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Soil erosion: Prediction and control

The Proceedings of
A National Conference
on Soil Erosion
May 24-26, 1976
Purdue University,
West Lafayette, Indiana

Price: Hardbound, $10.00
Softbound, $7.00

Soil Conservation Society of America
7515 Northeast Ankeny Road
Ankeny, Iowa 50021

Field test of a distributed watershed erosion/sedimentation model

Roger E. Smith

We can extend our understanding of erosion phenomena by exploring the relation between sediment production and movement and the associated watershed hydraulic processes. A model that describes unsteady water and sediment movement on a watershed as a time-and-space distributed process has been assembled to help in examining the various factors within an individual storm that contribute to sediment production. The techniques and numerical processes used resemble, but perhaps are more topographically flexible than, those used by Woolhiser and associates (*10*), Rovey (*7*), and others. If such a model can simulate hydraulic processes over the watershed with relative accuracy, then I would expect that the underlying relation between watershed hydraulics and watershed erosion could be explicitly studied. For this purpose, both surface and small channel flow need to be represented, and accurate simulation of infiltration is crucial.

I introduced the model employed in this study earlier (*8*). I evaluated here using data from a natural rangeland watershed.

Construction of the Simulation Model

The hydrologic simulation of the watershed consists of the numerical solution of partial differential equations for the unsteady movement of water on a surface or in a channel with a distributed input. This input at any point on the surface is the difference between the rainfall rate and the infiltration rate. Outflow from the lower edge of the surface becomes in turn the distributed input for a channel. The elementary watershed is described as an assembly of surface and channel units; each unit consisting of a channel with a watershed surface contributing to one or both sides of the channel. Each of these elements consists of a warped surface, which may include flow convergence, non-uniform flow path length, and variable surface slopes, $S_o = S_o(x)$.

A key element in runoff simulation is calculation of point infiltration rate, f, and, therefore, excess rainfall rate. The infiltration model used

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is essentially that described by Smith and Chery (*9*), developed from porous media flow simulation. This four-parameter model calculates time of start of runoff (or time of poinding, t_p) as a function of rainfall pattern $[r(t)]$ and initial soil saturation, and then calculates an infiltration decay curve through the point $[r(t_p),\ t_p]$, asymptotic to a final infiltration capacity, f_c (theoretically equal to the saturated conductivity):

$$f = f_c + A(t - t_o)^{-\alpha},\quad t \geq t_p, \qquad [1]$$

where f_c is the final minimum infiltration rate f; A, α are parameters; t_o is the hypothetical vertical asymptote of curve; and t_p is the time of ponding.

Sediment movement on the watershed is described by a partial differential equation linked to the water movement equation, and consisting of an equation of continuity with relations describing sediment detachment/deposition rate at any point on the surface or in a channel. The particular equations used were outlined in more detail previously (*8*).

The kinematic equations of surface water flow describe the depth and velocity of water at any point on the surface or channel portions of the model watershed. From this, any dependent relation for sediment transport capacity and hydraulic detachment rate can also be computed at any point on the model watershed.

