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Sediment problems in the arid and semiarid Southwest

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The aspects of sediment to be dealt with here are mainly those relating to transport in intermittent streams, the preponderant drainage pathway in the Southwest. Sediment, like the runoff that carries it, is greatly affected by the climate and physiography characterizing these arid and semiarid regions of the Southwest.

The dominant characteristic of the climate in this region is a water deficiency or aridness. Basically, aridity involves a comparison between water supply and water need. Numerous investigators have attempted to express the dryness of a region with aridity indexes (*2, 7, 11*). The Meigs system and the UNESCO bioclimatic (*12*) emphasize the importance of aridity seasonal distribution of rainfall and divide a major climatic type into many subtypes. Figure 1 is a map based on the Meigs classification delineating the arid and semiarid zones on the North American continent. Most intermountain areas of the southwestern United States are classified as arid to some extent and, therefore, water deficient. The two-letter and two-digit classification shown delineates the climatic pattern. The first letter classifies the degree of aridity (extremely arid, arid, or semiarid) and the second the season of dominant precipitation. The first digit represents the mean temperature of the coldest month, and the second represents the mean temperature of the warmest month.

Langbein and Schumm (3) showed that erosion can be related in a crude way to the annual precipitation required to produce runoff. They found from an analysis of 94 stations that erosion is maximum in the low precipitation areas (Figure 2). Their work illustrates in a striking way the importance of sedimentation in arid and semiarid regions and the desirability for research in such areas. Sedimentation, including the phases of detachment, transport, and deposition, is critical throughout much of the Southwest, and potential economic benefits from studies to control or reduce it are great.

The rationalization of the Langbein-Schumm results is important in understanding this delicate ecological balance in the arid lands of the Southwest. These lands have sparse vegetation to protect the land surface from the erosive force of the raindrop impact. High-intensity thunderstorms are common throughout the area, and the infrequent but large precipitation excesses exert extreme erosive shear forces on the land surface. Thus, although the annual water yields from arid watersheds are generally low, the extremely high-intensity storms generate high sediment concentrations and yields per unit area.

Runoff volumes differ markedly because of variability in precipitation and topography. The scientist working with sediment data in an area must therefore understand hydrology, soils, and hydraulics. Because of the complex cause-effect interactions involved and the difficulty of measuring and obtaining samples of all variables, statistical principles must be used in analysis rather than physically based prediction schemes. The confidence limits of design considerations are wide, and many questions remain unanswered. Although high-speed computers are making analyses easier and quicker, the same natural and measurement errors and uncertainty and natural variabilities are present, and computer results must be carefully studied for physical and logical realities. The wide variability in sediment sources and transport considerations makes research on sediment problems prohibitive under other than a few combinations of the variables

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producing the cause-effect relationships. Models must be used to transfer results to unmeasured watersheds.

For completeness of discussion, a few words should be said about geologic erosion. The cycle of erosion is a conceptual framework of reference for geomorphology and sediment problems. The concept postulates that the landscape evolves through a series of stages termed "youthful," "mature," and "old age," which follow an initial uplift. Associated throughout these ages is a gradual bevelling of the land surface to a base level in "old age." Thus, younger ages involve greater relief and greater land and stream slopes, which imply the presence of greater potential energy to transport sediments downstream.

