_* = y/y\, ;\ x_* = x/L_o \quad [15]$$

Substitution of equations [13] and [14] into equation [15] yields the dimensionless depth profile:

$$y_* = x_*^{1/3} \quad [16]$$

Experimentally obtained depths can be normalized by dividing by y_o as calculated from equation [14] and plotting against the cube root of dimensionless distance, $x_*^{1/3}$.

Several authors have reported depths of overland flow as a function of distance in the main flow direction for various rainfall conditions. Equation [16] was evaluated for a smooth surface using data of Emmett (1970), Wenzel (1970), Yoon (1970), and Li (1972). The characteristics of the data used in the evaluation are given in Table 1 and by Gilley (1982).

For Reynolds numbers from 126 to 900, channel slopes of 0.5 to 1.0% and rainfall intensities of 13 to 444 mm/h over a hydraulically smooth surface, Shen and Li (1973) determined values for the regression coefficients shown in equation [14]. For rainfall intensities reported in mm/h, values of b and c in equation [14] are given as 7.21 and 0.41, respectively. These values and the theoretical value of k_w = 24 were used to calculate y_o for the experimental data from smooth surfaces examined in this study.

A plot of dimensionless depth, y_*, versus the cube root of dimensionless distance, $x_*^{1/3}$, for a smooth surface is shown in Fig. 1. Results of linear regression analyses of the data shown in Fig. 1 are given in Table 2. Students-t test was used to evaluate the hypothesis that the regression coefficient equals one and the intercept equals zero at the 99% confidence level. The regression was found to be highly significant with the regression coefficient not significantly different from one nor the intercept significantly different from zero.

A plot of dimensionless depth versus the cube root of dimensionless distance for a rough surface is shown in Fig. 2. Figure 2 was prepared from data collected by Woo (1956) and Emmett (1970) and results of linear regression analyses of these data are presented in Table 2. The characteristics of the data used in the analyses are listed in Table 1.

Again, the regression was found to be highly significant. Using the students-t test, the hypothesis that the regression coefficient equals one and the intercept equals zero cannot be rejected at the 99 % confidence level. Thus, analyses of overland flow depth profiles for both smooth and rough surfaces suggest that equation [16] is an appropriate dimensionless relationship, and that equation [14] properly accounts for the effects of roughness and raindrop impact on the Darcy-Weisbach friction factor.

TABLE 1. SUMMARY OF DATA USED IN EVALUATING EQUATION FOR PREDICTING OVERLAND FLOW DEPTH.

Data source	Surface condition	Measurements in set	Slope, %	Rainfall intensity, mm/h
Woo (1956)	Rough	18	0.1 and 0.2	47
Emmett (1970)	Smooth	28	3.4	79 and 288
Emmett (1970)	Rough	28	1.7	151 and 214
Wenzel (1970)	Smooth	20	0.5	24 and 381
Yoon (1970)	Smooth	14	0.5 and 1.0	13 and 95
Li (1972)	Smooth	20	0.6 and 1.1	318 and 445