In the results reported below, point rainfall detachment rate, d_r, is

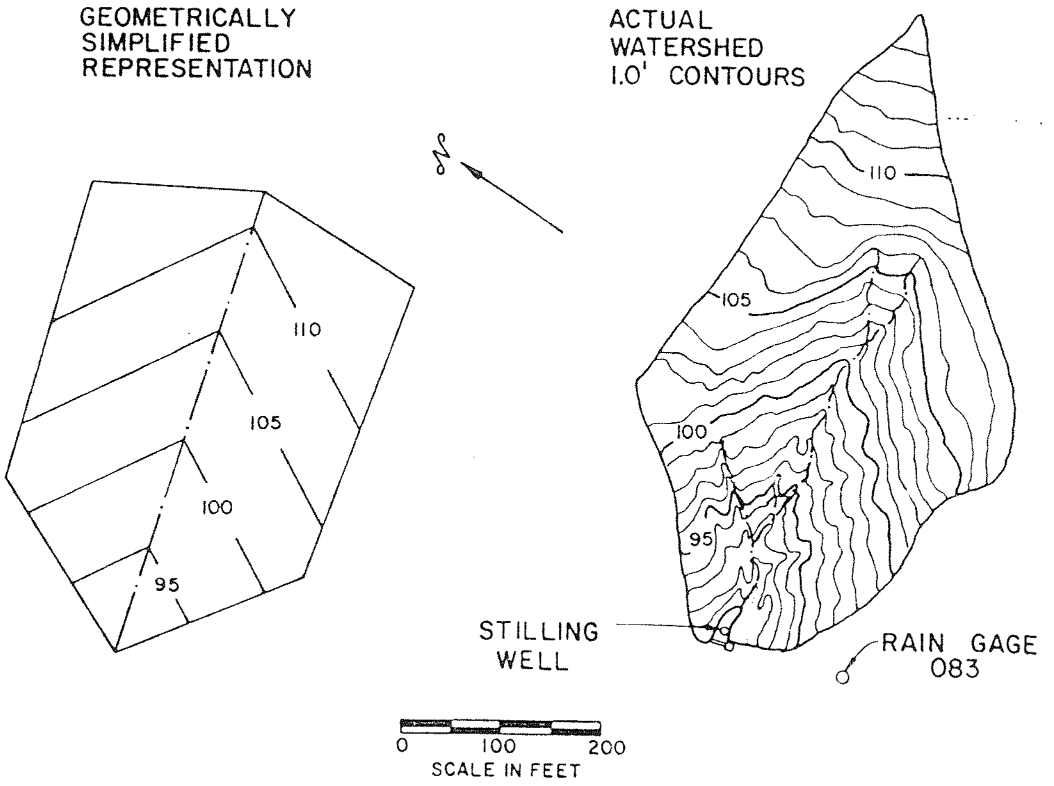

Figure 1. Contour map of study watershed at Lucky Hills, Tombstone, Arizona, and the simplified analog used in the model.

assumed proportional to the square of the rainfall rate, as proposed by Meyer and Wischmeier (*5*), modified by the mean depth of water on the surface;

$$d_r = K_r r^2 \left[e^{-Hh^2}\right] \qquad [2]$$

where K_r is a constant parameter, r is the rainfall rate, H is a parameter, and h is the mean depth of surface flow. The term in brackets is a purely conceptual model of the effect of surface flow depth, h, on rainfall erosivity, and should be considered unverified.

Hydraulic detachment rate has been tentatively assumed proportional to hydraulic transport capacity. Thus, the interrelation between detachment and sediment carrying-capacity proposed by Foster and Meyer (*2*) is modified to that assumed by Einstein (*1*):

$$d_f = K_f(C_{mx} - C) \qquad [3]$$

where d_f is the hydraulic detachment rate, K_f is a parametric coefficient, C_{mx} is the concentration of sediment that can be carried by the flow at any instant, and C is the actual sediment concentration. Sediment carrying capacity, C_{mx}, on the watershed surface is taken to be a function of critical tractive force, after a relation given by Kilinc and Richardson (*4*):

$$c_{mx} = \frac{K_o[u(\tau_o - \tau_c)]^{1.58}}{\gamma u h} \qquad [4]$$

where u is the local velocity; τ_o is the tractive force; τ_c is the critical tractive force, a parameter; γ equals the unit weight of sediment; and K_o is a parameter. Other relations could easily be used in the model.

In the channels, the present model employs the unit stream power relation of Yang (*11*), which assumes

$$\log C_{mx} = A + B \log[uS_o - (uS_o)_c] \qquad [5]$$

where A and B are parameters, S_o is the local surface slope, and $(uS_o)_c$ is the critical unit stream power (a parameter).

Seven parameters describe the erosion characteristics of the watershed, three describe the surface water hydraulics and four the infiltration model. Two parameters represent surface microtopography, and eighteen describe the total topography of surfaces and the channel. All of these are considered watershed descriptors, and are not varied to fit individual rainfall events. Evaluation of the relative sensitivity of the erosion parameters that I have used will depend on model comparison with several different watersheds, although K_o and H apparently are more sensitive than K_f, for example. Infiltration parameter sensitivity has been discussed by Rovey (*7*).

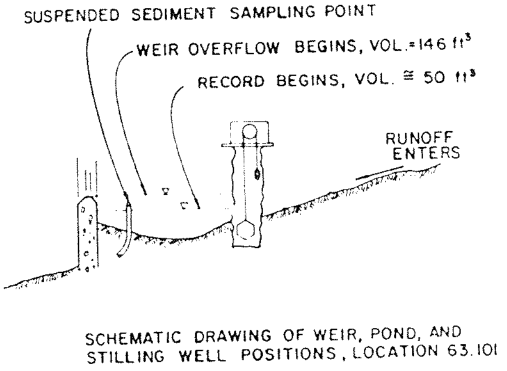

Figure 2. Schematic drawing of weir, pond, stilling well, and sediment sampling positions.