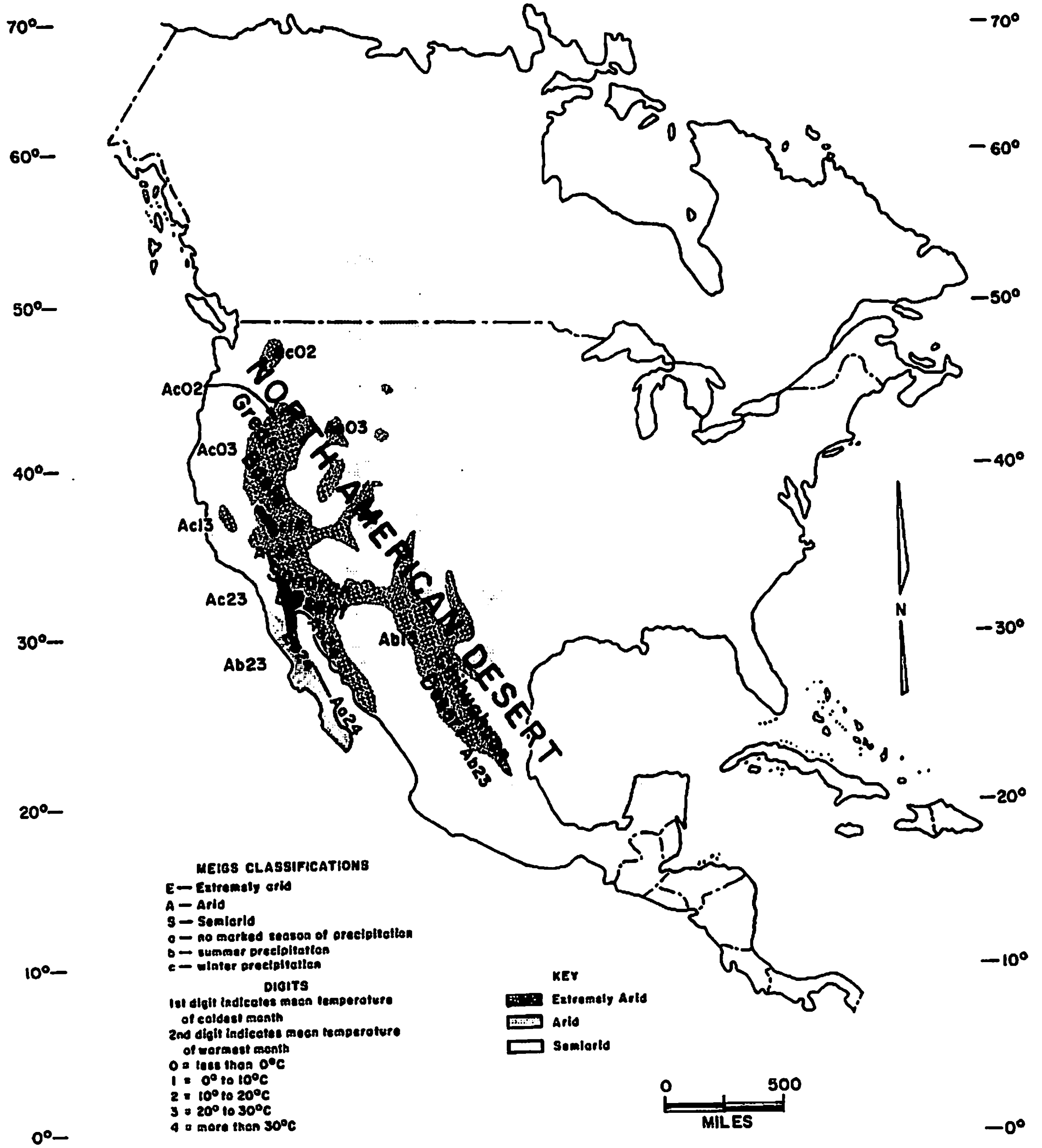

Figure 1. Arid lands of North America from Deserts of the World *(after Meigs) (6).*

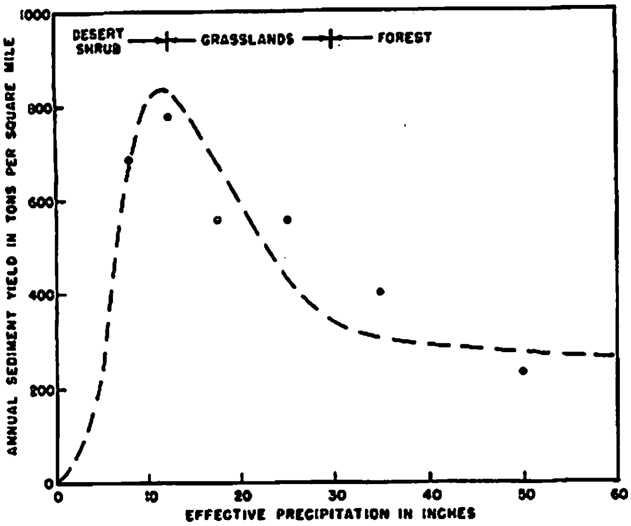

Figure 2. Effect of rainfall variation on sediment yield, determined from records at sediment stations (3).

Although there are numerous problems with such a concept, such as defining the base level or peneplain for large areas or in considering that the river is unlikely to represent a single stage throughout its length, the idea is useful in the intermountain area where most watersheds are relatively more "youthful" than "old age." Therefore, high sediment concentrations would be expected in the stream because energy is readily available to move the sediment, given the same geologic material, plant cover, rainfall depths, and distributions, etc.