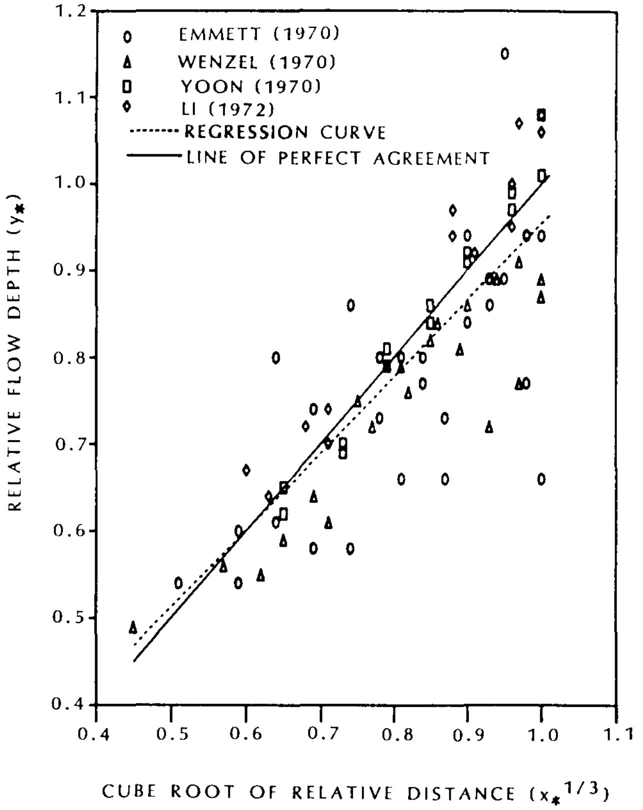

Fig. 1—Relative flow depth vs. the cube root of relative distance for a smooth surface.

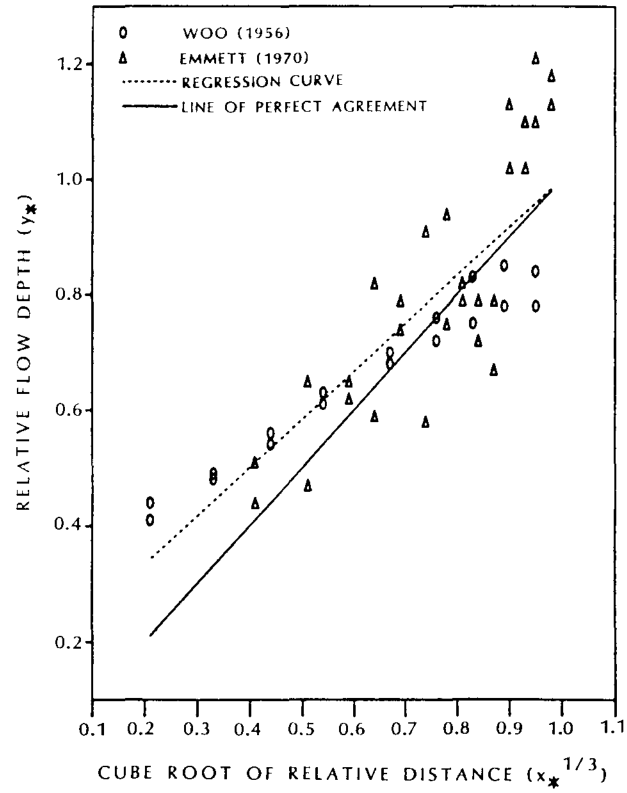

Fig. 2—Relative flow depth vs. the cube root of relative distance for a rough surface.

Soil Detachment From Raindrop Impact

From experimental measurements of drop impact pressure for various drop sizes, impact velocities and water layer depths, Wang and Wenzel (1970) developed the following empirical relation for (d/y) < 1.0:

$$\phi = 0.2 \left(\frac{d}{y}\right)^{1.83} \quad [17]$$

where ϕ = dimensionless impact pressure at the bottom of the water layer directly under the drop impact point; and d = equivalent drop diameter. Dimensionless impact pressure is also given by (Wang and Wenzel, 1970):

$$\phi = P/\rho\ V^2 \quad [18]$$

where P = impact pressure; ρ = density of water; and V = drop impact velocity. From equations [17] and [18], the following relation is obtained:

$$P = 0.2\,\rho\, V^2 \left(\frac{d}{y}\right)^{1.83} \quad [19]$$

The impact pressure shown above is a measure of shearing forces due to velocity fields generated by pressure gradients. Impact pressure is assumed in the present study to be related to the normal component of raindrop velocity for inclined surfaces. Thus:

$$P = 0.2\,\rho\,\cos^2\theta\ V^2 \left(\frac{d}{y}\right)^{1.83} \quad [20]$$

where θ = slope angle. Soil detachment by a single raindrop, D, is further assumed to be a linear function of maximum impact pressure:

$$D = K_d\, P \quad [21]$$

TABLE 2. STATISTICAL ANALYSES OF MODEL EQUATIONS.

