#189

GEO BOOKS

EROSION

Research techniques, erodibility and sediment delivery

Edited by Terrence J. Toy

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Research Techniques,

Erodibility and Sediment Delivery

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3. Erosion research and mathematical modeling

Kenneth G. Renard*

ABSTRACT

Recent water quality legislation has accelerated the need for erosion control. Although past efforts have not directly recognized the relationship between hydrologic processes and erosion, future work will undoubtedly combine the hydrologic and erosion models. Because water is the major transporting agent (excluding wind erosion), estimating erosion requires knowing the rates and amounts of water available within a watershed. The availability of watershed models and large storage computers facilitates such efforts.

The Universal Soil Loss Equation, an empirical model developed from extensive data, is used widely for estimating erosion in the United States. It is being modified to extend its applicability and to improve its accuracy in producing estimates. The modifications and combinations of this erosion equation with a hydrologic model are illustrated.

Other available techniques for estimating erosion, like physical component and stochastic models, are discussed with an example of each to illustrate some advantages and disadvantages. The physically-based schemes undoubtedly have the most potential for predicting erosion differences caused by changes in land use. As demands for land intensify, erosion must be minimized, since it often irreversibly reduces the productive capacity of our soil resources.

An example of a model incorporating several of the analytical schemes is presented and is illustrated with some data from the Walnut Gulch Experimental Watershed. A stochastic runoff generating model was used along with an analytical component model of the stream water-sediment transport and a mystery black box model to describe the properties of stream width, depth, and slope, using a stream-order concept.

INTRODUCTION

Recent water quality legislation (e.g., in the USA, PL 92-500, the 1972 Water Quality Improvement Act) has accelerated the

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need for erosion control information. Although past modeling efforts have not always directly recognized the relation between hydrologic processes and erosion, future work will undoubtedly combine the cause and effect in such models. Because water is the major transporting agent (except in those arid areas where wind erosion processes are dominant), estimating erosion requires knowing the intensity of rainfall and the rates and amounts of water available within a watershed. The greater availability of physically based models and the availability of computers with large storage facilitates such efforts.

Several analytical techniques are available for estimating erosion and sediment yield, which will generally involve combinations of the techniques as shown in Figure 6. For example, because of the uncertainties of the physical laws involved, or inadequate data to verify a physically based model, a stochastic model may be used. This type of model follows probabilistic laws with the process developing sequentially in time, unlike purely probabilistic models which are not time dependent. Mystery models (also called 'Magic' or 'Black Box') utilize a given input (e.g., precipitation or runoff) which with a mathematical transformation or function, which may or may not be physically based, produces the output. Finally, the analytical component model uses the physics of soil erosion process(es) and produces the output required. Although this last modeling approach is the most expensive for predictions (because of the more detailed physical modeling, increased computer and field investigation is required), it should provide the most reliable results, especially when management alternatives are involved, and should be the main object of future effort.

Many developments have been made in recent years in simulating the hydrologic cycle, or components of it, on a watershed. Such a rapidly developing field is difficult to keep abreast with and is certainly beyond the scope of a detailed treatment in this paper. More information can be obtained by reading Chow (1964), Amorocho and Hart (1964, Diskin (1970), DeCoursey (1970), Snyder (1970), Woolhiser (1970), Dooge (1973), and Riley and Hawkins (1975). Only recently have researchers begun to couple erosion/sediment transport routines to hydrologic models, but the efforts undoubtedly will become more prevalent in the immediate future.

Figure 7 (from Baver, 1965) illustrates the factors affecting soil erosion by water. The dispersive action and transporting power of water are affected by the dispersive effects of falling raindrops and the amount and velocity of runoff which, in turn, are affected by the resistance of the soil to these factors. The figure summarises the factors narratively, but in modeling efforts a mathematical expression is needed. Kiline and Richardson (1973) stated that sediment discharge by means of overland flow is a function of:

(1) hydraulic properties of flow,
(2) physical properties of soil, and
(3) surface characteristics.

