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SIMPLE PROCEDURAL METHOD FOR ESTIMATING ON-SITE SOIL EROSION

Prepared for

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AUTHORIZATION

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In accordance with the study plan, the report on the simplified method for estimating on-site soil erosion is submitted.

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LIST OF SYMBOLS

Symbol	Description
A	area
A_b	area of bare soil
a	distance in Einstein's equation
a_1	coefficient in raindrop splash equation
C	runoff coefficient
C_a	sediment concentration height above the land surface in the flow
C_c	canopy cover
C_g	ground cover
C_1	parameter describing antecedent and steady infiltration
D_e	effective rainfall duration
D_f	flow detachment coefficient
D_t	total rainfall duration
d_{si}	diameter of i^{th} particle size
d_{so}	median particle size
E	dimensionless distance ratio in Einstein's equation
e_i	expected value
F	actual accumulated infiltration volume
F_p	infiltration prior to ponding
F_1	first approximation of F
F_2	second approximation of F
f	Darcy-Weisbach grain resistance friction factor
f_i	frequency of i^{th} particle size
g	acceleration of gravity
i	rainfall intensity

Symbol	Description
i_e	excess rainfall rate
i_s	percentage of each i^{th} particle size
J_1, J_2	dimensionless integrals in Einstein's equation
K_g	overall flow resistance factor
K_h	overall maximum flow resistance factor
K_ℓ	overall minimum flow resistance factor
K_o	grain resistance flow factor
L	length of plane
O_i	observed value
Q	water discharge rate
q	unit width water discharge rate
q_{bi}	bed load transport capacity of i^{th} particle size
q_{si}	suspended load transport of i^{th} particle size
q_t	total sediment transport capacity
q_{ti}	sediment transport capacity for i^{th} particle size
S	slope of the ground surface
S_s	specific gravity of sediment
t_p	time to water ponding
U_*	shear velocity
V	mean flow velocity
V_c	volume of canopy cover interception
V_g	volume of ground cover interception
V_i	intercepted rainfall volume
V_s	sediment settling velocity
V_{ti}	potential transport volume for i^{th} particle size

LIST OF SYMBOLS - continued

Symbol	Description
$\mathcal{V}_a$	volume of available detached sediment
$\mathcal{V}_{ai}$	supply volume for i^{th} particle size
$\mathcal{V}_r$	raindrop splash detachment volume
$\mathcal{V}_t$	potential transport volume
$\mathcal{V}_{yi}$	volume yield for i^{th} particle size
Y_s	total sediment yield by weight
Y_w	water yield
y	flow depth
W	width of plane
w	dimensionless velocity ratio in Einstein's equation
α	soil parameter
β	hydraulic conductivity in wetted zone
γ	unit weight of water
δ	parameter in critical shear force equation
ε	distance above land surface in flow
κ	von Karman's number
ν	kinematic viscosity of water
ρ	density of water
σ	dimensionless distance ratio in Einstein integrals
τ	effective shear stress from grain resistance
τ_c	critical shear force
τ'	boundary shear stress from total resistance
ϕ	porosity of soil

I. INTRODUCTION

GENERAL

As population increases, the development of water and land resources continues to grow. The population growth causes increased demands for recreation sites, housing, water, timber, energy and mineral resources. The need for housing and other resources has promoted numerous construction and resource acquisition activities that negatively infringe on the natural landscape. This infringement often takes the form of some types of landscape modification including changing of slope gradients, removal of native vegetation, increased construction of roadways, alteration of drainage patterns, and disturbing the top soil. All of these landscape infringements can act singularly or jointly to change the water and sediment yield from a given site. Because most of the forest lands are located in the headwater regions of streams, the excessive erosion and sedimentation may have a detrimental impact on the watershed, on the quality of water produced and on water resource utilization and development downstream. A method to estimate on-site soil erosion is needed.

Numerous approaches can be used to determine water and sediment yield from natural or disturbed land surfaces. Some approaches are based on regression equations such as the Universal Soil Loss Equation. Such approaches have the serious drawback of assuming that the physical environment is both time and space invariant. An alternative to regression type models is physical process models. In spite of the complexity of the physical process governing soil erosion, numerical modeling of the process systems is the most viable way to estimate the time dependent and space dependent water and sediment yield.

The complexity of a numerical model often curtails practical application in some cases. A simplified physical process approach which approximates the complicated numerical solution is appealing, and necessary to meet the needs of field practitioners.

CLASSIFICATION OF MATHEMATICAL MODELS

In general, two types of mathematical models are presently used for determining water on sediment yield from watersheds or land surfaces. One type, the lumped parameter or "black box" or "simulation programming" type, interprets input-output relations using oversimplified forms which may or may not have physical significance. All processes related to movement of the water and sediment through the watershed are "lumped" together into one or two coefficients. The classic example of a lumped parameter model is the rational formula for estimating peak discharge, i.e., $Q = CiA$ where Q is the peak discharge, i is the rainfall input, A is the drainage area, and C is the runoff coefficient which represents all drainage hydrologic processes.

Such a model is easy to use, but has limited physical meaning and can often be very inaccurate. Physical process models, however, avoid this "lumping" by decomposing the overall hydrologic and hydraulic phenomena into their respective components such as infiltration and sediment detachment from raindrop splash. By decomposing the selected phenomena into its separate components, each individual process can be analyzed and refined or altered to meet the needs of the user. Consequently, as each process component is upgraded, the model becomes more representative of the physical system.

Use of component process models also allows input of variables that hold physical significance to the user and the field situation. All of the above characteristics of component process models allow for greater flexibility than other model types.

Advantages of physical process component models over other model types are numerous. In general, physical process models are superior to regression type models or "black box" type mathematical models. This is because they require less data to develop, the input variables to process models are physically significant, they indicate system response caused by changing one or more physically significant values, and they are not stationary in either time or space and therefore they can be used for predicting the future response of the system to developments in real time.

Simplified process models go a step back from the more complicated process models that deal with time and space. In general, the more complicated time-space models solve finite difference formulation of the various processes at each time-space point. The simplified model retreats from this approach and averages the processes over both time and space. For most cases, however, the complex procedure provides the best or most exact solution. The main disadvantage of the complex models is that they require computer applications and knowledge of the mathematical formulations and assumptions which are often beyond the capability of the average field user.

The limitations of regression type or "black box" models and the user restrictions imposed by more complex physical process models have induced the development of simplified physical process component models. Such simplified models can provide the field user with an easy to use, accurate methodology for determining water and sediment yield from natural or disturbed land surfaces.

SCOPE OF THE PRESENT STUDY

This report presents a simple procedural method for evaluating the on-site erosion rates based on classifications of storm sizes, soil characteristics, vegetative cover densities, ground cover densities, surface disturbance, geometry and physiography of overland flow surfaces. This simple method is developed for easy and quick estimation of water and sediment yield. Some of the physical processes considered are interception, infiltration, surface runoff, sediment transport, and soil detachment by raindrop splash and by surface runoff. The sediment yield estimation is made according to different sediment sizes. The attention of determining sediment yield by sizes is increasing because different sizes of sediment have different uptake rates for water pollutants such as nitrogen or phosphorus.

The developed procedure has been tested utilizing a numerical model and field data. The test results of both water and sediment yield are good. Examples of application indicate that the procedure is both accurate and easy to use within the described test conditions.

II. MODEL DEVELOPMENT

BASIC CONCEPTS AND EQUATIONS

Erosion, water runoff and sediment yield are common hydraulic and hydrologic phenomena that are governed by complex physical processes. Mathematical models can be constructed that accurately simulate these complex processes in time and space. However, such models are often as complex and difficult to understand and use as the process system they intend to simulate. Model simplification can reduce this complexity, and if such simplification leaves the basic physical processes intact, the model may not necessarily lose its accuracy. Simplification while leaving the process components intact is the basis for the simplified on-site water and sediment yield model. The following sections will describe the physical processes that are accounted for in the simplified model and how they are linked together to provide a realistic representation of natural phenomena. These processes include interception losses, infiltration, water runoff, sediment runoff, erosion by raindrop splash and erosion by overland flow.

ASSUMPTIONS

In order to develop this simplified procedure the following assumptions are made: (1) the design storms can be represented by a constant intensity and duration, (2) the flow reaches maximum discharge instantaneously, (3) the sediment yield can be approximated by examining the overall sediment availability during the storm and the total sediment transport capacity for the whole runoff period, and (4) the armoring effect of water layer and loose soil is negligible. In general, these assumptions will yield a conservative overestimation of sediment and water yields.

INTERCEPTION LOSSES

A certain volume of rainfall is intercepted and stored by canopy and ground cover. In the simplified on-site erosion model it is assumed that the volume of rainfall that can be intercepted by vegetation will be estimated for both canopy and ground cover. The total intercepted volume is then:

$$V_i = C_c V_c + C_g V_g \tag{1}$$

where V_i is the total intercepted volume in depth, C_c is the canopy cover density, V_c is the potential volume of canopy cover interception, C_g is the ground cover density, and V_g is the potential volume of ground cover interception.

The length of rainfall time needed to satisfy interception losses is found by dividing V_i by the rainfall intensity i. This interception loss time is then subtracted from the total storm duration to give the length of time of effective rainfall, or

$$D_e = D_t - V_i/i \tag{2}$$

where D_e is the effective rainfall duration and D_t is the total storm duration. Although interception losses are continuous over the storm period it is assumed that the losses occur at storm initiation (Figure 1).

INFILTRATION LOSSES

The next rainfall losses to be considered are losses from soil infiltration processes. These processes determine the volume of water that is available for runoff from the land surface. The time to ponding, or determination of when runoff begins, and the volume of infiltrated water are the most important infiltration characteristics.

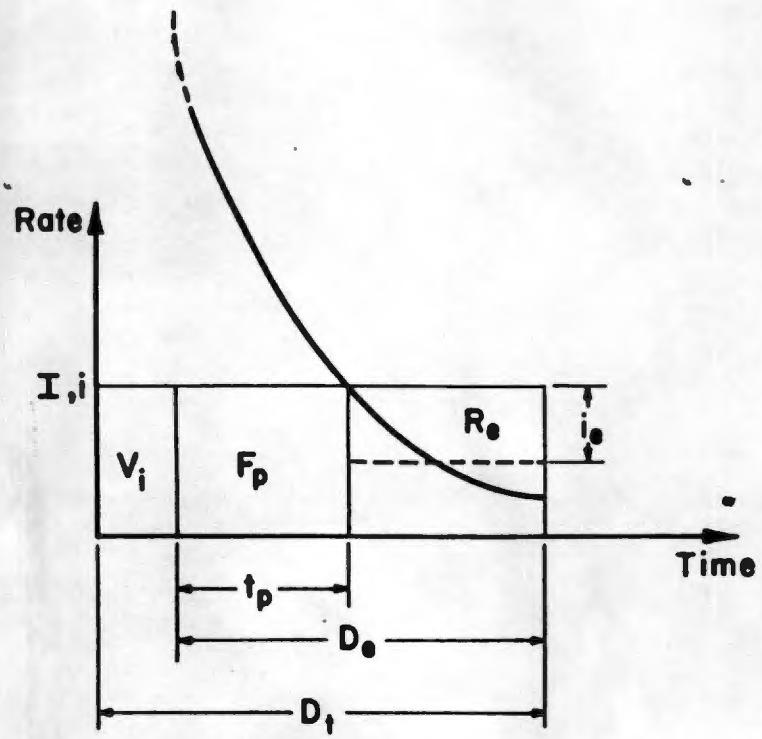

Figure 1. Definition Sketch for Hydrologic Processes

Under a constant rainfall with steady soil parameters the time of ponding can be found by Mein and Larson (1971)

$$t_p = \frac{\alpha}{i(\frac{i}{\beta} - 1)} \tag{3}$$

where t_p is the time to ponding since beginning of effective rainfall, α is the soil parameter which is $\phi(S_w - S_i)\psi_{ave}$, ϕ is the soil porosity, S_w is the degree of saturation in the wetted zone, S_i is the degree of saturation at the antecedent moisture condition, ψ_{ave} is the average capillary suction pressure and β is the hydraulic conductivity in the wetted zone which is approximately one-half of the saturated hydraulic conductivity. Note that if $i \leq \beta$ runoff will not occur.