Dependent variable	Regression equation	Coefficient of determination, r^2	F	β_1 Students-t	β_1 Standard error	β_0 Students-t	β_0 Standard error
Overland flow depth for smooth surface	$y_* = 0.883\,x_*^{1/3} + 0.071$	0.686	162	-1.70	0.069	0.737	0.095
Overland flow depth for rough surface	$y_* = 0.833\,x_*^{1/3} + 0.167$	0.717	112	-2.12	0.079	1.52	0.109
Soil detachment from raindrop impact	$D_{s_*} = 0.814\,D_{r_*} + 0.068$	0.790	86.4	-2.11	0.088	0.571	0.116
Sediment transport capacity of overland flow	$T_* = 1.21\,q_* - 0.054$	0.734	30.5	0.965	0.219	-0.256	0.202

where K_d = soil detachment factor. Substituting equation [20] into equation [21] results in the following relation:

$$D = 0.2\, K_d\, \rho \cos^2\theta\, V^2 \left(\frac{d}{y}\right)^{1.83} \quad [22]$$

Equation [22] is proposed to describe soil detachment from a single drop impact. If several drops, a_i, of the same diameter, d_i, and velocity, V_i, strike a water layer per unit area and time then the soil detachment, D_s, caused by these drops is given by:

$$D_s = 0.2\, K_d\, \rho \cos^2\theta\, a_i\, V_i^2 \left(\frac{d_i}{y}\right)^{1.83} \quad [23]$$

If drops with n varying diameters strike the water surface then:

$$D_s = 0.2\, K_d\, \rho \cos^2\theta \sum_{i=1}^{n} a_i\, V_i^2 \left(\frac{d_i}{y}\right)^{1.83} \quad [24]$$

where a_i = number of drops in the i^{th} class; d_i = mean drop diameter in that class; and V_i = velocity of the drops with diameter, d_i.

If the normalizing detachment rate, D_{so}, is defined as that rate of detachment per unit area that would occur with

$$\sum_{i=1}^{n} a_i$$

drops per unit time of diameter, d_o, and impact velocity, V_o, striking a surface film of water with depth, y_o, equation [24] yields:

$$D_{so} = 0.2\, K_d\, \rho \cos^2\theta \sum_{i=1}^{n} a_i\, V_o^2 \left(\frac{d_o}{y_o}\right)^{1.83} \quad [25]$$

Normalized drop diameter, d_o, is defined as equal to normalized water depth, y_o. The number of drops per unit area, per unit time,

$$\sum_{i=1}^{n} a_i,$$

would be the same as the total number of drops per unit area, per unit time in the experiment under evaluation. Normalized drop impact velocity, V_o, is defined to equal the terminal velocity of the largest diameter drop or drop class in the experiment under examination.

Using the normalized quantities described above, the following dimensionless variables can be introduced:

$$D_{s*} = D_s/D_{so};\ d_{*i} = d_i/d_o;\ \text{and}\ V_{*i} = V_i/V_o \quad [26]$$

If equation [24] is divided by equation [25] and the other identities in equation [26] are substituted, the following dimensionless equation is obtained:

$$D_{s*} = \frac{D_s}{D_{so}} = \frac{\sum_{i=1}^{n} a_i\, V_{*i}^2 \left(\frac{d_{*i}}{y_*}\right)^{1.83}}{\sum_{i=1}^{n} a_i} \quad [27]$$

To simplify notation the quantity on the right side of equation [27] will be defined as relative raindrop impact pressure, D_{r*}. Thus:

$$D_{s*} = D_{r*} \quad [28]$$

Normalized detachment for the steady-state case can also be expressed as a function of dimensionless distance by substituting the expression for y_* into equation [27].

Equation [27] was tested using experimental data of Palmer (1964), Lattanzi, et al. (1974), Harmon and Meyer (1978) and Walker et al. (1978). The characteristics of the data used in the evaluation are shown in Table 3.