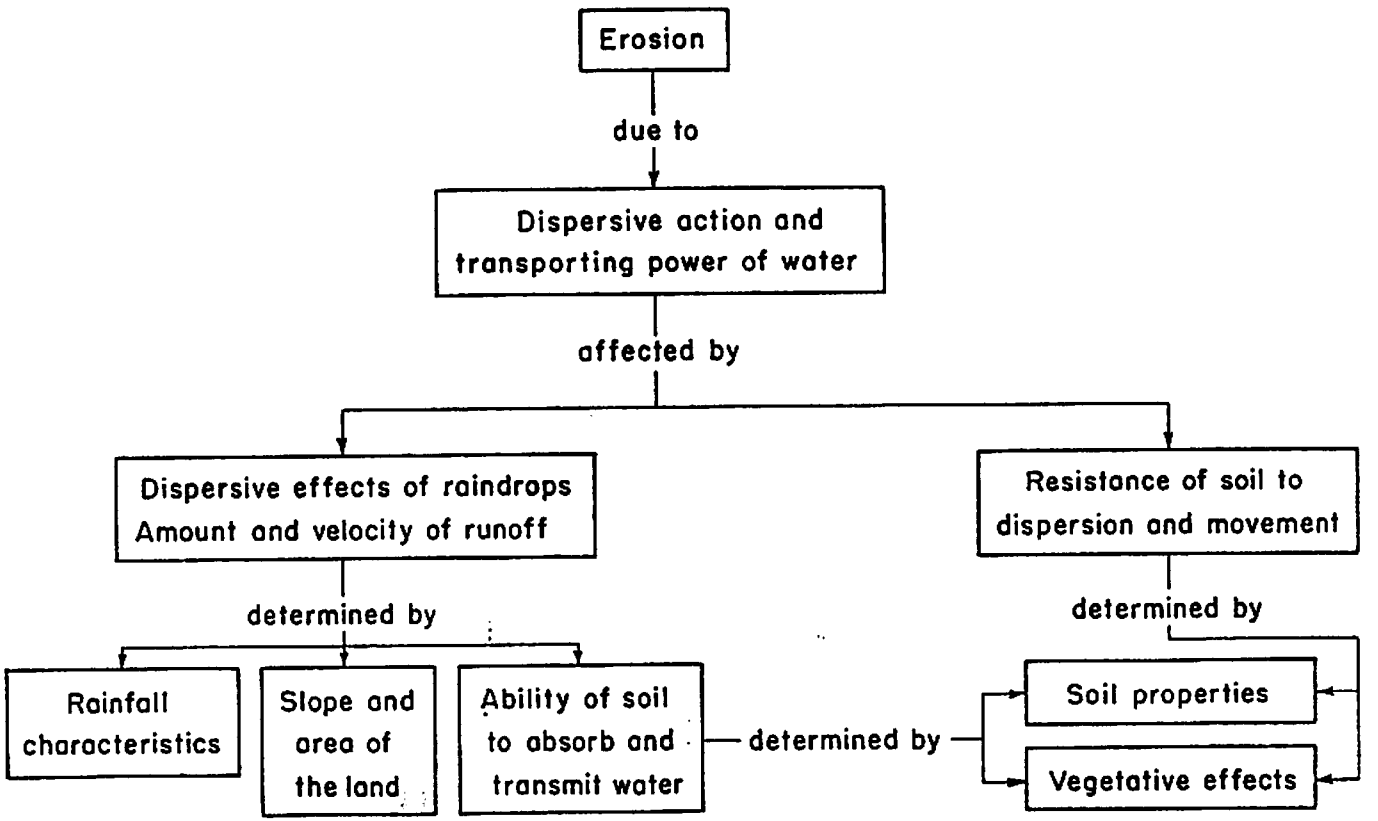

Figure 7. Factors affecting soil erosion by water. (Baver, 1965)