The volume of infiltration can be expressed as (Mein and Larson, 1971)

$$F - \alpha \ln\left(1 + \frac{F}{\alpha}\right) = C_1 \tag{4}$$

with

$$C_1 = \beta(D_e - t_p) + F_p - \alpha \ln\left(1 + \frac{F_p}{\alpha}\right) \tag{5}$$

and

$$F_p = it_p \tag{6}$$

where F is the accumulated infiltration and F_p is the accumulated infiltration prior to ponding.

Equation 4 is a nonlinear implicit equation, the following approximate solution can be made (Li et al., 1976)

$$F_1 = \frac{1}{2}\left[C_1 + \sqrt{C_1(C_1 + 8\alpha)}\right] \tag{7}$$

where F_1 is the first approximation of F. Because the error on this approximation could range up to 8%, unacceptable results may be obtained when the amount of rainfall excess is small. Another formulation can be utilized to yield a better approximation, i.e., (Li et al., 1976).

$$F_2 = \alpha \left[(1 + \frac{F_1}{\alpha}) \sqrt{(\frac{F_1}{\alpha})^2 + 2\left[\frac{C_1}{\alpha} - \frac{F_1}{\alpha} + \ln (1 + \frac{F_1}{\alpha})\right]} - (\frac{F_1}{\alpha})^2 \right] \quad (8)$$

which has an error consistently less than 0.003%.

RUNOFF DETERMINATION

Once the infiltration volume is determined, the average rainfall excess rate and the total runoff volume can be determined.

Rainfall Excess Rate. The rainfall excess rate can be determined by the following equation:

$$i_e = i - \frac{F_2 - F_p}{D_e - t_p} \quad (9)$$

where i_e is the rainfall excess rate.

Runoff Rate. The runoff rate, q, at the end of overland flow plot is

$$q = \int_0^L i_e d_x = i_e L \quad (10)$$

where L is the length of plot.

Water Yield. The total runoff volume or water yield is

$$Y_w = W \int_0^{D_e - t_p} dt = Wq(D_e - t_p) \quad (11)$$

where Y_w is the water yield in volume, and W is the width of overland plot.

SEDIMENT TRANSPORT CAPACITY

After the runoff rate q is known, the sediment transport capacity rate can be calculated. This is accomplished after determination of several intermediate steps. First the overall flow resistance is assumed as

$$K_g = K_\ell + (K_h - K_\ell)\, C_g^{\,2} \qquad (12)$$

where K_g is the parameter describing the overall flow resistance associated with cover effects, K_ℓ is the parameter describing the minimum resistance for the area (C_g=0), K_h is the parameter describing the maximum resistance for the area (C_g=1.0), and C_g is the ground cover. An increase in C_g produces a rapid increase in K_g as seen in Figure 2.

Both q and K_g are then used to find the average flow depth as

$$y = \left(\frac{qK_g \nu}{8gS}\right) \qquad (13)$$

where y is the flow depth, ν is the kinematic viscosity of water, g is the acceleration of gravity and S is the slope of the ground surface.

The mean flow velocity is then

$$V = \frac{q}{y} \qquad (14)$$

The flow parameters calculated above are then used to determine sediment transport capacity. The procedure for determining the sediment transport capacity given by Simons et al. (1975) is used in this report.

The first sediment transport parameter that should be determined is the tractive force or boundary shear stress. The effective boundary shear stress acting on the grain can be determined by

$$\tau = \frac{1}{8} f\rho\, V^2 = \frac{1}{8} \frac{K_o}{q} \nu\rho V^2 \qquad (15)$$

where τ is the effective boundary shear stress, f is the Darcy-Weisbach friction factor for grain resistance only, ρ is the density of water and K_o is the parameter describing grain resistance only.

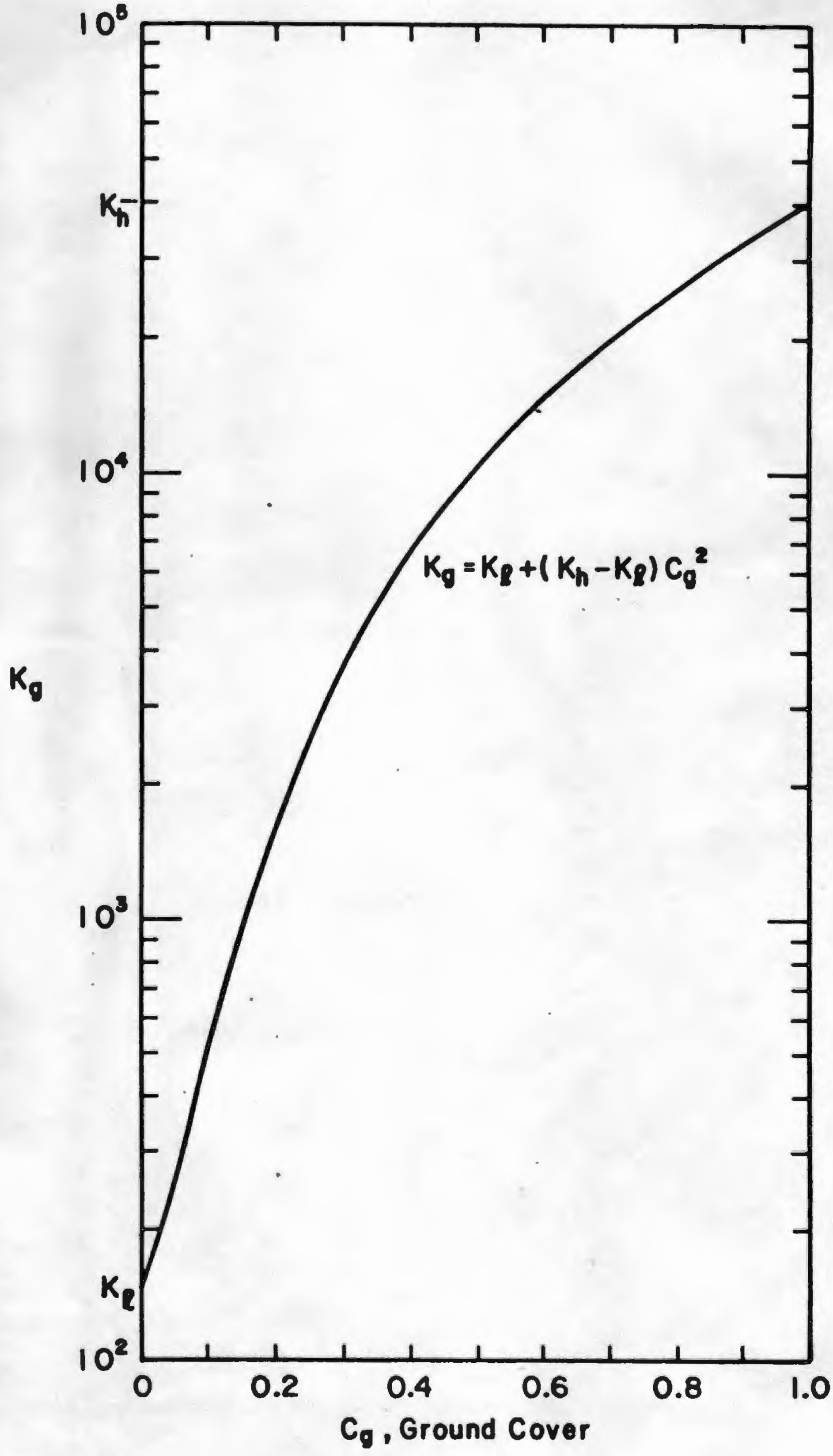

Figure 2. Assumed Variation of Overall Resistance with Ground Cover

The boundary shear stress, τ', considering total resistance (form and grain resistance) is

$$\tau' = \gamma y S \tag{16}$$

where γ is the unit weight of water. Note that τ' is usually much larger than τ. The shear velocity, U_*, is then

$$U_* = \frac{\tau'}{\rho} \tag{17}$$

The sediment transport capacity rate is the integral of all the individual sediment size transport rates or

$$q_t = \int_0^\infty (q_{ti} f_i) \, di \tag{18}$$

where q_t is the total transport capacity rate, q_{ti} is the potential transport rate for each size, and f_i is the frequency of each size i. Equation 18 can be given in the discrete form as

$$q_t = \sum_{i=1}^{N} (q_{ti} i_s) \tag{19}$$

where i_s is the percentage of each sediment size of bed material and N is the total number of sizes considered. Each individual size transport, q_{ti}, is composed of bed load transport q_{bi} and suspended load transport, q_{si} or

$$q_{ti} = q_{bi} + q_{si} \tag{20}$$

The bed load transport rate can be calculated using the Meyer-Peter, Muller formulation (USBR, 1960) as

$$q_{bi} = \frac{12.85}{\sqrt{\rho}} (\tau - \tau_c)^{1.5} \tag{21}$$

where τ_c is the critical shear force for the given particle size. The critical shear force for particle movement is determined from the Shields criteria of

$$\tau_c = \delta\gamma(S_s - 1)\, d_{si} \tag{22}$$

where δ is a parameter depending on flow conditions, S_s is the specific gravity of the sediment, and d_{si} is the sediment size in question. The value of S_s usually ranges from 2.60 to 2.70, but δ is dependent on flow conditions and should be adjusted to the actual field situation. If τ_c is greater than τ there is no sediment movement. The suspended load is determined using the Einstein method (1950), or

$$q_{si} = C_a U_* a \frac{E^{w-1}}{(1-E)^w} \left[\left(\frac{V}{U_*} + 2.5\right) J_1 + 2.5 J_2\right] \tag{23}$$

where C_a is the sediment concentration at distance a above the land surface, and E, A, a, J_1 and J_2 are given below.

The concentration term is related to the bed load transport as

$$q_{bi} = 11.6\, C_a U_* a \tag{24}$$

The distance a is assumed to be

$$a = 2\, d_{si} \tag{25}$$

The dimensionless parameter, E, relates flow depth to sediment size as

$$E = \frac{a}{y} \tag{26}$$

The dimensionless parameter, w, relates the in water settling velocity of the sediment to the shear velocity or

$$w = \frac{V_s}{\kappa U_*} \tag{27}$$

where V_s is the settling velocity of the sediment and κ is von Karman's number taken as 0.40.

Settling welocities are a function of particle size and water properties and can be formulated (ASCE, 1975) as

$$V_s = \frac{2.9517\, d_{si}^{\,2}}{\nu} \quad \text{when} \quad d_{si} < 0.0002 \text{ feet} \tag{28}$$

or

$$V_s = \frac{(36.064\, d_{si}^{\,3} + 36\nu^2)^{\frac{1}{2}} - 6\nu}{d_{si}} \quad \text{when } d_{si} \geq 0.0002 \text{ ft}$$

The terms J_1 and J_2 are integrals resulting from integration of the equation describing the vertical concentration of sediment in the flow. The first integral, J_1, is given as

$$J_1 = \int_E^1 \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma \tag{29}$$

where σ is a dimensionless relative position value,

$$\sigma = \frac{\varepsilon}{y} \tag{30}$$

and ε is the distance above the land surface in the flow. The other integral is similar and is given as

$$J_2 = \int_E^1 \ell n\sigma \left(\frac{1-\sigma}{\sigma}\right)^w d\sigma \tag{31}$$

These two integrals can be evaluated by successive integrations of a power series expansion given by Li (1974). Rearranging equation (24), and substitution into equation (23) gives a simpler form or

$$q_{si} = \frac{q_{bi}}{11.6} \frac{E^{w-1}}{(1-E)^w} \left[\left(\frac{V}{U_*} + 2.5\right) J_1 + 2.5\, J_2\right] \tag{32}$$

The total potential transport rate, equation (19) becomes

$$q_t = \sum_{i=1}^{N} (q_{si} + q_{bi})\, i_s \tag{33}$$

The potential transport capacity can be found as

$$V_t = \frac{W}{\gamma S_s} \int_0^{D_e - t_p} q_t \, d_t$$

or

$$V_t = \frac{q_t (D_e - t_p) W}{\gamma S_s} \tag{34}$$

where V_t is the nonporous volume of potential transport.