Experimentally measured water depths were reported by Palmer (1964). Palmer (1964) found that depressions in the soil surface occurred at the shallower water depths as a result of raindrop impact. In this analyses only data collected from those tests producing minimal depressions or no depressions were examined.

Equation [13] was used to calculate water depths for the experimental conditions reported by Lattanzi et al. (1974), Harmon and Meyer (1978), and Walker et al. (1978). A value for surface roughness, k_w, of 200, obtained from data collected by Parsons (1949) and Marelli (1974) for bare soil surfaces, was assumed.

Lattanzi et al. (1974) and Harmon and Meyer (1978) simulated rainfall with an oscillating nozzle (Bubenzer and Meyer, 1965) having drop characteristics as described by Meyer (1958). The number of drops in each of seven size classes was determined for substitution into equation [24].

For each of the data sources evaluated in the present investigation, several soil detachment rates were reported. A single soil detachment rate for each data

TABLE 3. SUMMARY OF DATA USED IN EVALUATING EQUATION FOR PREDICTING SOIL DETACHMENT FROM RAINDROP IMPACT.

Data source	Soil material	Measurements in set	Mean drop diameter, mm	Water depth, mm
Palmer (1964)	Silty clay loam	7	2.9, 4.7 and 5.9	6.0-20.0
Lattanzi, Meyer and Baumgardner (1974)	Silt loam	3	2.1	0.5-1.1
Harmon and Meyer (1978)	Silt loam	4	2.1	0.5-1.4
Walker, Kinnell and Green (1978)	Sand	11	2.7 and 5.7	3.0-16.9

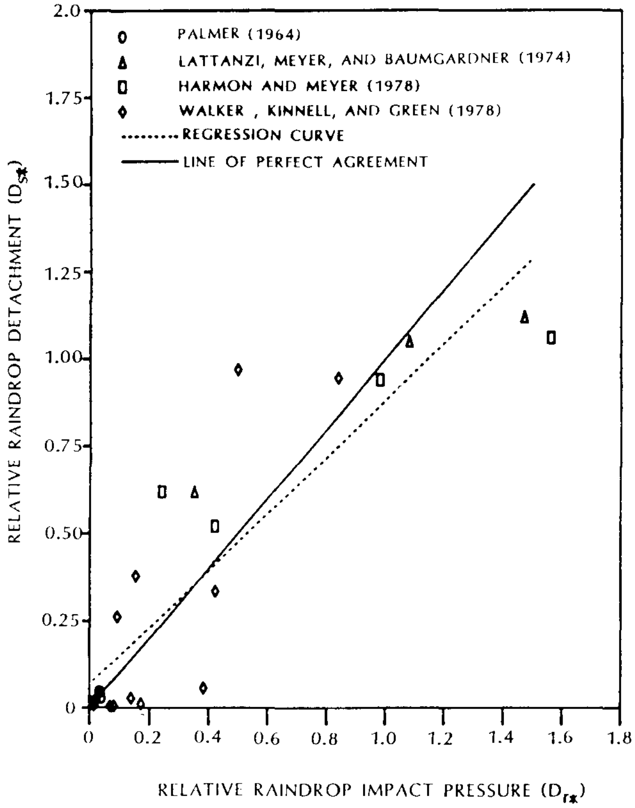

Fig. 3—Relative raindrop detachment vs. relative raindrop impact pressure.

source was selected and the experimental information was then substituted into equation [24] to determine the soil detachment factor, K_d, for a particular soil material. This value of K_d was then substituted into equation [25] to obtain normalized raindrop detachment.

A plot of relative raindrop detachment versus relative raindrop impact pressure is presented in Fig. 3 and the results of linear regression analyses of this information are shown in Table 2. The regression was found to be highly significant. Using the students-t test, we cannot reject the hypothesis that the regression coefficient equals one nor the hypothesis that the intercept equals zero at the 99% confidence level. Analyses of the detachment data suggest that equation [27] is an appropriate dimensionless relationship and that equation [25] properly accounts for the effects of raindrop diameter, raindrop velocity and flow depth upon detachment.