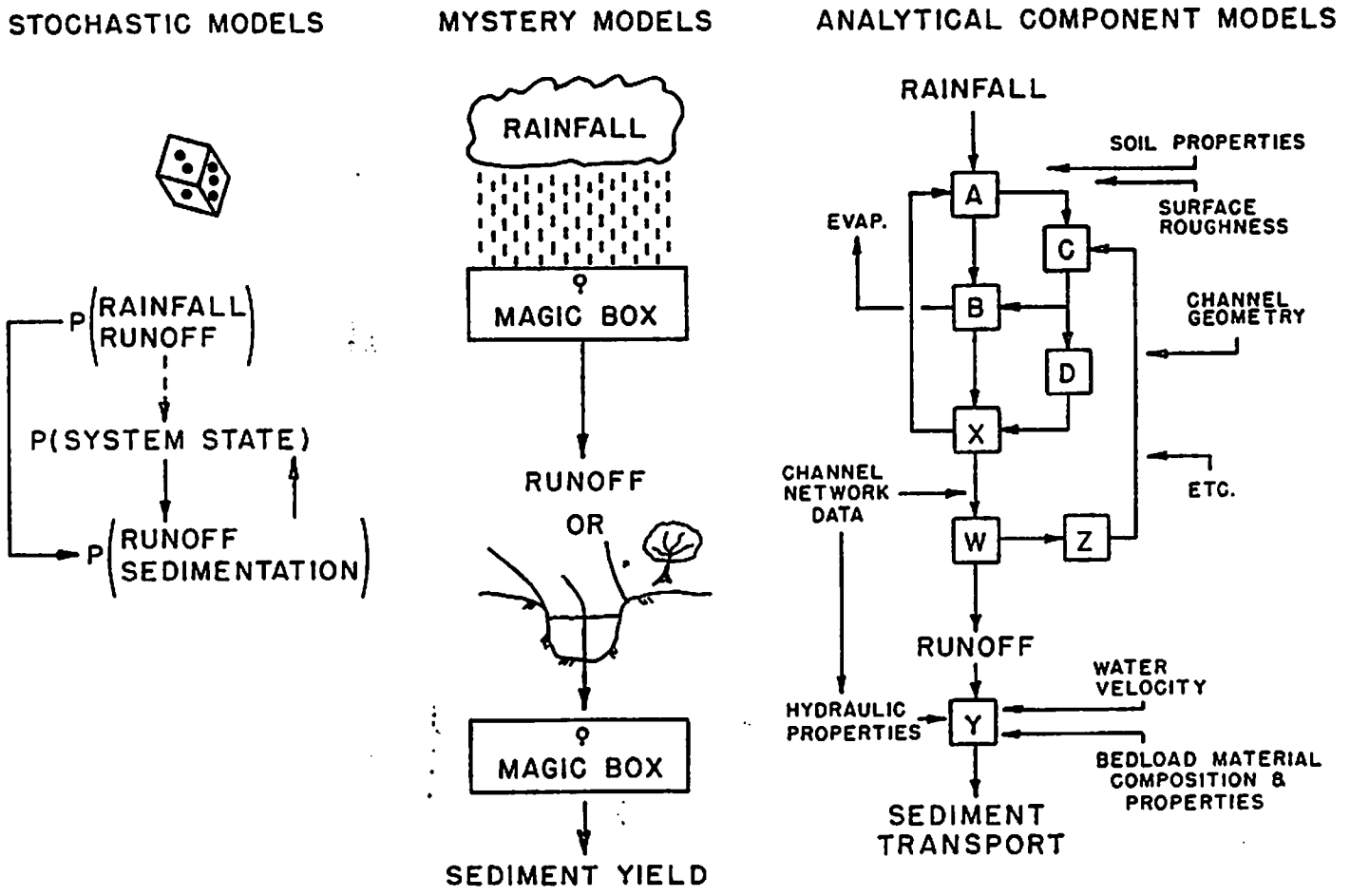

Figure 6. Approaches to sediment modeling from watersheds. (Modified from R.E. Smith, 1973 - unpublished).