Erosion on bare fields and fresh embankments is characterized by formation of rills. Although this model was developed to simulate erosion on natural rangeland areas where small rills ordinarily are not found, it may be considered that

Table 1. Summary of results of simulation of 1975 runoff events on Lucky Hills watershed 63.101.

		Measured Rainfall		Initial	Peak Discharge[b]			Runoff Volume		Measured Sediment	Simulated Sediment
Runoff Event (1975)		Peak Rate (in/hr)	Total Volume (in)	Relative Saturation Estimate	Corrected Observed[a] (ft^3/sec)	Simulated (ft^3/sec)	Simulated (in/hr)	Observed (in)	Simulated (in)	Leaving Pond (t)	Entering Pond (t)
July	5	5.16	0.48	0.40	1.73	1.82	0.66	0.071	0.076	0.029	0.035
	12	6.96	1.07	0.60	10.95	10.43	3.66	0.558	0.509	0.234	0.389
	17	9.30	2.86	0.60	15.1[c]	15.28[c]	5.40[c]	2.07	2.14	1.250	1.980
	23	1.50	0.29	0.84	0.7	0.63	0.24	0.025	0.031	0.0002	0.007
Sept.	3	1.86	0.40	0.72	0.38[b]	0.125	0.06	0.037	0.015	0.0004	0.002
	7	5.34	0.47	0.77	3.0[b]	2.98	1.02	0.140	0.129	0.057	0.064
	13	2.16	0.75	0.74	2.96	3.21	1.14	0.287	0.254	0.050	0.112
									Annual total[d]	1.69	2.52 t

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[a] "Corrected observed" is used to describe the values of pond inflow derived by simulating the action of the pond storage, outflow, and leakage on the stilling well record.

[b] Peaks are estimated for the records where the delay of the stilling well threshold effect severely distorts the record.

[c] Second of two peaks, which the record indicates to be the larger.

[d] From volumetric measurements, assuming 70 lb/ft^3 bulk, about 1.2 t have been deposited in the pond over the last 3 years, most in 1975.

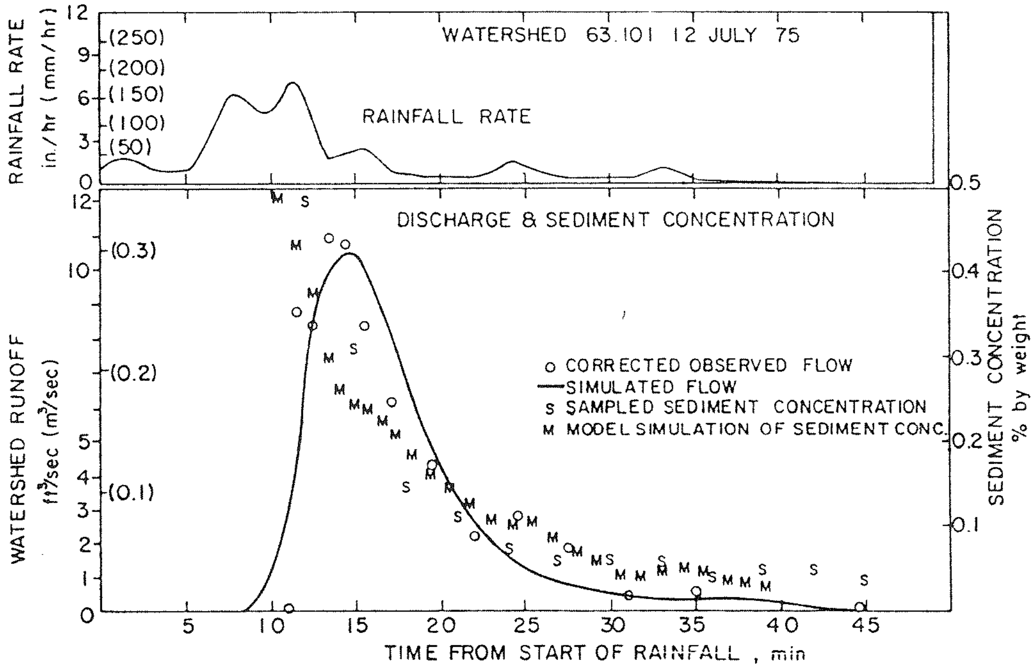

Figure 3. Simulation results for the storm and runoff event of July 12, 1975.