DETERMINATION OF SEDIMENT SUPPLY

The potential sediment transport represents the capacity of the system. The supply of sediment comes from two mechanisms, detachment by raindrop splash and detachment by overland flow. The raindrop splash detachment can be formulated as a simple power function of rainfall intensity (Meyer, 1971) or as

$$V_r = a_1{}^2 \, LW \, (1-\phi) \, A_b \tag{35}$$

where V_r is the nonporous volume of detached material by raindrop splash, a_1 is an empirically determined constant describing erodibility of the soil, and A_b is an area reduction factor.

The variable A_b represents the fraction of unprotected or bare soil in the area and is given as

$$A_b = 1 - C_g + C_c + (C_g C_c) \tag{36}$$

where $(C_g C_c)$ accounts for areas of cover overlap. Sediment supply by overland flow detachment is determined by

$$V_f = D_f(V_t - V_r) \tag{37}$$

where V_f is detachment by overland flow, and D_f is the flow detachment coefficient.

If $V_t < V_r$ then there is no overland flow detachment because the transport rate is limited by the transporting capacity. The total available sediment supply is then

$$V_a = V_r + V_f \tag{38}$$

DETERMINATION OF CONTROLLING PROCESS

Sediment yield is controlled by either supply or capacity. If supply is greater than capacity, capacity controls and vice versa. As particle size changes so does the capacity and supply. Therefore supply and capacity must be compared for each particle size. The individual capacity or potential yield is given as

$$V_{ti} = \frac{q_{ti}\ i_s(D_t - t_p)W}{\gamma S_s} \tag{39}$$

where V_{ti} is the individual demand for the particle size.

The available supply is

$$V_{ai} = i_s\ V_a \tag{40}$$

where V_{ai} is the available supply for the ith particle size. Values of V_{ti} and V_{ai} can be compared. If V_{ti} is greater than V_{ai} then supply controls, if V_{ai} is greater than V_{ti} then demand controls or

$$V_{yi} = V_{ai} \quad \text{if} \quad V_{ti} > V_{ai} \tag{41}$$

and

$$V_{yi} = V_{ti} \quad \text{if} \quad V_{ti} < V_{ai} \tag{42}$$

where V_{yi} is the volume yield for the particle size fraction. The total yield will then be

$$Y_s = \gamma S_s \sum_{i=1}^{N} V_{yi} \tag{43}$$

where Y_s is the sediment yield by weight.

MODEL LINKAGE

By linking the different physical processes described above, a simplified yet accurate method for determining water and sediment yield from a selected site can be developed. The conceptual linkage used in the computer model is shown in Figure 3. Note how each process is divided from the others into a separate component. By separating each process, the user can substitute or alter each component to meet the needs of the area being studied.

RELATIONSHIP OF SIMPLIFIED AND COMPLEX MODELS

The simplified model is composed of the same components as found in the complex model (see Li et al., 1977). The basic workings of the complex model have previously been presented by Li (1974) and Simons et al. (1975). The difference between the two models is that the complex model involves routing of water and sediment in real time and space whereas the simplified model is essentially the integrated result of the time-space products. The complex model can also deal with variable intensity rainfall events, a procedure which is not presently available in the simplified model. The simplified model, however, is still quite accurate yet easier to use and understand.

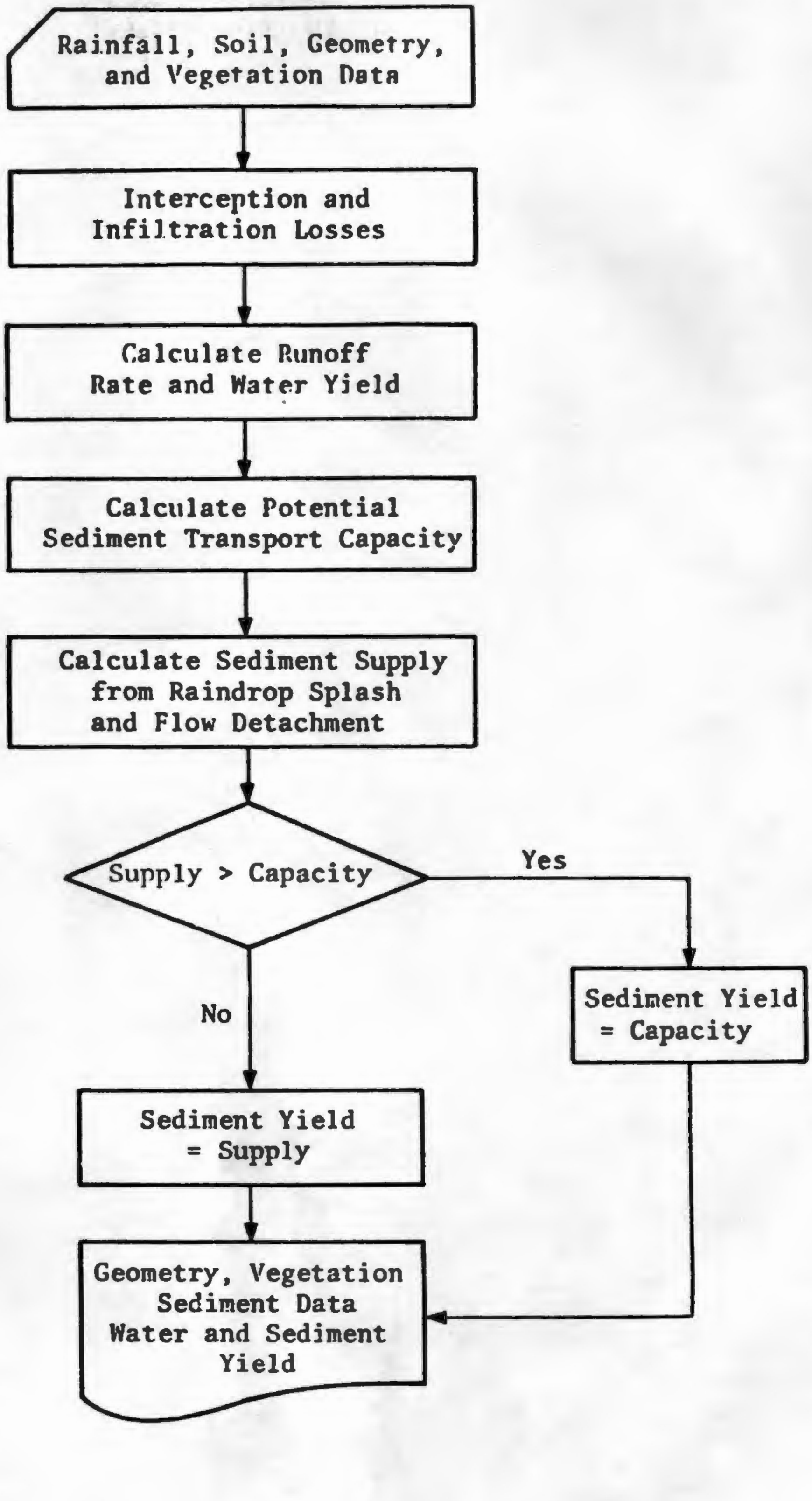

Figure 3. Flow Chart of Conceptual Linkage of Model Components

III. APPLICATION OF SIMPLIFIED MODEL

FIELD TEST OF SIMPLIFIED MODEL

In order to test the applicability of the simplified model, data from field experiments collected by Van Liew (1976) were utilized. Van Liew (1976) during the summers of 1975 and 1976 collected field data from experimental runoff plots on the Edna Mine in the Yampa Coal field of Routt County, Colorado. The 1975 data were for overland flow simulation only and are not considered here. The 1976 data consists of rainfall simulation and resultant overland flow. The experimental plots used by Van Liew were rectangular in shape and had various, selected slopes. Rainfall intensities studied were 1.44 (36.5) and 2.26 (57.4) inches per hour (mm/hr). Model results suggest that the supposed 1.44 in./hr rate was closer to 2.26 in./hr, therefore a rate of 2.26 in./hr was assumed for one case studied. Each plot consisted of bare soil composed of sandstone, siltstone and shale particles. Median grain size of the in place composite samples was 0.0175 mm (0.00069 inches). Water yields for each experiment were given by Van Liew and sediment yields were computed by integrating Van Liew's sediment hydrographs. The results of the integration were comparable to those calculated using Van Liew's average transport rates and similar to those shown by Van Liew (1976). The integrated values were used because the time span for the average transport rate determination was not precisely known and the values from figures given by Van Liew (1976) had to be scaled by hand and were not deemed as accurate. Although Van Liew (1976) conducted six rainfall simulation experiments, only two were utilized for sediment calibration of the model. One of the other four cases was a multiple rainfall intensity event with the suspect 1.44 in./hr intensity as the primary input. The other cases were the first experiment in the series, a 7 percent slope, and two 1 percent slopes. These three cases were not used in sediment calibration runs, but were used as test cases using calibrated parameters. The original input data for the calibration runs and three test runs are listed in Table 1.

TABLE 1. Experimental Data

No.	i in./hr	Duration Minutes	Slope	Length, ft	Width, ft
1	2.26	50	0.07	31.29	12.69
2	2.26	46	0.07	31.29	12.69
3	2.26	51	0.01	32.31	12.31
4	2.26	63.9	0.01	31.31	12.31
5	2.26	56.4	0.07	31.29	12.69

Note: Rainfall intensity adjusted from 1.44 to 2.26 in./hr for run No. 4.

Experimental runs number 1 and 2 were used as calibration runs and 3 through 5 were used as the test runs. Both ground and canopy cover for the sites were zero. The parameters describing overall resistance and grain resistance for the sites, K_g and K_o, were assumed equal to 50, a commonly reported value for smooth bare soil (Woolhiser, 1975). The coefficient a_1 for the raindrop splash detachment (Eq. 35) was assumed to be 0.0001 which is approximately what Van Liew (1976) reports in his results. The power on this same equation is set at 2.0. A composite grain size distribution for the on-site spoil material was extracted from information provided by Van Liew (personal communication). This grain size distribution was plotted then subdivided into 14 size classes as presented in Table 2. Note that size fraction percents were taken at finer intervals for the larger sizes. This was done to enable better model simulation where a small change in size changes the overall sediment transport considerably.

TABLE 2. Sediment Size Distribution for Simulation

Geometric Mean (mm)	Percent of Sample
.00063	6.5
.00316	30.5
.0250	31.0
.0884	6.0
.1768	4.0
.3536	4.0
.6124	1.8
.8660	1.2
1.1180	1.0
1.3693	0.5
1.6202	0.5
2.0917	0.5
3.1623	3.5
8.000	9.0

CALIBRATION

The simplified model is first calibrated for water yield by finding the optimum α or β in Eqs. 4, 5, and 6. Increasing either α or β decreases runoff and vice-versa. The method of optimization used involves setting β and then minimizing the objective function, in this case a least squares function, by adjusting α using a one-dimensional optimization technique as presented by Simons and Li (1976). This approach is symbolized below as

$$\underset{\beta}{\mathrm{Min}} \left\{ \underset{\alpha}{\mathrm{Min}} \left(\sum_{i=1}^{N} (O_i - e_i)^2 \right) \right\}$$

where Min is to minimize the function with respect to the subscript, the parameter O_i is the observed value, e_i is the expected or simulated value, and N is the number of data sets used. Runs 1 to 4 were used for calibration of the water yield. This was done to provide a better calibration of the highly variable α and β parameters. Some constraints were placed on the α and β parameters, the primary constraint being a lower limit of 0.10 inches for α. The simplified model was reprogrammed and run to provide a matrix of objective function values for various α and β pairs. The results of these simulations are presented in Table 3. Note that the lower constraint of $\alpha = 0.10$ in. was reached.