In equation form, the variables to be considered are:

$$q_s = \phi\ (u,\ q_o,\ d,\ d_{s0},\ \chi,\ \nu,\ g,\ \rho,\ \rho_s,\ S_0,\ p) \quad (1)$$

where q_s = sediment discharge

u = water velocity

q_o = inflow rate or rainfall excess

d = depth normal to slope

d_{s0} = mean sediment particle size

χ = distance downslope

ν = kinematic viscosity of water

g = acceleration of gravity

ρ = mass density of water

ρ_s = mass density of sediment

S_0 = slope

p = porosity of sediment.

With some manipulation, they showed that the sediment concentration (C_s) could be related to combinations of the variables in Equation 1.

$$C_s = \phi\ (\mathbb{R},\ \mathbb{F},\ S_O,\ P,\ S_f) \quad (2)$$

Thus, sediment concentration is a function of the Reynolds number ($\mathbb{R}$), Froude number ($\mathbb{F}$), slope, porosity, and surface roughness (S_f).

The land phase of the hydrologic-erosion cycle can be divided into several components. The major components might include infiltration, evapotranspiration, groundwater recharge, streamflow routing (overland flow and channel routing), sediment detachment by raindrop impact and by the shear from overland flow, and sediment transport (both in overland flow and rill/channel flow). Each of these components has attracted specialists who have developed mathematical approximations to the processes controlling the component. The development has generally been toward an understanding of the physical laws governing the component and an attempt to make the empirical models approximate more closely the associated physical situation. In such an approach, the watershed to be modeled may be subdivided to reflect the heterogeneity of the area's physiography or may be lumped into a single system to describe the entire area.

COMPONENT MODELING

The component modeling concept can be best illustrated by a conceptual chemical transport model developed by an Agricultural Research Service team. Figure 8 illustrates how a complex watershed shape was transformed into computational units for this hydrologic-sediment-chemical model. Each increment of a watershed was expressed by a series of planes (zones I, II, III, IV). The width and slope of each zone were representative of the prototype watershed. Flow

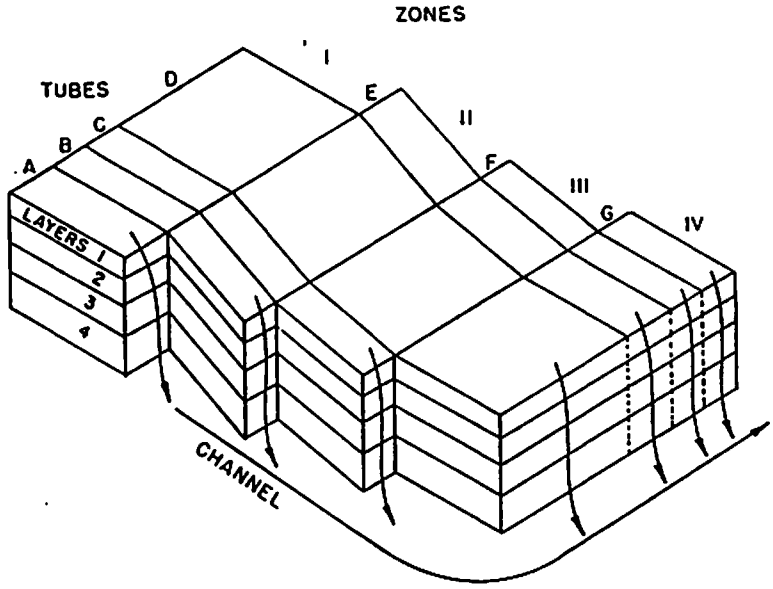

Figure 8. A conceptual watershed transformation into analytic computational units. (Frere, Onstad, and Holtan, 1975)

then goes through tubes (A, B, C, D, E, F, G) and cascades from zone to zone with infiltration persisting while surface water is available. Flow could also directly enter a channel from a tube in any zone (zone I, tube A). Subdivisions can either be added or deleted to simulate the surface of the watershed being modeled.