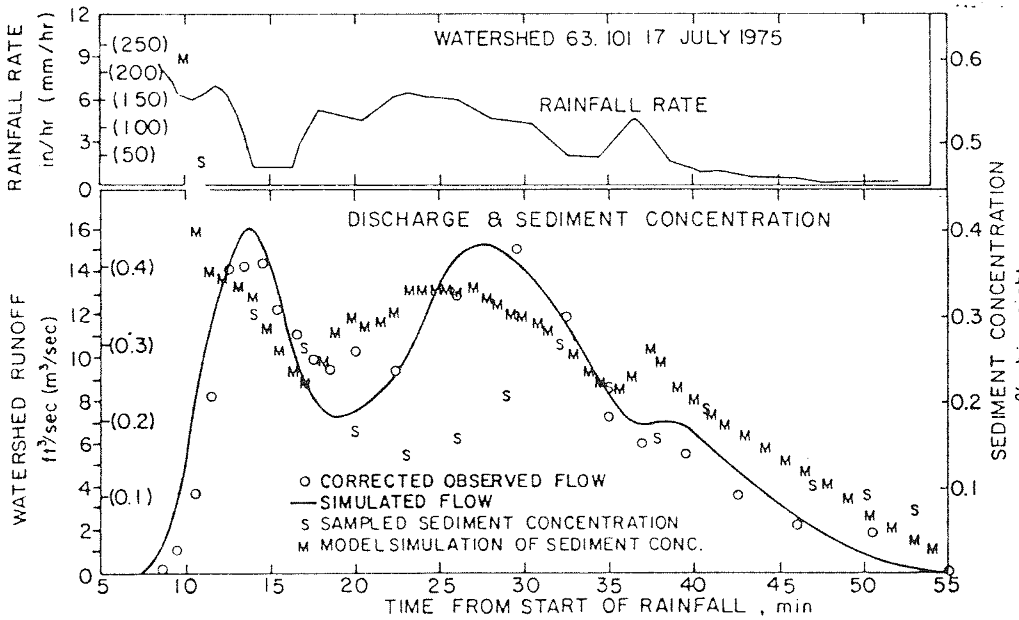

Figure 4. Simulation results for the storm and runoff event of July 17, 1975.

rill and interrill erosion is treated indirectly by the distinction between rainfall detachment rate, equation 2, and sediment carrying capacity, equation 4. Nevertheless, the explicit distributed description of hydraulic depth and velocity on the watershed presents unique opportunity to treat rills in detail, as they modify the assumption that hydraulic radius is equal to mean flow depth. Some such methods of treatment have been mentioned previously (*8*).

Experimental Application

Because of the availability of records for both water and sediment production, a 3-acre rangeland watershed in the Lucky Hills area near Tombstone, Arizona (ARS location 63.101) was chosen for experimental comparison. Figure 1 shows the topographic map and the first geometric approximation used by the model. The geometric model preferentially preserves the mean length of overland flow and total area. It could be made more visually similar by division into two or three tandem surface-channel units.

Rainfall accumulation for individual storms was carefully read from 24-hour, 6-inch raingage charts. Rainfall rate is taken by determining the slope of a line of arbitrary time length, whose ends fall on this accumulated rain depth curve. This procedure removes the instantaneous changes in rates resulting from more simple differentiation procedures, and is also in keeping with the response precision of the raingage record. One can choose the amount of averaging by choice of the length of time over which averaging occurs.