Once the model was calibrated for water yield it was then adjusted for sediment transport. Two types of grain size inputs were considered. First, and most important, was transport of the individual size fractions as presented in Table 2. Transport of individual size fractions is important particularly for water quality studies. For example, fish habitat in streams is dependent on the size of sediment carried into the stream by contributing slopes. The transport of individual particle sizes can also help pinpoint those sizes that may have attached nitrogen, phosphorous, pesticides or other hazardous material or viruses. As shown in Figure 4, the simulation of run No. 1 is quite good because the composite on-site material is similar to the single on-site material sample collected before the run. Note that the simulated run deviates from observed run No. 2 because of variability of the on-site material. The shape of the simulated run

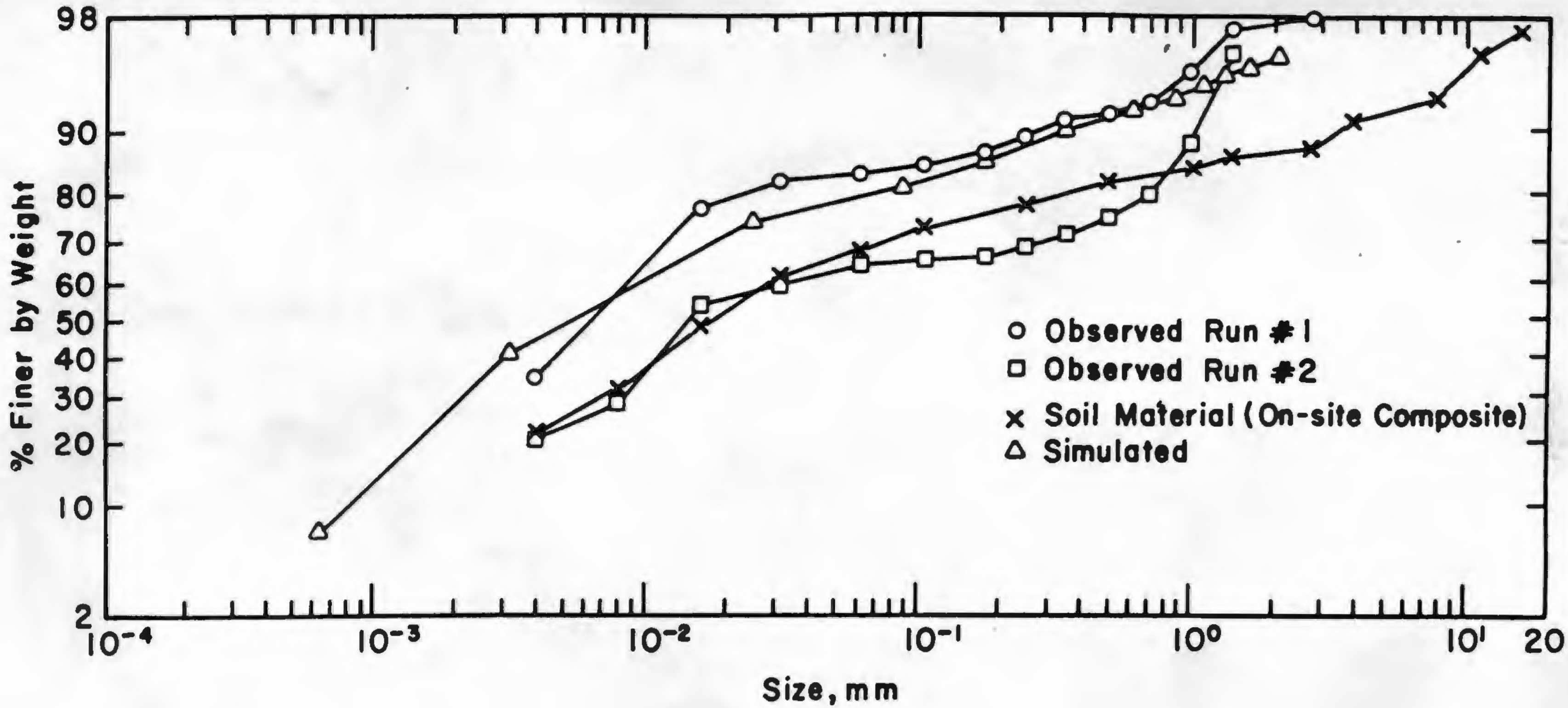

Figure 4. Simulated and Measured Size Distribution of Transported Material

still approximates that of run No. 2. Although not apparent on this scale there is a slight difference in percent transport as each size fraction for simulated runs No. 1 and 2, this is caused by differences in water flow rates. Adjusting the model to transport different sediment sizes also provides a better model representation of the actual transport taking place on the area being studied. The model adjustment for various sizes is done by varying the δ parameter in Eq. (22). Lowering δ in effect allows movement of the larger particle sizes. The δ parameter is adjusted until the simulated size distribution for the transported material approximates the observed size distribution. The results of this adjustment in comparison to observed runs No. 1 and 2 indicate small differences.

Once adjusted for size distribution the model is calibrated for D_f. The parameter D_f is varied until the optimum, simulated yields are generated. Increasing D_f increases yield and vice versa. For the calibration of D_f only, runs No. 1 and 2 were analyzed. The result is given in Table 3. Runs No. 1 and 2 were used because their high sediment yields were assumed to have less "noise" or errors than the lower yields for the 1 percent slopes. Runs No. 3, 4 and 5 were again withheld as test runs.

The model was recalibrated for D_f using a single representative grain size, in this case d_{50}. The choice of the representative grain size is debatable and d_{50} is used here for comparison purposes only. When a single representative grain size is used for simulation much information is lost as explained above. The use of a single grain size also eliminates the adjustment of δ, a parameter used to produce realistic model simulation of actual size transport. Although the model can accurately simulate sediment yields when using a representative grain size it is recommended that the single representative size method should only be used for rapid estimation of sediment yields for comparison purposes.

TABLE 3. Optimum Parameters for Simulation of Van Liew Data

α = 0.10 inches		β = 0.908 inches/hour
Fourteen Size Fractions		One Representative Size
δ	0.01	0.01
D_f	0.00115	0.00367

RESULTS

Once calibrated the model was then used to simulate water yield and sediment yield for all five runs. Results are shown in Table 4 below.

TABLE 4. Simulated and Measured Water and Sediment Yields

No.	Water Yield, cubic feet Measured	Water Yield, cubic feet Simulated	Sediment Yield, lbs Measured	Sediment Yield, lbs by Sizes	d_{50}
1	29.32	29.77	14.90	15.43	15.34
2	31.39	26.99	14.45	13.94	13.90
3	31.00	30.51	6.38	4.63	4.41
4	36.35	39.56	4.99	6.00	5.70
5	36.57	34.23	10.45	17.77	17.66

Note: Nos. 3, 4 and 5 are test runs.

The results shown in Table 4 are also plotted in Figures 5 and 6. The overestimation of sediment yield for run No. 5 can be explained in Van Liew's (1976) statement that, "...surface manipulation to provide experimental conditions for erodible...surfaces (runs No. 1 and 2)