Equation [24] considers the maximum impact pressure at the soil water interface caused by each raindrop. This equation could predict similar soil particle detachment from several small drops impacting at relatively low velocities as from a few larger drops with large impact velocities. If the detachment equations are to provide proper soil loss estimates, the experimental drop sizes and impact velocities should be similar to values found under natural rainfall conditions.

Soil detachment from a single drop impact is shown in equation [22] to be related to the ratio of drop diameter to water depth. As the water depth approaches zero, soil detachment will go to infinity - clearly an unrealistic value. The regression relation incorporated into equation [22] was obtained from experimental data where the ratio of drop diameter to water depth was less than one. Thus, the soil detachment equation would be expected to be best suited for experimental conditions where overland flow depth was greater than raindrop diameter. Mutchler (1970) found that maximum splash amount from waterdrop impact occurred when raindrop diameter exceeded water depth. Additional research data are needed to define a raindrop induced point pressure relationship for conditions where overland flow depth is less than raindrop diameter.

The soil detachment factor, K_d, is a model parameter which is not readily available. This parameter would be expected to vary among different soil and soil tilth conditions and, therefore, must be evaluated for individual sites. At present, the only technique available for evaluating the soil detachment factor is rainfall simulation testing.

Soil detachment by raindrop impact could vary as a time dependent function. Moldenhauer and Koswara (1968) found that in some cases the rate of particle detachment by raindrop impact increases rapidly at the beginning of a rainfall event, reaches a peak, and then decays exponentially while in other cases it increases with time. Sufficient research data are not presently available to define the time dependent effect of particle detachment by raindrop impact.

Sediment Transport Capacity of Overland Flow

Bagnold (1966) related sediment transport capacity to stream power, ω, the product of bottom shear (γ y S) and flow velocity:

$$\omega = (\gamma \, y \, S) \, V_f \quad [29]$$

where γ is the specific weight of water and the other quantities are as previously defined. The stream power concept relates the work or energy expenditure of a stream to the quantity of sediment transported by the flow. The stream power relation has been used primarily to predict bed load sediment transport. Sediment transport capacity, T, was assumed to be a linear function of stream power:

$$T = K_t \, \omega \quad [30]$$

where K_t = sediment transport factor. Substituting equation [29] into equation [30], yields the following relation:

$$T = K_t \, (\gamma \, y \, S) \, V_f \quad [31]$$

This equation can be written in non-dimensional form by introducing the following normalizing quantities. Let:

$$q_o = i \, L_o \quad [32]$$

where q_o is the flow rate per unit width at $x = L_o$ and depth, y_o. Using the quantities defined above, normalized runoff velocity, V_{fo}, is given as:

$$V_{fo} = q_o / y_o \quad [33]$$

Substituting the normalizing quantities introduced in equation [33] into equation [31] and simplifying yields:

$$T_o = K_t \, (\gamma \, y_o \, S) \, V_{fo} \quad [34]$$

The following dimensionless variables can now be introduced:

$$T_* = \frac{T}{T_o} \; ; q_* = \frac{q}{q_o} \quad \ldots\ldots\ldots\ldots [35]$$

If these dimensionless variables are incorporated into equations [11] and [31] the following relation results:

$$T_* = q_* \quad \ldots\ldots\ldots\ldots [36]$$

For steady state conditions, relative sediment transport capacity can also be described as a function of dimensionless distance:

$$T_* = x_* \quad \ldots\ldots\ldots\ldots [37]$$

Equation [36] was evaluated using experimental data of Marelli (1974), Walker et al. (1978) and Mutchler and Greer (1980). The characteristics of the data used in the evaluation are shown in Table 4. Equation [31] was used to determine the sediment transport factor, K_t, for each data source using a single sediment transport capacity rate. Normalized sediment transport capacity was then obtained from equation [34] and the calculated value of K_t. A plot of relative sediment transport capacity of flow, T_*, versus relative flow rate, q_*, is shown in Fig. 4 and results of linear regression analyses of this information are presented in Table 2.