Frere, Onstad and Holtan (1975), in the erosion portion of the model, utilized Foster's modification of the Universal Soil Loss Equation (USLE) given as:

$$A = EKCPLS \tag{3}$$

where terms (KCPLS) are defined in the USLE and

$$E = (aR + bcQq_p^{1/3}) \tag{4}$$

and where

A = the estimated soil loss
a,b = weighting parameters (a + b = 1)
c = equality coefficient
R = rainfall factor from USLE
Q = runoff volume, and
q_p = peak runoff rate.

The results of their effort were encouraging and indicated that an erosion routine could be successfully included in a hydrologic model.

MYSTERY MODEL

Flaxman (1972) recently presented one example of a Mystery or Black Box model. He used the multiple regression technique on many watersheds in the western United States which led to the following prediction equation:

$$\log(Y + 100) = 6.21301 - 2.19113 \log(X_1 + 100) + 0.06034 \log(X_2 + 100) - 0.01644 \log(X_3 + 100) + 0.04250 \log(X_4 + 100) \quad (5)$$

where

X_1 = precipitation-temperature ratio

X_2 = average watershed slope

X_3 = percent of soil particles coarser than 1 mm in the surface 2 in.

X_4 = soil aggregation index

Y = sediment yield ($AF/mi^2/yr$).

This model has been used widely in the western United States by the Soil Conservation Service, United States Department of Agriculture, and has been observed to correlate quite well with existing data. When the method was compared with data from Walnut Gulch, it fitted the data quite well (Renard and Simanton, 1973). The independent variables used in this model have physical significance, but the equation certainly does not describe the individual processes involved nor is this its intent. Thus, the classification of mystery or magic box model should be evident. Some experience is probably required to adjust variable X_1 for orographic variations in basin and range topography.

STOCHASTIC MODEL

Woolhiser and Todorovic (1971) presented a stochastic model for predicting the sediment yield for an ephemeral stream where the yield was produced by a series of events of relatively short durations. They suggested that sediment yield from a watershed with ephemeral streams may be treated as the sum of a random number of random variables. In this model, the distribution of the sediment yield per event must be obtained empirically, but the sediment-yield counting process can be related to the precipitation counting process by a rainfall-runoff model. They compared their model to data from two small watersheds near Hastings, Nebraska. They also applied the stochastic model of sediment yield to the problem of estimating mean and variance of annual sediment yield when only short concurrent records of sediment yield and runoff are available, which can be supplemented by longer records of precipitation and runoff.

Sakhan, Riley and Renard (1972) developed a simulation model to describe the dynamics of a channel in terms of: (1) two one-dimensional streamflow equations, (2) a one-

dimensional sediment transport equation (for the stream bed), and (3) a stochastic sediment transfer at the stream bed which also included the bed load. This complex model was then solved using a hybrid computer. The model thus postulated illustrates what often happens, i.e., the description of most systems incorporates aspects of various types of modeling schemes.

COMBINATION MODELS

In most models, the investigators resort to using combinations of the techniques shown in Figure 6. Most scientists and engineers recognize that the most realistic way to transfer knowledge from measured to unmeasured watersheds is to use physically-based (component) models. However, they are restricted since some of the processes are so complex, or inadequately understood and documented, that the input (e.g., precipitation) is described stochastically, and the subsequent model portions are described by physically-based components, e.g., the sediment yield work by Renard (1972) and Renard and Laursen (1975). Inadequate data may also be a problem for using physically-based component models where detailed physical data for a prototype is difficult if not impossible to obtain.

The channel profiles in ephemeral streams in the southwestern United States tend to be convex up, because of the transmission losses, or concave up, because of more flow downstream due to tributary inflow. These contrasting profiles partly result from the precipitation patterns. Thus, the spacing of thunderstorms, both temporally and spatially, is important for estimating the sediment yield (sediment transport).

A stochastic ephemeral runoff model (Diskin and Lane, 1972, and Lane and Renard, 1972) was used to generate the tributary inflow, as an alternative to a rainfall-runoff model. The model was based on Walnut Gulch data and generated intermittent and independent runoff events. Two variables used to describe the runoff season were: (1) date at the beginning of the thunderstorm season, and (2) the number of runoff events per season at a watershed outlet. The position of the temporal runoff event within a one-day period and the interval to the next event was described by a random variable (a numerical variable whose specific value cannot be predicted with certainty before an experiment), with the runoff volume also expressed by a random variable. Then, the peak discharge is related to the volume. The random variables were described by statistical distributions which were related to watershed area.