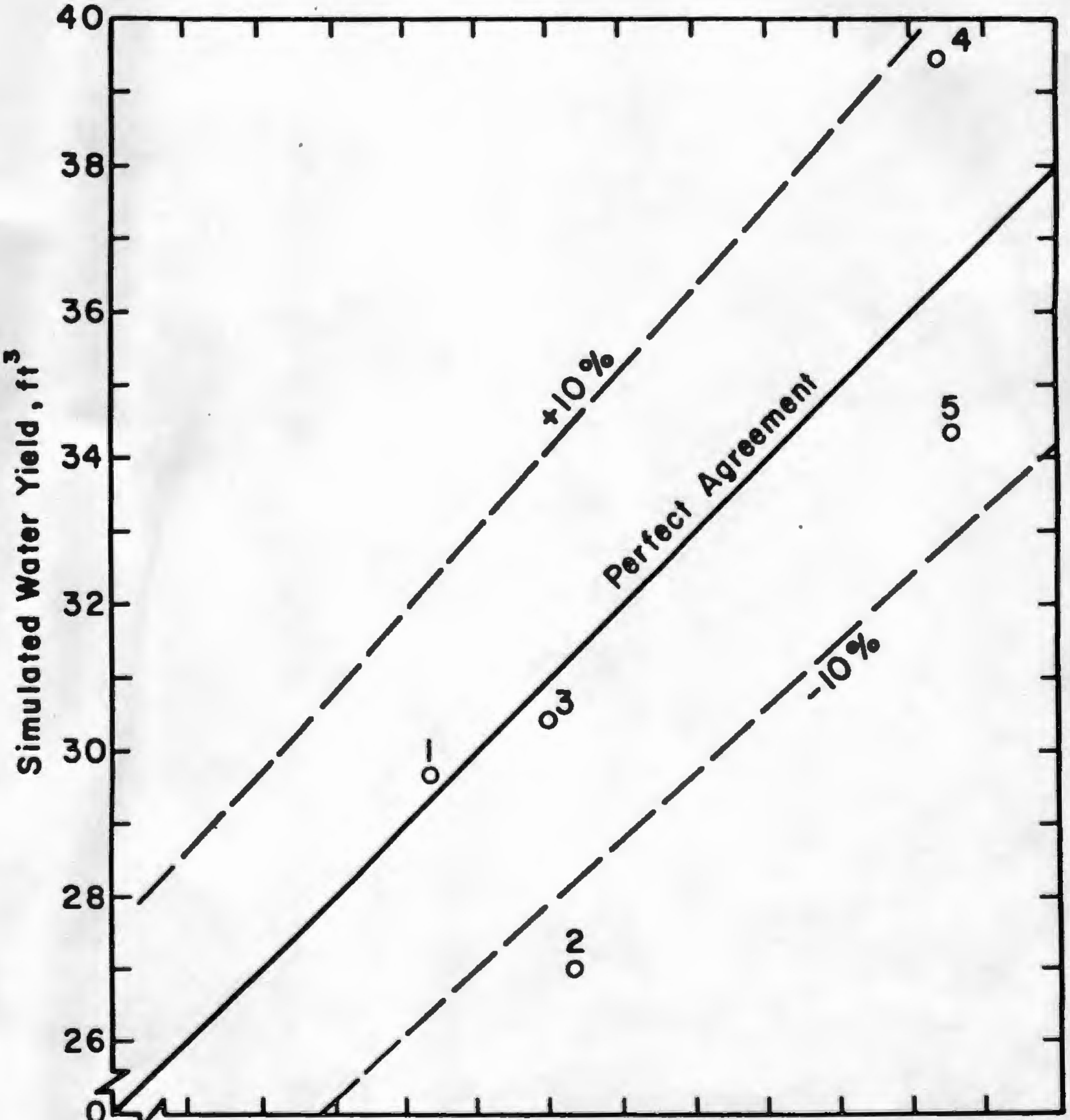

Figure 5. Comparison of Measured and Simulated Water Yield

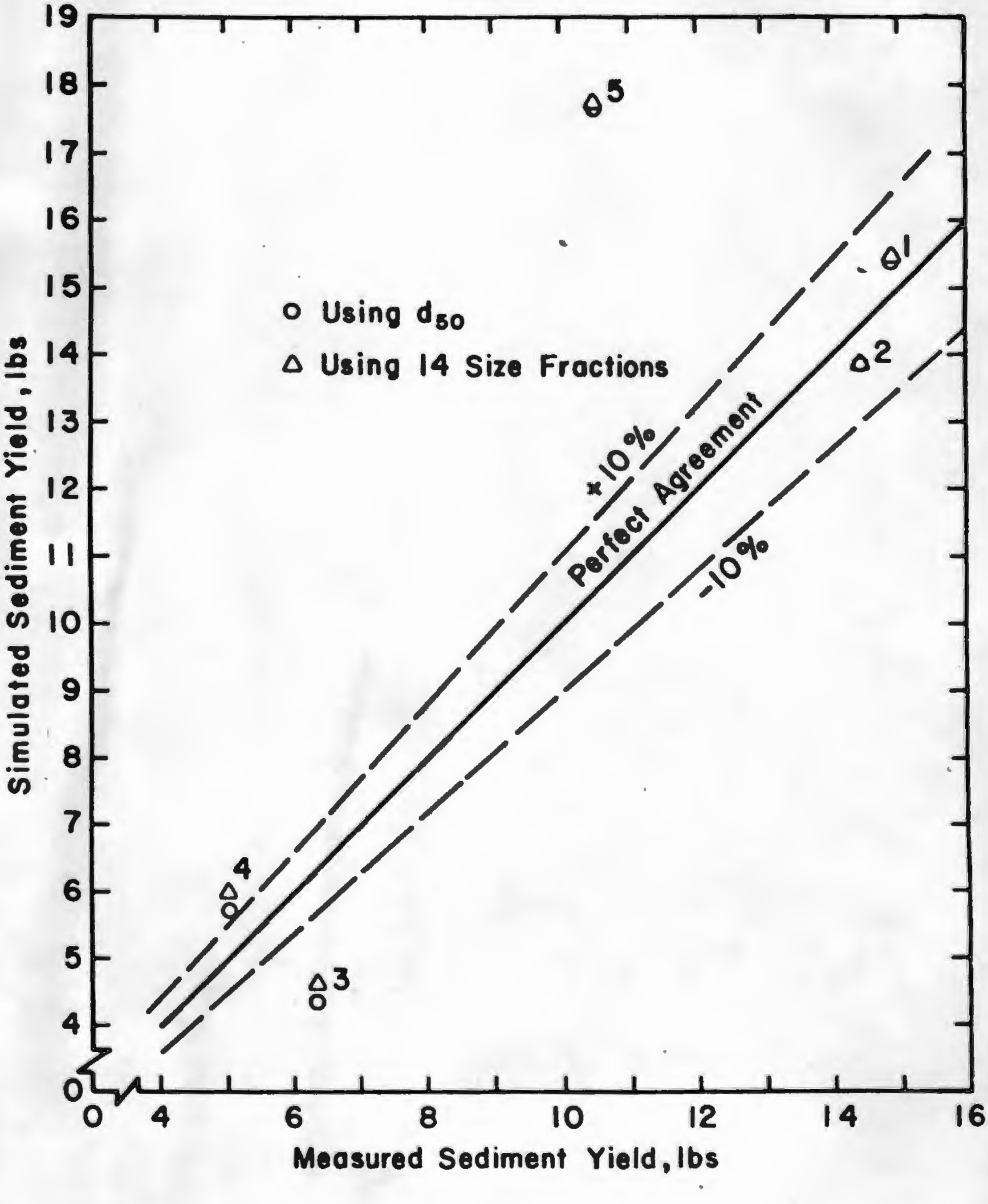

Figure 6. Comparison of Measured and Simulated Sediment Yield

substantially increased the availability of loose bed material...." The effects of these surface manipulations are apparent when the simplified model is used to estimate sediment yield for the same average slope on unmanipulated surface such as run No. 5. Because the values from the manipulated slopes were used to calibrate the simplified model, application to an unmanipulated slope should and does simulate sediment yields that are higher than measured values. Differences between actual and predicted yield for the 1 percent slopes, runs No. 3 and 4, can be attributed to the relative magnitude of measurement errors in relation to sediment yield. However, the good comparison between measured and simulated sediment yields for runs No. 3 and 4 tend to support the use of the simplified model. The simulated yields for the d_{50} size are consistently less than the 14 size fractions. A χ^2 goodness of fit test indicates that the 14 size method gives better results for the two calibration runs and the three test runs. The overall performance of the simplified model is quite good. Although some discrepancies between measured and predicted sediment yields are present, these differences can be explained in part by preparation of the test plots and relative measurement errors as mentioned earlier.

COMPARISON OF SIMPLIFIED AND COMPLEX MODEL SIMULATIONS

Simulations of water and sediment yields for the five runs were generated by a complex water and sediment routing model. This model was developed by Li (1974) and recently upgraded by Li et al. (1977). Results of these simulations are presented in Table 5 and Figure 7.

The comparison of the simplified and complex models is quite good. This is expected as the simplified model closely simulated the physical processes. Similar close comparisons were obtained by Simons et al. (1976)

TABLE 5. Simplified versus Complex Model

No.	Water Yield, cubic feet Actual	Simplified	Complex	Sediment Yield, lbs. Actual	Simplified	Complex
1	29.32	29.77	29.76	14.90	15.43	15.41
2	31.39	26.99	26.88	14.45	13.94	13.92
3	31.00	30.51	30.07	6.38	4.63	4.39
4	36.35	39.56	39.62	4.99	6.00	5.79
5	36.57	34.23	34.40	10.45	17.77	17.83

Note:

1) Complex model is uncalibrated for water yield but uses values comparable to the simplified model.
2) Sediment yield determined by 14 size fractions, complex model calibrated for runs No. 1 and 2 only.

from simplified and complex model simulations for several hypothetical cases and are shown in Figures 8 and 9. These results further indicate the applicability of the simplified model.

The computer time required to simulate using the complex model is on the order of 10-15 times more than the simplified model. This time savings alone negates any improvement in accuracy obtained by the complex model for these simple cases. For larger or more complicated planes or watersheds and routing application, however, the complex simulation model is superior to the simplfied model because of its time-space routing structure.

USE OF SIMPLIFIED MODEL

The simplified model has been shown to be a viable, accurate alternative to the complex model for small, uncomplicated land surfaces. This allows the simplified model to be used with confidence for estimation of on-site overland water and sediment yields. The simplified model, once the water and sediment coefficients are estimated or