Figure 2 illustrates the arrangement of water depth and sediment sampling instrumentation at the pond behind a 1:3 broad-crested weir. About 40 cubic

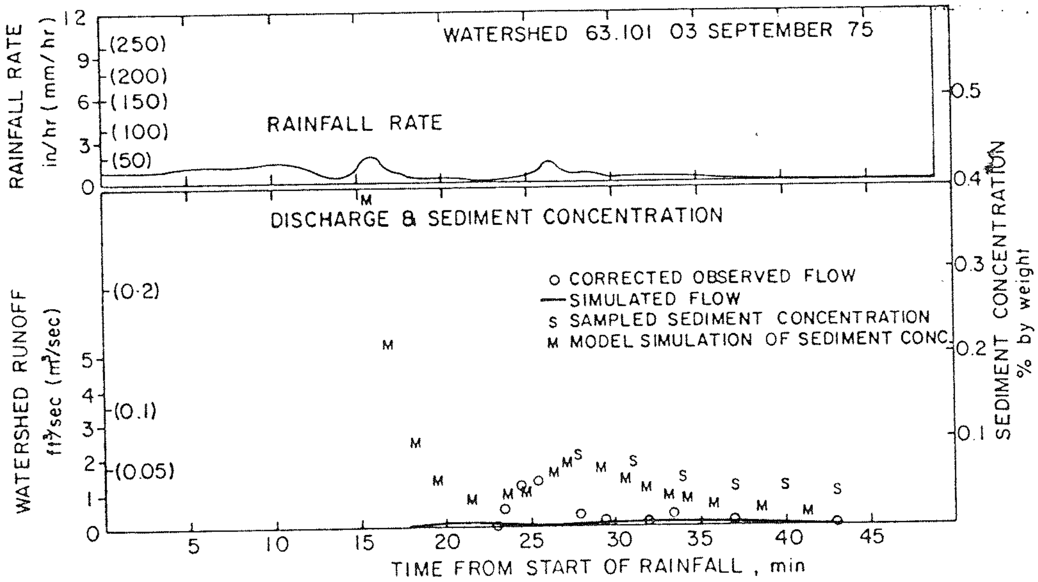

Figure 5. Simulation results for the storm and runoff event of September 3, 1975. This simulation was least successful of the 1975 series modeled by percentage error in peak and volume, but the event also was the lowest in ratio of runoff to rainfall and thus the most sensitive.

feet (1.12 m^3) of runoff must accumulate before the stilling well record begins. Before the weir spills, 146 cubic feet must accumulate. Therefore, the pond record is treated as an input-output-storage system, and the input rate is calculated before it is compared with simulated runoff.

The model was calibrated arbitrarily on the July 17, 1975 event. Infiltration parameters were basically obtained from an infiltrometer run made in 1962 plus numerical simulation, using soil water properties obtained in a 1968 soil survey (3). Hydraulic resistance parameters were adjusted to obtain adequate hydrologic fit, and then the parameters of the sediment detachment and transport equations were adjusted. After calibration, all of the remaining 1975 runoff events were simulated, using these same parameter values, leaving one degree of freedom--the estimated initial soil water saturation at the soil surface.

Discussion of Results

Table 1 and Figures 3 through 6 illustrate typical results of this experimental application of the model. The initial lag of about 40 cubic feet (1.12 m^3) causes a late start and an over-estimation of runoff for almost every event, which is severe for the smaller ones. In events of July 17 and September 13 (not shown) there may be a 1- to 2-minute timing error (assuming the model is accurate) because simulated runoff occurs significantly before the pond could have been filled. Rainfall records were read from a chart where 1 inch (2.54 cm) of depth is 1 inch of chart, and 1 hour is about 0.5 inch (1.2 cm) of chart. Timing accuracy is difficult under these circumstances, even if the runoff and rain charts' clocks corresponded exactly.