The Laursen transport relation (Laursen, 1958) was used to provide answers to the sediment movement process as an insight to ephemeral stream behavior. For analytic simplification, the stream cross section was assumed rectangular. Although this assumption has limitations, ephemeral streams are often wide and shallow with width-depth ratios greater

than 50. When it is assumed that depth equals the hydraulic radius, the error is less than 5 percent, as long as the width-depth ratio exceeds 15.

For each stream width increment, the water discharge per unit width can be obtained with the Manning equation:

$$q = Vy = \frac{1.49}{n} \; y^{5/3} \; S_0^{1/2} \tag{6}$$

where:

q = discharge per unit width ($L^3/T/L$);
V = average velocity (L/T);
y = depth of flow (L);
S_0 = bed slope (L/L); and
n = Manning coefficient.

The sediment yield for individual flow events can be obtained from the relationship:

$$Q_s = B \int_T q_s dt = B \int_T \frac{\overline{C} q_w}{265} \, dt \tag{7}$$

where:

Q_s = sediment yield
B = stream width
q_s = sediment discharge rate per unit width
q_w = water discharge rate per unit width at time t
T = time of an individual hydrograph
$\overline{C}$ = sediment concentration.

From the Laursen equation

$$\overline{C} = \sum_i \left[P_i \left(\frac{d_i}{y} \right)^{7/6} \left(\frac{\tau_o'}{\tau_c} - 1 \right) f \left(\frac{\sqrt{\tau_o/\rho}}{w} \right) \right] \tag{8}$$

where:

$\overline{C}$ = mean instantaneous total sediment concentration (% by weight)
P_i = bed material fraction of diameter, d_i ($\sum_i P_i = 1.0$)
d_i = diameter of sediment particle
y = depth of flow
τ_o' = boundary shear stress associated with sediment diameter
τ_o = boundary shear or tractive force at the stream bed = $\gamma y S_0$
τ_c = critical tractive force for the beginning of sediment movement
ρ = mass density of water
f = function of the term; and
w = fall velocity of sediment.

To complete the model, expressions were needed for the tributary occurrence in a channel segment, as well as information on tributary characteristics like the bed slope,

channel width, drainage area, and the frequency of tributary intersections. A Horton (1945) and Strahler (1957) stream order concept analysis was completed for some stream segments on Walnut Gulch, and it was observed that the relationships (stream order versus area, width and slope) such as Leopold and Miller (1956) observed could also be determined in Walnut Gulch. The frequency of tributary occurrence by each stream order was then expressed with a geometric distribution function.

This model was then tested with sediment concentration data from Walnut Gulch and some simulations were made (Fig. 9). The upper part of the figure illustrates runoff in 'losing' streams, i.e., where the water yield decreases as watershed area increases.

The water yield values were then used in the Diskin-Lane model (parameters in the model were related to drainage area), and synthetic runoff data for each storm was generated for input to the Manning-Laursen transport routine. Summing the results from equation 7 produced the relationship, shown at the bottom of Figure 9, showing a general decrease in sediment yield as watershed area increased.

Other work has shown (Renard, 1974) that the composition of the bed material is very important in the model's ability to generate reliable data. From observing the ranges of bed material sizes on the 23,000-acre sub-watershed of Walnut Gulch, the range of sediment yield that might be encountered was determined. This range (Fig. 9) is quite large and illustrates that if such a model is widely adopted in the future, information will be required on the temporal and spatial variability of bed material.

The model also indicates what might happen to the sediment yields if the water yield was either increased or decreased. Thus, the symbols + and x show an increase and decrease, respectively, in runoff for a 500-acre watershed and the associated change in sediment yield. To consider that the results are widely transferrable, one must realize that the composition of the stream bed may change which was not considered in constructing the figure. This same model has also been used to generate long sequences of water and sediment yield (Renard and Lane, 1975) with input records from a much shorter duration.