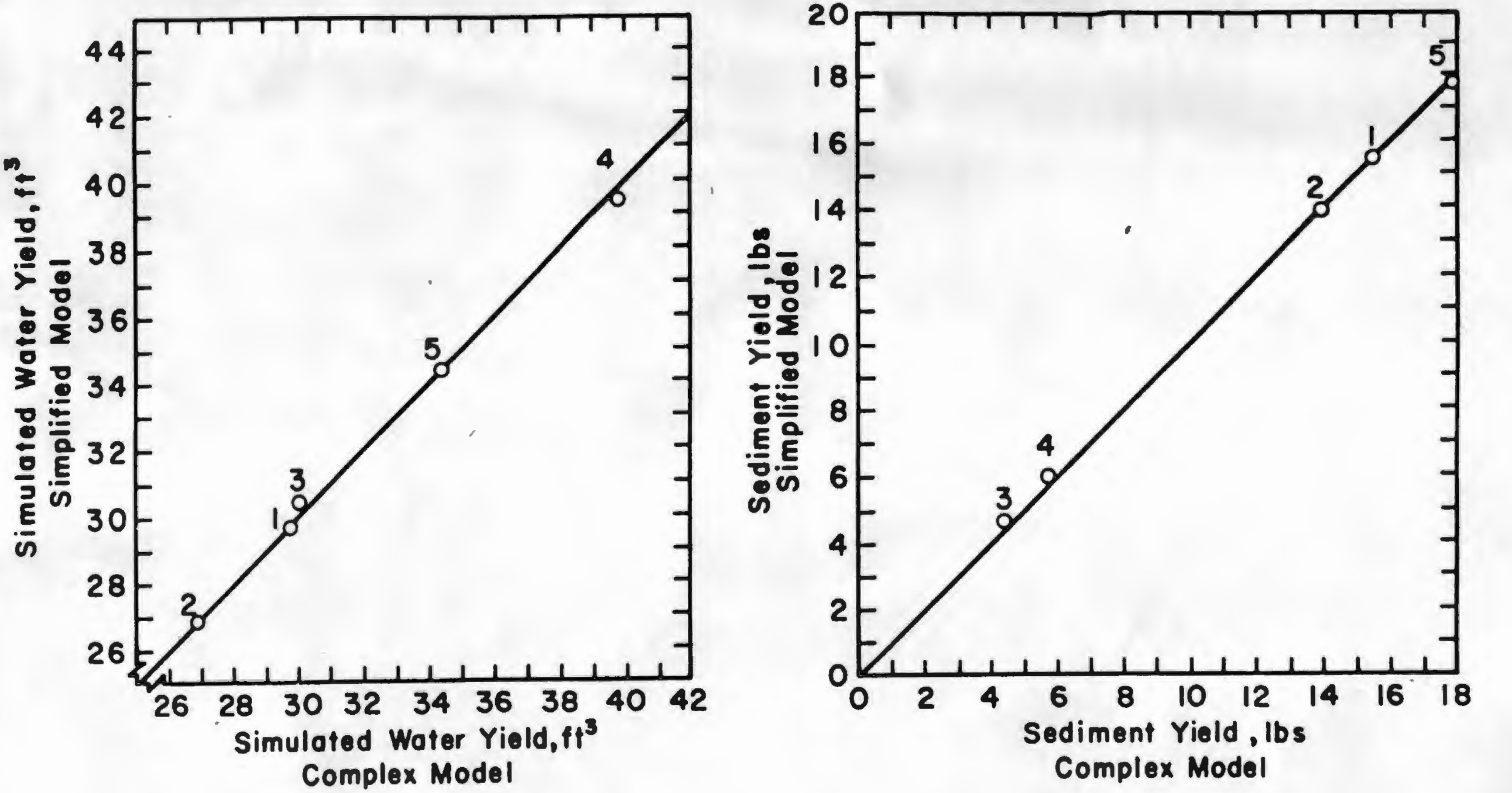

Figure 7. Simplified versus Complex Model Simulations

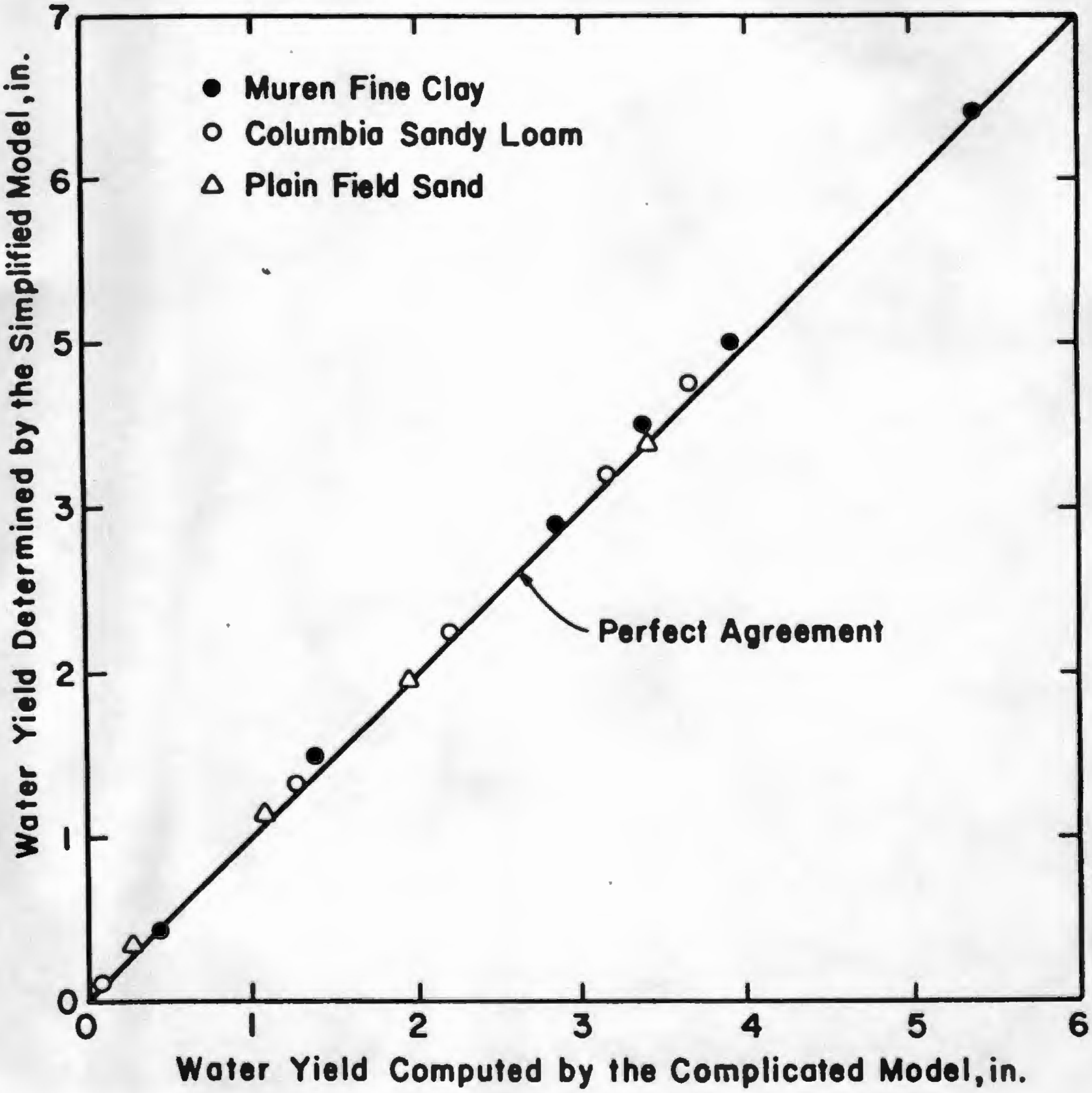

Figure 8. Comparison of Computed Water Yield

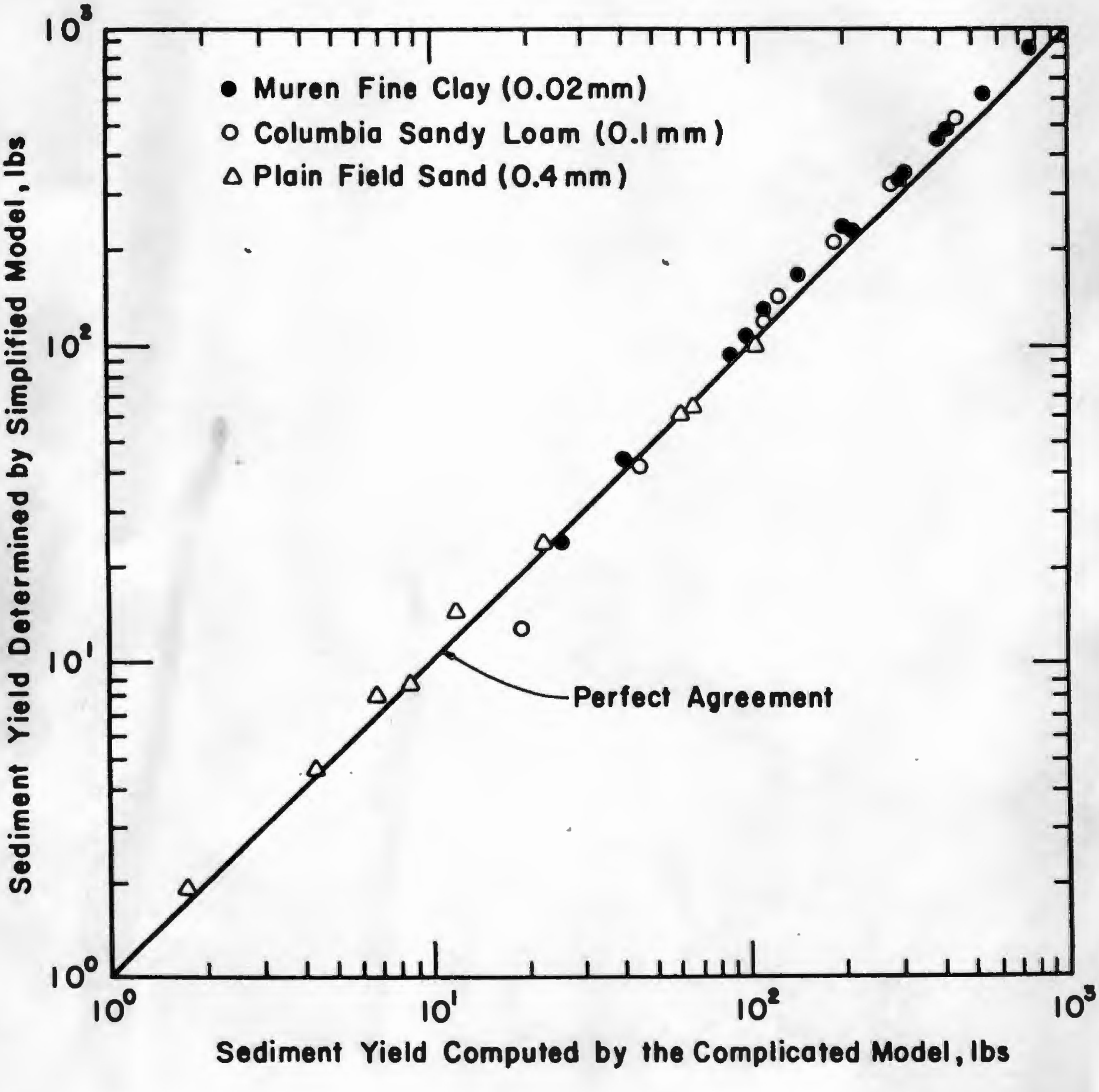

Figure 9. Comparison of Computed Sediment Yield

calibrated, can be used to predict the response of land surfaces to various treatment conditions. Examples of applications could cover vegetation characteristics, soil characteristics, and rainfall intensities. Examples of how the effects of landscape modifications might be assessed using the simplified model are given below.

Example 1--

Assume: i = 2.5 in./hr
S = 0.10
C_g = 0.90
C_c = 0.0
K_ℓ = 150
K_h = 40000
d_{50} = 0.0175 mm
V_g = 0.07 inch
V_c = 0.50 inch

Duration = 60 minutes
L = 200 feet
W = 20 feet
ψ_{ave} = 3.0 inches
ϕ = 0.5
S_i = 0.90
β = 1.0 in./hr
σ = 0.047
a_1 = 0.0001
D_f = 0.014

What would be the increases in sediment and water yield if C_g were reduced to 0.6, 0.3 and 0? The results of simulations using the simplified model are listed in Table 6 and shown in Figure 10.

TABLE 6. Response of Hypothetical Surface to Changes in Ground Cover

C_g	Water Yield (cubic feet)	Magnitude of Increase in Water Yield	Sediment Yield (lbs)
0.9	379.57	0	1.85
0.6	383.45	1.01	7.85
0.3	387.33	1.02	20.27
0.0	391.21	1.03	444.82

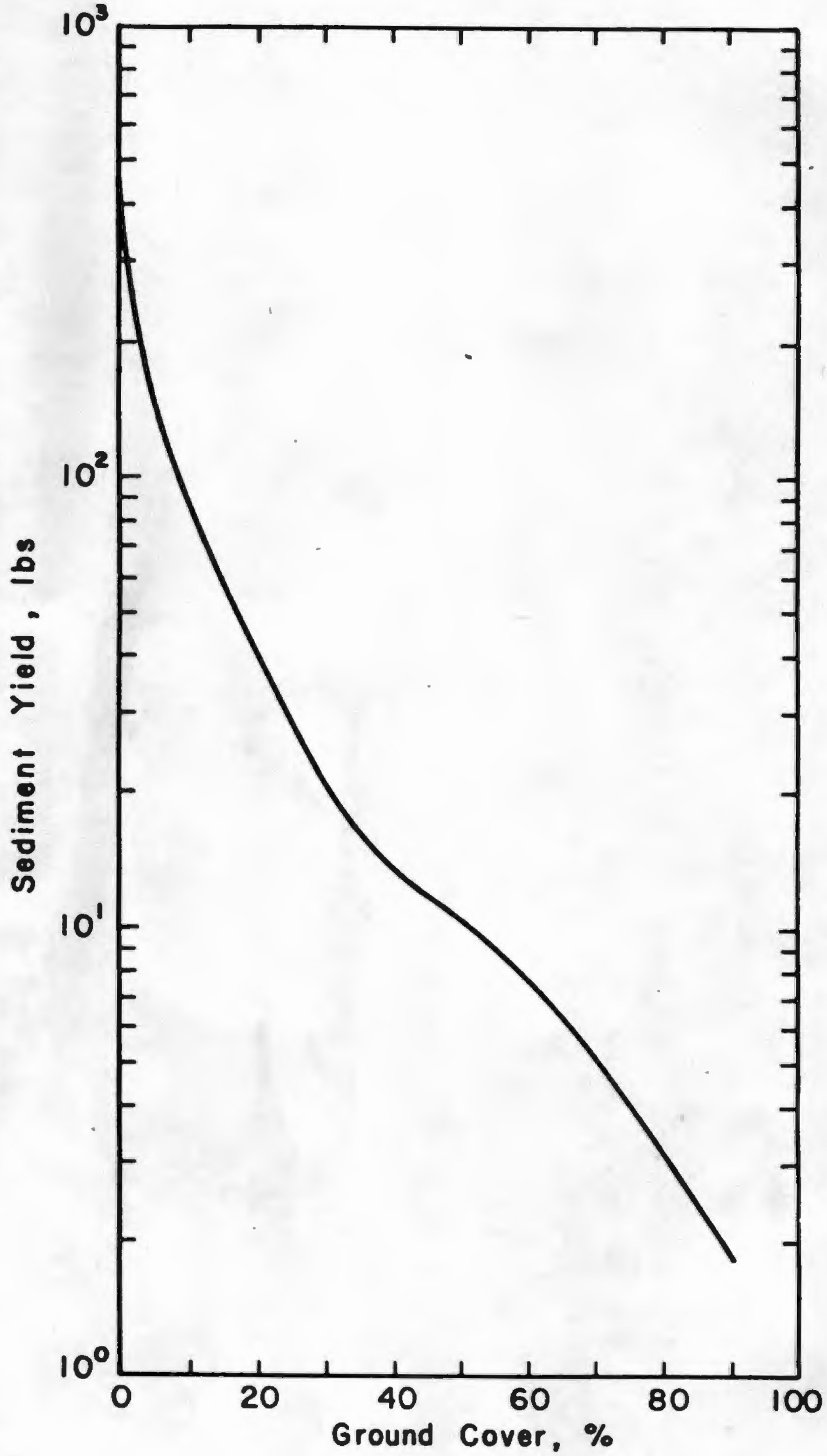

Figure 10. Sediment Yield versus Ground Cover for Example 1

The strong relationship between sediment yield and ground cover is demonstrated in Figure 10. Similar results were presented by Simons et al. (1975) for response investigation using a complex model. Other landscape alterations may be considered.

Example 2--

Using the data for example 1 above, determine the response of the surface to a slope increase of 50 percent, a decrease of 50 percent, under zero ground cover.

The results of this response investigation are given in Table 7 below.

TABLE 7. Response of Hypothetical Surface to Changes in Slope

Slope, Percent	Sediment Yields (lbs)
15	590.35
10	444.82
5	274.21

The effects of changing a slope gradient after removal of the vegetation can be extreme. In examples 1 and 2 above, assuming other soil properties remain constant, a 50 percent change in slope coupled with removal of the ground cover results in an increase of 526.15 lbs in sediment yield.

There are numerous other cases that could be investigated. The simplified model is formulated in a manner which allows rapid appraisal of any set of conditions. Input sequencing and a listing of the program are given in Appendices I and II respectively.