Simulated peak runoff rates were within 10 percent of corrected, mea-

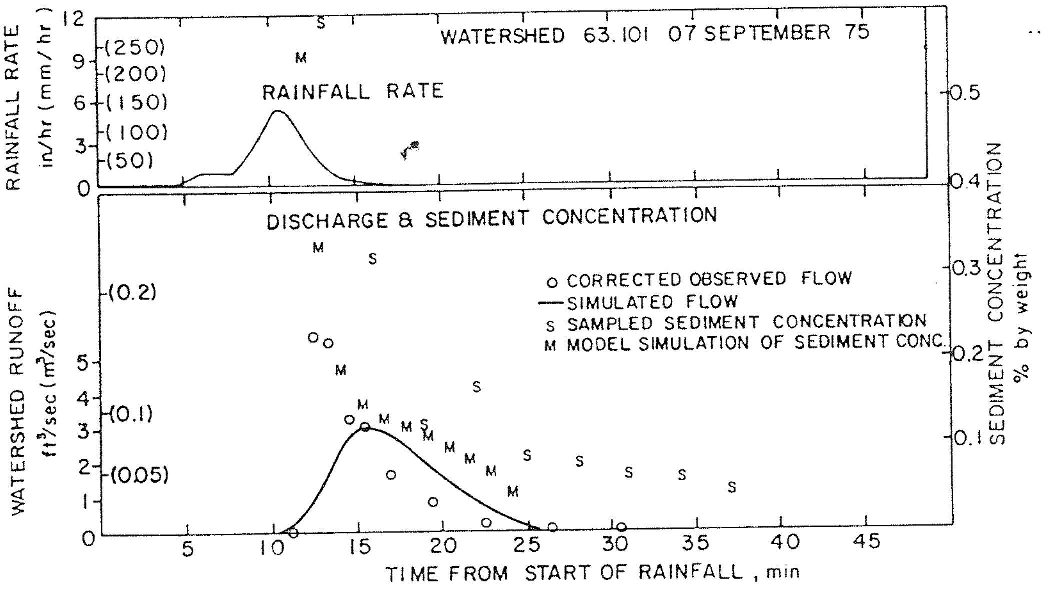

Figure 6. Simulation results for the storm and runoff event of September 7, 1975. The simulated runoff hydrograph indicates the possibility of about a 2-minute error in timing between the raingage and weir pond level recording clocks.

sured peaks for all but the September 3 event (Figure 5) where runoff was less than 10 percent of the rainfall volume, and peak runoff rate was the smallest of the modeled storms. Because this rainfall event and that of July 23 barely filled the pond to the notch of the weir, potential errors in determining pond inflow rates are significant.

Simulated sediment concentrations were generally lower for the later parts of the smaller runoff events, which is consistent with pond storage and deposition. In fact, simulation of the pond as a sediment input-output system revealed that in later parts of all the smaller flow events, sediment was settling in the pond more rapidly than input runoff was supplying sediment.

For larger events, comparison of rainfall records and the simulation indicates that rain drop splash detachment is too large in the model for rainfall peaks later in the storm. This was most apparent in the results in figure 4 for the event of July 17. The major differences between simulated and measured sediment concentration in the runoff correspond directly with the last two peaks in rainfall rate. Further experiments with the rainfall detachment rate, equation 2, with better experimental data, seem needed. This effect may be a time-related exhaustion of initially loosened material, or an underestimate of the effect of depth of water (parameter H in equation 2) on decrease of rainfall splash energy. Foster (1976 personal communication) has also suggested that larger sediment, loosened by enhanced hydraulic detachment, is not reflected in the measured sediment concentration, because of settling in the pond, which does not occur for fines washed off by initial rainfall splash erosion.

The comparison of measured sediment leaving the pond with simulated sediment entering the pond and the survey of pond accumulation show (Table 1) the consistency of model performance and accuracy of prediction of annual sediment production. Especially in view of the measurement errors, the simulation of annual sediment production closely resembles the total value of pond outflow plus pond deposition.

To the extent that the watershed surface shape is faithfully represented, areas of upland erosion and deposition may be mapped by this model (*8*). Since the topographic simplification of this study was designed primarily to reproduce watershed outlet measurements, the erosion and deposition patterns produced are only approximate and are not reported.

Conclusions

This initial evaluation experiment has indicated relatively accurate simulation of the time-distributed output of runoff and sediment from a small upland watershed. My results support the hypotheses that better erosion prediction is related to more accurate hydrologic simulation.

The model used is a scientific, rather than an engineering, tool. Although conceptually more sophisticated than parametric engineering models, the small number of descriptive parameters employed is perhaps comparable with some engineering models. The universal soil loss equation was developed and has been proven as an engineering tool for predicting long-term average sediment yields, primarily from cropland. However, when the universal soil loss equation has been used to predict sediment yield on an event basis, rather large errors have resulted (*6*). For such detailed event or event series simulation, I propose the present model, whose ultimate purpose is to provide a hydrologic model framework with which to evaluate alternate detachment and transport equations in unsteady flow. Expressions for detachment rates other than those used here may prove more accurate, but should be compared using better quality experimental data than presented here.

Further study should include evaluation of the time variation in rain splash detachment, and applicability to fallow field erosion characterized by rill formation. However, any such tests should avoid the data distortion caused by using ponded measuring structures, as indicated by these results. Other sites at Walnut Gulch, Arizona, are now in operation, and use flume structures to directly measure watershed runoff and sample unponded values of total sediment load.

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