SUMMARY

The modeling schemes available for erosion work, as well as their assets and liabilities, have been treated cursorily. To make erosion-sedimentation estimates, one must consider the costs of the model and its accompanying investigations. Analytical component models should produce the most reliable, although most expensive, simulations. The additional computer costs, as well as field data requirements, can outweigh any savings gained from additional model refinement.

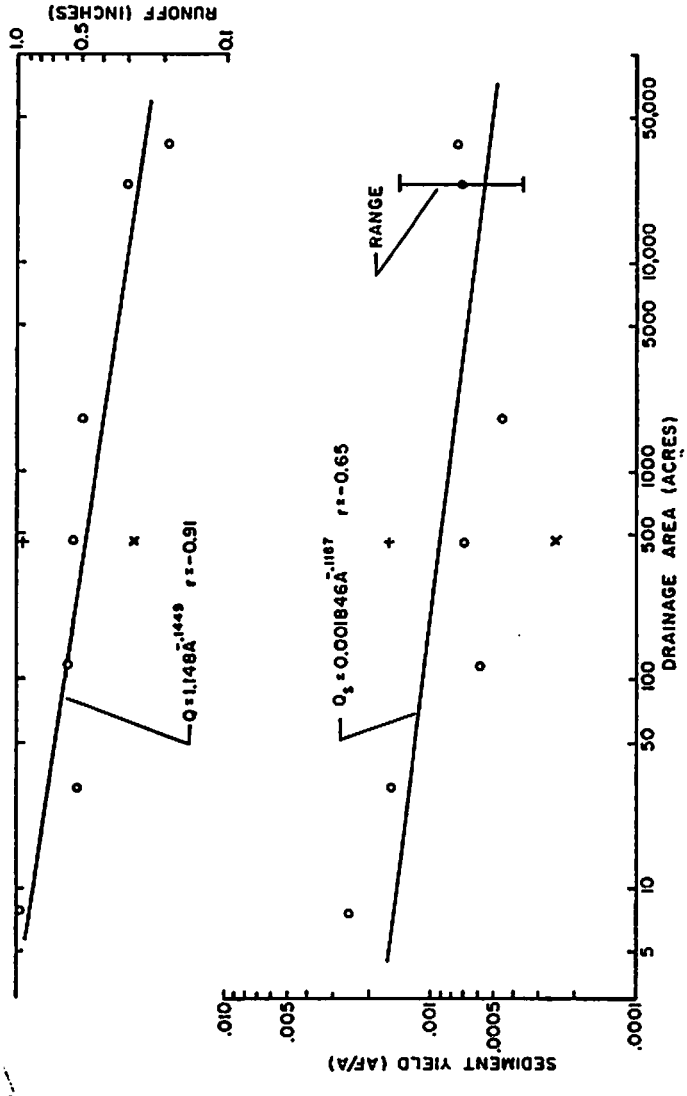

Figure 9. Average annual runoff and sediment yield as a function of drainage area for watersheds in southeastern Arizona, based on Walnut Gulch data and a run-off sediment generation model. (Renard, 1972)

3. Mathematical modeling

Similarly, none of the methods are independent of good field data on erosion-sediment transport rate which is difficult to obtain but essential for model calibration. Developing unattended equipment to collect water-sediment samples at a reasonable cost will greatly assist the modeler.

Mystery models are quite widely available and have been tested over wide ranges of field conditions. However, they are difficult to use if land use changes, and they may not produce realistic estimates for areas outside of that for which they were developed.

Stochastic models work well for estimating erosion-sedimentation because of the complex interactions between hydrologic and erosion processes.

When describing a field situation, as was illustrated with the Walnut Gulch Watershed, combining all modeling approaches may be necessary. This combination approach then allows possible multiple uses for the data, like predicting the effect of changing water yield on sediment yield, as well as the probability of various sediment yields for various watershed sizes.

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