IV. CONCLUSIONS

A simplified model for estimating water and sediment yield from overland flow surfaces has been presented. Based on accepted numerical representations of physical processes the simplified model has been shown to accurately simulate field experimental tests. The simplified model is as accurate as a more complex type under the tested conditions. The simplified model, however, requires far less computer access or knowledge of the computer programming. At present, the simplified model is constrained to land surfaces of limited extent, and constant rainfall conditions. Extension of its applicability to more complex cases is forthcoming. The simplified water and sediment yield model can and does provide a realistic, easy to use tool for determining water and sediment yield from land surfaces under various environmental constraints and human activity.

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APPENDIX I

Input Sequence for Program SIMSED

Input Sequence for Program SIMSED

This program was written to provide a simplified method for determining sediment and water yield from a single plane and is named SIMSED, SIMplified SEdiment Determination, for future reference. Input data required are rainfall characteristics, plane geometry, vegetation characteristics and soil parameters. Output includes selected input data, rainfalls for which runoff occurs, time to ponding from beginning of storm, runoff volume, and total sediment yield. Most jobs should run with storage of 30,000 user words and 10 seconds of time.

The input sequence for this program is:

Card No	Columns	Format	Variable	Contents
1	1-80	20A4	NAME	User name for area being modeled
2	1-10	F10.2	SLENG	Length of plane, feet
	11-20	F10.2	WIDTH	Width of plane, feet
	21-30	F10.2	SLOPE	Slope of plane, decimal fraction
3	1-10	I10	NRAIN	Number of rainfall intensities considered
4	1-10	F10.2	DT	Total rain duration, minutes
5 (can be more than one card)	1-10	F10.2	RAIN(1)	First rainfall intensity, (inches/hour)
	11-20	F10.2	RAIN(2)	Second rainfall intensity, (inches/hour)
	...	"	etc	etc
6	1-10	F10.2	POTH	Average soil capillary suction pressure head in the wetted zone, inches
	11-20	F10.2	HYCO	Soil hydraulic conductivity in wetted zone, inches/hour
	21-30	F10.2	SI	Antecedent soil saturation, decimal fraction
	31-40	F10.2	POROS	Soil porosity, decimal fraction

Card No	Columns	Format	Variable	Contents
6 (cont)	41-50	F10.2	DCOEF	Coefficient for raindrop soil detachment equation
	51-60	F10.2	DPOW	Exponent for raindrop soil detachment equation
	61-70	F10.2	SS	Soil specific gravity
	71-80	F10.2	SEDN	Number of sediment sizes considered
7 (can be more than one card)	1-10	F10.2	DMBIN(1)	First representative sediment size to be considered
	11-20	F10.2	DMBIN(2)	Second representative sediment size to be considered
	...	"	etc	etc
8 (can be more than one card)	1-10	F10.2	DPRCNT(1)	Decimal fraction of total weight for first representative sedimen size
	11-20	F10.2	DPRCNT(2)	Decimal fraction of total weight for second representative sediment size
	...	"	etc	etc
9	1-10	F10.2	DOF	Overland flow sediment detachment coefficient
10	1-10	F10.2	GC	Ground cover, decimal fraction of area
	11-20	F10.2	CC	Canopy cover, decimal fraction of area
	21-30	F10.2	GCI	Interception depth for ground cover, inches
	31-40	F10.2	CGI	Interception depth for canopy cover, inches
	41-50	F10.2	OFL1	Lower limit of overall friction factor
	51-60	F10.2	OFL2	Upper limit of overall friction factor
11	1-10	F10.2	CROSUF	Grain resistance flow factor
	11-20	F10.2	VISCO	Kinematic viscosity of water in ft-lb-sec system (Note this is divided by 100,000 in the program so input correctly)

Example Input and Output for Program SIMSED

Below is example input and computer output for program SIMSED based on Example 1 in the text.

Input:

SLENG	=	200. feet
WIDTH	=	20. feet
SLOPE	=	0.10
NRAIN	=	2
DT	=	60 minutes
RAIN(1)	=	2.5 inches/hour
RAIN(2)	=	5.0 inches/hour
POTH	=	3.0 inches
HYCO	=	1.0 inches/hour
SI	=	0.9
POROS	=	0.5
DCOEF	=	0.0001
DPOW	=	2.0
SS	=	2.65
SEDN	=	1.
DMBIN(1)	=	0.0175 mm
DPRCNT(1)	=	1.
DOF	=	0.014
GC	=	0.9
CC	=	0.0
GCI	=	0.07 inches
CCI	=	0.5 inches
OFL1	=	150.
OFL2	=	40000.
CROSUF	=	50.
VISCO	=	1.05 $(\times 10^{-5})\ \frac{ft^2}{sec}$

Output:

SAMPLE OUTPUT FOR TWO RAINFALL INTENSITIES AND ONE SEDIMENT SIZE

GEOMETRY, VEGETATION, AND WATER AND SEDIMENT YIELDS FOR SELECTED RAINFALL INTENSITIES

```
WIDTH,FT.=  20.0  LENGTH,FT.= 200.0  SLOPE,PERCENT=  10.0  AREA,ACRES=   .09
GROUND COVER,PERCENT OF AREA= 90.00      CANOPY COVER,PERCENT OF AREA=  0.00
SEDIMENT SIZE,MM=  .017     RAINFALL DURATION,HOURS= 1.00
```

RAINFALL INTENSITY IN.HR.	TIME TO PONDING HR.	RUNOFF VOLUME CU.FT.	SEDIMENT YIELD LBS.
2.5	.065	379.57	1.85
5.0	.020	1203.34	8.25

(Note that time to ponding is time from beginning of rainfall, not beginning of infiltration.)

APPENDIX II

Program Listing for SIMSED

Program Listing for SIMSED

Below is a list of labels for primary variables in Program SIMSED.

FORTRAN Label of Primary Variables	Definition
ABARE	Area of bare soil
AR	Particle size-flow depth ratio for Einstein's equation
AREA	Area of plane surface
BMV	Coefficient for Einstein's equation
CC	Canopy cover
CCI	Canopy cover interception
CROSUF	Grain resistance flow friction factor
CSLSUF	Overall flow friction factor
DA	Available material from raindrop splash and overland flow detachment
DCOEF	Coefficient for raindrop splash detachment equation
DEPTH	Depth of overland flow
DMB	Sediment size
DMBIN	Vector of sediment sizes
DOF	Overland flow sediment detachment coefficient
DPOW	Power of raindrop splash detachment equation
DPRCNT	Vector of sediment size fractions
DQCOM	Detached soil volume in cubic feet
DT	Rainfall duration
DTHOLD	Duration of infiltration, after interception
DUREXS	Duration of runoff

FORTRAN Label of Primary Variables	Definition
DV	Detachment volume, in cubic feet, from raindrop splash
EXR	Rainfall excess rate, inches/hour
FJ	Integral in Einstein's equation
FRA	Infiltration rate
FVB	Particle fall velocity
GC	Ground cover fraction
GCI	Ground cover interception
HYCO	Hydraulic conductivity in wetted zone
NRAIN	Number of single intensity rainfall events
OFL1	Lower value of overall flow resistance factor
OFL2	Upper value of overall flow resistance factor
POROS	Porosity of soil
POTH	Average soil capillary suction pressure in wetted zone
Q	Discharge rate, cfs/ft
QSED	Vector of sediment discharge rates for each size fraction
QV	Runoff volume in cubic feet
RA	Rainfall intensity
RAIN	Vector of rainfall intensities
SEDCOM	Potential sediment transport in cubic feet
SEDN	Number of sediment sizes considered
SEDQ	Bed material and total load discharge rate
SEDR	Sediment supply from overland flow detachment
SEDV	Sediment yield for each representative particle size