The regression was found to be highly significant. Using the students-t test, we cannot reject the hypothesis that the regression coefficient equals one nor the hypothesis that the intercept equals zero at the 99% confidence level. Thus, we conclude that these data support the dimensionless relationship given by equation [36].

In development of the model equations it was assumed that all the sediment available for transport was provided by raindrop impact. Soil detachment by runoff was assumed to be negligible. The suitability of this assumption must be carefully examined when applying the model equations to specific conditions.

The sediment transport capacity relation used in this investigation does not take into consideration differences in the particle size distribution of sediment. A constant availability of readily transportable soil material was assumed in development of the transport capacity equation. The supply of these easily transportable soil soil particles was assumed to be unaffected by the accumulation of other less transportable material.

The sediment transport factor, K_t, is also a parameter which is not readily available. Rainfall simulaton testing is required for proper evaluation of this parameter. Research data defining the effects of surface roughness and sediment characteristics on the sediment transport factor are presently not available.

TABLE 4. SUMMARY OF DATA USED IN EVALUATING EQUATION FOR PREDICTING SEDIMENT TRANSPORT CAPACITY OF OVERLAND FLOW.

Data source	Soil material	Measurements in set	Slope, %	Rainfall intensity, mm/h
Marelli (1974)	Loam, Silt loam and Silty clay	6	1.0	64
Walker, Kinnell and Green (1978)	Sand	2	0.5	45 and 150
Mutchler and Greer (1980)	Silty clay loam	5	0.2	76

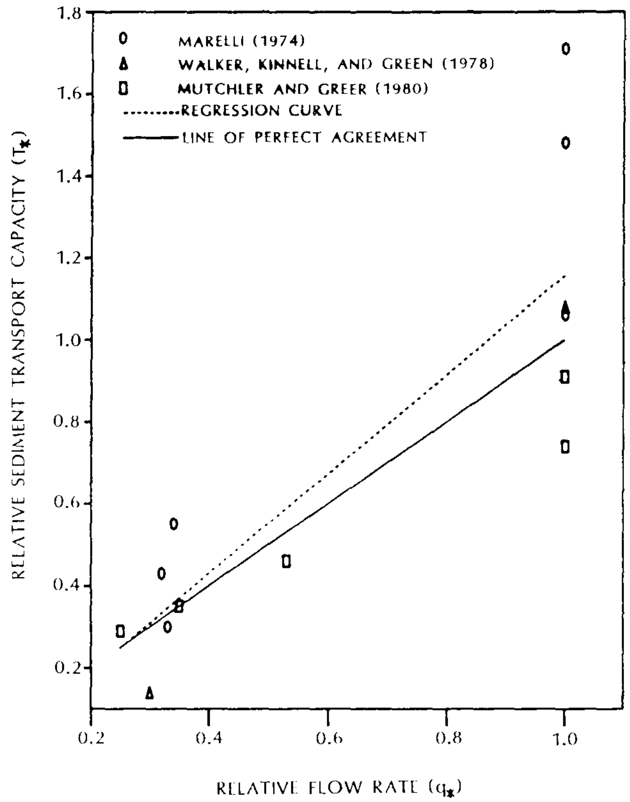

Fig. 4—Relative sediment transport capacity vs. relative flow rate.

SUMMARY AND CONCLUSIONS

The soil erosion process in the interrill overland flow range is governed by soil detachment from raindrop impact and the transport of soil materials by shallow overland flow. Both of these processes may be significantly influenced by depth of overland flow. Model equations are identified which include the effects of varying overland flow depth on soil detachment and transport.

Overland flow depth was determined by the Darcy-Weisbach equation. The Darcy-Weisbach friction coefficient was estimated from an empirical relation including rainfall intensity and flow Reynolds number. A dimensionless equation was used to predict depths of overland flow for varying rainfall intensities and surface roughnesses.