FORTRAN Label of Primary Variables	Definition
SI	Antecedent soil saturation
SJ	Integral for Einstein's equation
SLENG	Slope length
SLOPE	Gradient of slope
SS	Specific gravity of sediment
SUSP	Suspended sediment discharge rate
SV	Shear velocity
TAO	Effective boundary shear stress
TAOC	Critical shear
TP	Time to ponding
VISCO	Viscosity of water
VMEAN	Mean velocity of flow
WIDTH	Width of slope
YIELD	Total yield if more than one sediment size is considered
ZR	Fall velocity-shear velocity ratio for Einstein's equation

```
      PROGRAM SIMSED (INPUT,OUTPUT)
      COMMON/GEOM/SLENG,WIDTH,SLOPE
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMH,DOF,FRA,DV
      COMMON/SEDS/DMBIN(50),DPRCNT(50),SEDN,PS,ISED
      COMMON/VEGE/GC,CC,GCI,CCI,OFL1,OFL2
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
      COMMON/FLOW/VISCO,CROSUF
      COMMON/PRNT/J,KQONT,TP,QV,SEDV,YIELD
      DIMENSION NAME(20)
C      PROGRAM SIMSED DETERMINES WATER AND SEDIMENT
C      YIELD FOR A SIMPLE PLANE SURFACE WITH VEGETATION
C      THIS MAIN PROGRAM COORDINATES THE CALLING
C      OF DIFFERENT COMPONENTS OF THE PROGRAM
    9 CONTINUE
C      READ IN NAME OF AREA
      READ 100,NAME
  100 FORMAT(20A4)
      IF(EOF(5LINPUT))999,10
   10 CONTINUE
      PRINT 199
  199 FORMAT(1H1)
      PRINT140,NAME
  140 FORMAT(20X,20A4//)
C      READ IN DATA THROUGH SUBROUTINE DATA
      CALL DATA
C      CALCULATE VOLUME OF VEGETATION INTERCEPTION
      VI=CC*CCI+GC*GCI
      KQONT=0
      DO 800 J=1,NRAIN
      RA=RAIN(J)
C      CALCULATE TIME REQUIRED TO MEET INTERCEPTION LOSSES
      DTHOLD=DT-VI/RAIN(J)
C      DETERMINE INFILTRATION WITH SUBROUTINE INFIL
      CALL INFIL
C      DETERMINE SOIL DETACHMENT BY RAINFALL IMPACT
C      BY USE OF SUBROUTINE DETACH
      CALL DETACH
C      DETERMINE SEDIMENT TRANSPORT BY USE OF SUBROUTINE SEDIMT
      CALL SEDIMT
  800 CONTINUE
      GO TO 9
  999 CONTINUE
      STOP
      END
```

```
      SUBROUTINE DATA
C       THIS SUBROUTINE READS IN THE REQUIRED DATA AND
C       SETS THE NECESSARY CONSTANTS
      COMMON/GEOM/SLENG,WIDTH,SLOPE
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMH,DOF,FRA,DV
      COMMON/SEDS/DMBIN(50),DPRCNT(50),SEDN,PS
      COMMON/VEGE/GC,CC,GCI,CCI,OFL1,OFL2
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
      COMMON/FLOW/VISCO,CROSUF
C       READ PLANE GEOMETRY
      READ 120,SLENG,WIDTH,SLOPE
C       READ RAIN PARAMETERS
      READ 100,NRAIN
      READ 120,DT
      READ 120,(RAIN(I),I=1,NRAIN)
C       READ SOIL PARAMETERS
      READ 120,POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,SEDN
      NSED=INT(SEDN)
C       READ IN SEDIMENT SIZE AND PERCENT DATA
      READ 120,(DMBIN(I),I=1,NSED)
      READ 120,(DPRCNT(I),I=1,NSED)
C       READ OVERLAND FLOW DETACHMENT COEFFICIENT
      READ 120,DOF
C       READ VEGETATION PARAMETERS
      READ 120,GC,CC,GCI,CCI,OFL1,OFL2
C       READ FLOW CHARACTERISTICS
      READ 120,CROSUF,VISCO
C       ADJUST INPUT AND SET CONSTANTS
      VISCO=VISCO/100000.
      DT=DT/60.
  100 FORMAT(8I10)
  120 FORMAT(8F10.2)
      RETURN
      END
```

```
      SUBROUTINE INFIL
C      THIS SUBROUTINE DETERMINES THE INFILTRATION RATE,
C      THE TIME OF PONDING, AND THE PERIOD OF RUNOFF
C      ALL OF THESE COMPUTATIONS ARE DONE BY AN ANALYTICAL FORMULATIO
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMB,DOF,FRA,DV
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
      AIN=POROS*(1.-SI)*POTH
      BIN=HYCO
      IF(RA.LE.BIN) GO TO 20
C      CALCULATE TIME TO PONDING FROM BEGINNING OF EFFECTIVE RAINFALL
      TP=AIN/((RA*RA/BIN)-RA)
      IF(TP.GE.DTHOLD) GO TO 20
C      CALCULATE FIRST INFILTRATION APPROXIMATION
      FTP=TP*RA
      DUREXS=DTHOLD-TP
      CHOLD=(1.+FTP/AIN)
      C1=BIN*DUREXS+FTP-AIN*ALOG(CHOLD)
      CHOLD=C1*(C1+8.0*AIN)
      FTOT=0.5*(C1+SQRT(CHOLD))
C      CALCULATE SECOND INFILTRATION APPROXIMATION
      F1=FTOT/AIN
      CHOLD=F1*F1+2.0*((C1/AIN)-F1+ALOG(1.0+F1))
      CHOLD=SQRT(CHOLD)
      FTOT=AIN*((1.0+F1)*CHOLD-F1*F1)
      FTOT=FTOT-FTP
      FRA=FTOT/DUREXS
      IF(FRA.GE.RA) GO TO 20
      RETURN
   20 CONTINUE
      DUREXS=0.0
      FRA=RA
      RETURN
      END
```

```
      SUBROUTINE DETACH
C      THIS SUBROUTINE DETERMINES THE SOIL DETACHMENT
C      FROM RAINDROP IMPACT
      COMMON/GEOM/SLENG,WIDTH,SLOPE
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMB,DUF,FRA,DV
      COMMON/VEGE/GC,CC,GCI,CCI,OFL1,OFL2
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
C      DETERMINE AREA OF UNPROTECTED SOIL
      ABARE=1.-GC-CC+(GC*CC)
C      CALCULATE SOIL DETACHMENT RATE
      DQ=DCOEF*(RA**DPOW)
C      CALCULATE VOLUME OF SOIL DETACHED
      DV=DQ*DT*SLENG*WIDTH*(1.-POROS)/12.
C      REDUCE VOLUME TO CORRESPOND WITH AREA OF BARE GROUND
      DV=DV*ABARE
      RETURN
      END
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      SUBROUTINE SEDIMT
C      THIS SUBROUTINE DETERMINES THE SEDIMENT TRANSPORT
C      GIVEN THE RUNOFF RATE.  THIS SUBROUTINE
C      ALSO CONTAINS THE PRINTING OF THE REQUIRED OUTPUT.
      COMMON/GEOM/SLENG,WIDTH,SLOPE
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMH,DOF,FRA,DV
      COMMON/SEDS/DMBIN(50),DPRCNT(50),SEDN,PS,ISED
      COMMON/VEGE/GC,CC,GCI,CCI,OFL1,OFL2
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
      COMMON/FLOW/VISCO,CROSUF
      COMMON/PRNT/J,KQONT,TP,QV,SEDV,YIELD
      DIMENSION QSED(50)
      SLP=SLOPE
      IF(SLOPE.GT.0.25) SLP=SIN(ATAN(SLOPE))
      TP=0.0
      QV=0.0
      SEDV=0.0
      Q=0.0
C      CALCULATE RUNOFF RATE
      EXR=RA-FRA
      Q=EXR*SLENG*(1./(12.*3600))
      IF(J.EQ.NRAIN.AND.Q.EQ.0.0) CALL SEDPRT(3)
      IF(Q.LE.0.0) RETURN
      KQONT=KQONT+1
C      CALCULATE TIME OF PONDING FROM BEGINNING OF RAINFALL
      TP=DT-DUREXS
C      CALCULATE WATER YIELD
      QV=Q*WIDTH*DUREXS*3600.
C      CALCULATE RESISTACE AND FLOW PARAMETERS
      CSLSUF=OFL1+(OFL2-OFL1)*GC*GC
      DEPTH=(Q*CSLSUF*VISCO/(257.6*SLP))**(1./3.)
      VMEAN=Q/DEPTH
C      CALCULATE SHEAR FORCE AND SHEAR VELOCITY
      TAO=0.24225*CROSUF*VISCO*Q/(DEPTH**2.)
      SV=SQRT(62.4*DEPTH*SLP/1.938)
      BMV=2.5+VMEAN/SV
      NSED=INT(SEDN)
      SSEDQ=0.0
C      CALCULATE POTENTIAL TRANSPORT BY SUMMING FOR EACH SIZE FRACTION
      DO 750 ISED=1,NSED
      DMB=DMBIN(ISED)/304.8
      PS=DPRCNT(ISED)
      TAOC=0.010*62.4*(SS-1.)*DMB
      IF(TAO.GT.TAOC) GO TO 30
C      NO SEDIMENT TRANSPORT, SET VALUES
      SEDQ=0.
      GO TO 40
C      CALCULATE BED MATERIAL TRANSPORT
   30 SEDQ=(12.85/1.392)*(TAO-TAOC)**(1.5)
      FVB=(SQRT(36.064*DMB**3+36.*VISCO**2)-6.*VISCO)/DMB
      IF(DMB.LE.0.0002) FVB=2.9517*DMB**2/VISCO
C      CALCULATE SUSPENDED LOAD TRANSPORT
      ZR=FVB/(0.4*SV)
      AR=2.*DMB/DEPTH
      IF(AR.GT.0.9) GO TO 40
      CALL POWER (ZR,AR,FJ,SJ,1.0E-2)
      P=AR**(ZR-1.)/(11.6*(1.-AR)**ZR)
      SUSP=P*(BMV*FJ+2.5*SJ)
      IF(SUSP.GT.0.0) GO TO 45
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   40 SUSP=0.0
   45 CONTINUE
C       CALCULATE TOTAL SEDIMENT TRANSPORT
      SEDQ=(1.+SUSP)*SEDQ*PS
      QSED(ISED)=SEDQ
      SSEDQ=SSEDQ+SEDQ
  750 CONTINUE
C       CALCULATE POTENTIAL SEDIMENT YIELD
      SEDV=SSEDQ*WIDTH*DUREXS*3600.
      SEDCOM=SEDV/(SS*62.4)
C       DETERMINE SEDIMENT SUPPLY BY FLOW DETACHMENT
      DQCOM=DV
      SEDR=DOF*(SEDCOM-DQCOM)
      IF(SEDR.LE.0.0) SEDR=0.0
      DQCOM=DQCOM+SEDR
      YIELD=0.0
      DO 800 ISED=1,NSED
      DMB=DMBIN(ISED)/304.8
      PS=DPRCNT(ISED)
      DA=PS*DQCOM
      SEDV=QSED(ISED)*DUREXS*WIDTH*3600.
      SEDCOM=SEDV/(SS*62.4)
C       DETERMINE IF SUPPLY OR TRANSPORT CONTROLS SEDIMENT YIELD
      IF(DA.LT.SEDCOM) SEDV=DA*(SS*62.4)
      ISHOLD=INT(SEDV*100.)
      SEDV=FLOAT(ISHOLD)/100.
      IF(SEDV.LT.0.005) SEDV=0.0
      YIELD=YIELD+SEDV
      IF(NSED.GT.1) CALL SEDPRT(1)
      IF(NSED.EQ.1) CALL SEDPRT(2)
  800 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE POWER (Z,A,XJ1,XJ2,CONV)
C     THIS SUBROUTINE EVALUATES THE J1 AND J2 INTEGRALS
C     USED IN THE SEDIMENT TRANSPORT EQUATIONS
C     NOTATIONS
C     XJ1= VALUE OF J1 INTEGRAL
C     XJ2= VALUE OF J2 INTEGRAL
C     N = ORDER OF APPROXIMATION + 1
C     CONV = CONVERGENCE CRITERION
      N=1
      XJ1=0.
      XJ2=0.
      ALG=ALOG(A)
      C=1.
      D=-Z
      E=D+1.
      FN=1.
      AEX=A**E
      GO TO 1
    2 N=N+1
      C=C*D/FN
      D=E
      E=D+1.
      FN=FLOAT(N)
      AEX=A**E
    1 IF(ABS(E) .LE. 0.001) GO TO 3
      XJ1=XJ1+C*(1.-AEX)/E
      XJ2=XJ2+C*((AEX-1.)/E**2-AEX*ALG/E)
      GO TO 4
    3 XJ1=XJ1-C*ALG
      XJ2=XJ2-0.5*C*ALG**2
    4 IF(N .EQ. 1) GO TO 5
      CJ1=ABS(1.-FJ1/XJ1)
      CJ2=ABS(1.-FJ2/XJ2)
      IF(CJ1 .LE. CONV .AND. CJ2 .LE. CONV) RETURN
    5 FJ1=XJ1
      FJ2=XJ2
      GO TO 2
        END
```

```
      SUBROUTINE SEDPRT(IPRINT)
      COMMON/GEOM/SLENG,WIDTH,SLOPE
      COMMON/SOIL/POTH,HYCO,SI,POROS,DCOEF,DPOW,SS,DMB,DOF,FRA,DV
      COMMON/SEDS/DMBIN(50),DPRCNT(50),SEDN,PS,ISED
      COMMON/VEGE/GC,CC,GCI,CCI,OFL1,OFL2
      COMMON/RANE/NRAIN,DT,DTHOLD,RAIN(20),RA,DUREXS
      COMMON/FLOW/VISCO,CROSUF
      COMMON/PRNT/J,KQONT,TP,QV,SEDV,YIELD
C      THIS SUBROUTINE PRINTS THE CALCULATED VALUES
      NSED=INT(SEDN)
      SLPT=SLOPE*100.
      AREA=WIDTH*SLENG/43560.
      GCP=GC*100.
      CCP=CC*100.
      DMBP=DMB*304.8
      IF(IPRINT.EQ.2.AND.KQONT.GT.1) GO TO 2
      IF(KQONT.GT.1.OR.ISED.GT.1) GO TO 20
      PRINT 115
  115 FORMAT(20X*GEOMETRY,VEGETATION, AND WATER AND SEDIMENT YIELDS FOR
     1SELECTED RAINFALL INTENSITIES*//)
   20 PRINT 120,WIDTH,SLENG,SLPT,AREA,GCP,CCP,DMBP,DT
  120 FORMAT(24X*WIDTH,FT.=*F6.1,2X*LENGTH,FT.=*F6.1,2X*SLOPE,PERCENT=*
     16.1,2X*AREA,ACRES=*F6.2,2X/24X*GROUND COVER,PERCENT OF AREA=*F6.2
     25X*CANOPY COVER,PERCENT OF AREA=*F6.2/24X*SEDIMENT SIZE,MM=*F6.3,
     3X*RAINFALL DURATION,HOURS=*F5.2//)
      IF(IPRINT.EQ.3) GO TO 3
      PRINT 125
  125 FORMAT(26X*RAINFALL INTENSITY*5X*TIME TO PONDING*5X*RUNOFF VOLUME
     15X*SEDIMENT YIELD*/32X*IN.HR.*16X*HR.*16X*CU.FT.*14X*LBS.*//)
    2 PRINT 130,RAIN(J),TP,QV,SEDV
  130 FORMAT(32X,F4.1,17X,F6.3,11X,F10.2,8X,F9.2/)
      IF(ISED.GT.1.AND.ISED.GE.NSED) PRINT 135, NSED,YIELD
  135 FORMAT(2X/35X*TOTAL SEDIMENT YIELD, LBS.,FOR*I3,1X*SIZES=*F9.2///
      RETURN
    3 PRINT 140
  140 FORMAT(2X//25X*NO WATER DISCHARGE FOR THIS AREA*//)
      RETURN
      END
```

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