Soil detachment by raindrop impact was represented as the product of a soil detachment factor and the maximum impact pressure at the soil-water interface caused by raindrop impact. Impact pressure was estimated from an empirical equation involving drop impact velocity, drop diameter and water layer depth. Because raindrop size distribution, drop velocity and overland flow depth appear explicitly in the detachment equation, it may prove useful in evaluating results of erosion studies obtained using rainfall simulators with different raindrop characteristics.

The sediment transport capacity of runoff was estimated as the product of a sediment transport factor, bottom shear stress and flow velocity. Bottom shear stress was represented as the product of specific weight of water, water depth and channel slope. This relation appeared to provide proper estimates of sediment transport capacity.

The data base used to test the model equations was limited. Additional information is needed to evaluate these relations under more diverse experimental conditions. Results of a laboratory study conducted to obtain additional data are given by Gilley et al. (1985). As complex, individual erosion mechanisms become better defined, more reliable and comprehensive soil erosion models can be developed.

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LIST OF SYMBOLS

a_i Number of drops of a particular diameter, d_i

b Constant relating rainfall induced roughness to rainfall intensity, $k_r = b\, i^c$

c Constant relating rainfall induced roughness to rainfall intensity, $k_r = b\, i^c$

d Equivalent drop diameter, (length)

d_i Drop diameter of a particular size class, (length)

d_o Normalized equivalent drop diameter, (length)

d_{*i} Relative drop diameter of a particular size class, $d_{*i} = d_i/d_o$

D Raindrop detachment from a single drop, (mass/area/time)

D_{r*} Relative raindrop impact pressure

D_s Raindrop detachment from several drops, (mass/area/time)

D_{so} Normalized raindrop detachment from several drops, (mass/area/time)

D_{s*} Relative raindrop detachment from several drops, $D_{s*} = D_s/D_{so}$

f Darcy-Weisbach friction coefficient

f_r Darcy-Weisbach friction coefficient due to rainfall

f_w Darcy-Weisbach friction coefficient without rainfall

F F-distribution

g Gravitational acceleration, (length/time^2)

i Rainfall intensity, (length/time)

k_r Rainfall induced roughness in friction coefficient equation, $f_r = k_r/R_n$

k_w Surface roughness in friction coefficient equation, $f_w = k_w/R_n$

K_d Soil detachment factor, (time/length)

K_t Sediment transport factor, (time^2/length^2)

L_o Length of flow plane, (length)

P Impact pressure, (force/area)

q Flow rate per unit width, (volume/time/width)

q_b Base flow rate per unit width, (volume/time/width)

q_o Normalized flow rate per unit width, (volume/time/width)

q_* Relative flow rate per unit width, $q_* = q/q_o$

R_n Reynolds number, $R_n = V_f\, y/\nu$

S Channel bottom slope

S_f Friction slope

T Sediment transport capacity of flow, (mass/area/time)

T_o Normalized sediment transport capacity of flow, (mass/area/time)

T_* Relative sediment transport capacity of flow, $T_* = T/T_o$

V Drop impact velocity, (length/time)

V_i Impact velocity of drop with diameter, d_i, (length/time)

V_o Normalized drop impact velocity, (length/time)

V_f Flow velocity, (length/time)

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V_{fo} Normalized flow velocity, (length/time)
V_{*_i} Relative drop impact velocity of drop with diameter, d_i, $V_{*_i} = V_i/V_o$
x Distance in main flow direction, (length)
x_* Relative distance in main flow direction, $x_* = x/L_o$
y Flow depth, (length)
y_o Normalized flow depth, (length)
y_* Relative flow depth, $y_* = y/y_o$
β_o Intercept in regression equation
β_1 Regression coefficient in regression equation
γ Specific weight of water, (force/length)
θ Slope angle
ν Kinematic viscosity of water, (length^2/time)
ρ Density of water, (mass/volume)
ϕ Dimensionless impact pressure, $\phi = P/\rho\ V^2$
ω Stream power, $\omega = (\gamma\ y\ S)\ V_f$, (force/length/time)