Sediment transport provides the link between erosion and deposition. Much research has been devoted to this facet of sedimentation, but, unfortunately, many questions remain. A major hurdle to significant advancement in this facet involves field measurement. Sampling techniques being used to obtain sediment concentrations have remained essentially unchanged for several decades. Usually, a sampler is lowered into a moving stream to remove an aliquot of the water-sediment mixture. Such devices do not sample the entire flow depth, and they must be moved across the flow section to integrate the total discharge. When the flow depth is rapidly changing, as occurs in many ephemeral streams, it is often possible to sample only at one cross section and assume it is indicative of the entire flow section. Appreciable errors can be produced in such situations because the section sampled may differ significantly from the mean. However, as the roughness, porosity, and slope of the stream increase, better mixing should be expected and additional reliance placed on the samples for a single cross section.

Runoff Variability

The movement of water-sediment mixtures in alluvial channels is probably one of the least understood elements in water resources development planning. The streambed, where most of the energy is dissipated, is constantly changing form, and the flow in the channel is locally unsteady and nonuniform, with the departures varying widely from the steady or uniform states. Bed deformation is accomplished by the movement of many sediment grains. Because the grains must move with the stream current in a general direction downstream, bed deformation results in a sediment transport by the flow. Given a water and sediment discharge, the width, depth, velocity, and microslope of a stream result from mutual adjustments within limits not yet acceptably defined.

Runoff in most ephemeral streams is of short duration and follows closely the storm producing it. Generally, the channels are dry and runoff from each event traverses varying distances of the dry streambed, depending on the storm position in a watershed. Ephemeral streams in most of the intermountainous west are characterized by coarse alluvium beds with very high water intake rates. The water table is generally so deep that the coarse alluvium beneath the bed does not become saturated. The channel alluvium is analogous to a leaky bath tub with a void volume far greater than the runoff volumes from any single storm. Thus, infiltration into the streambed continues at a high rate throughout a runoff event, with the loss rate decreasing as the alluvium voids become filled.

Two runoff-producing storm types differing in their areal extent, one in the summer and the other in the winter, add further to the complex stream behavior. Winter storms covering wide areas produce varying amounts of rain or snow at low intensities. Such storms may produce runoff from an entire watershed or, when orographic influences are significant, rain may fall at lower elevations and snow at higher elevations. Temperatures during and after "winter" storms add to the extreme variability in runoff distribution.

Summer thunderstorms are a major runoff source for small watersheds, particularly in the southwestern United States. Again, the variability of rainfall in time and space within a watershed is so great that an individual storm generally produces runoff from only part of the area, or from different subwatersheds at widely different times, or both. Because of the streambed infiltration, runoff decreases significantly as it travels downstream for both individual storms and the annual total. Osborn (*8*) described thunderstorm precipitation characteristics and showed how the runoff might vary as a result of this precipitation variability.

Stream Behavior and Sediment Transport

The profile of a perennial stream is concave-up because, although both the discharge (Q) and the sediment load (Q_s) increase downstream, very little change is required in velocity and, therefore, the slope decreases. Several phenomena result from these conditions:

First, the flow depth increases, and even when the velocity increases to maintain the same particle shear, less slope is required; second, the discharge is less variable and seldom approaches the critical conditions for movement in the lower reaches; and, third, the greater depth results in less relative roughness and, therefore, less resistance and a lesser slope.

In an ephemeral stream in thunderstorm country the flow conditions are quite different. A flow in the upper reaches can disappear before reaching the watershed outlet. If these were the only flows, the equilibrium profile would be concave-down, as less and less water would require a greater and greater slope to be able to move the sediment load supplied from upstream. Actually there would not be an equilibrium unless at the downstream end there was a bottomless pit at the end of the vertical overfall. The development of concave-down profile is the tendency in any individual flood in an ephemeral stream with streambed infiltration. The flow and sediment load originate in a limited area, and downstream the discharge decreases and the sediment deposits. If the infiltration is constant per lineal foot of stream, the deposition rate increases, especially as conditions approach that critical for sediment movement. Coarse particles stop moving before fine particles, so the downstream tip of the deposit is the finest fraction of the load.

All storms do not occur in the headwater of a watershed. Generally, the thunderstorms are distributed randomly over the watershed. Overall sediment movement tends to increase in the downstream direction because more flows are encountered at any point in lower channel reaches. This is so, in part, because of the additional runoff arriving from upstream storms. The lower channel reach must move the sediment load coming in from the watershed with its "local" storms as well as the load supplied in the main channel from the upper watershed reaches.

Thus, there are two tendencies apparent in the ephemeral stream where there was only one in the perennial stream; to be concave-down because of the discharge loss through the dry bed, and to be concave-up because there is more flow downstream than upstream. The net effect may be almost balanced in any given watershed and thereby produce an apparently constant slope for great distances.

The slope of a stream is dictated by the necessity for the flow to attain a velocity sufficient to move the sediment load supplied and to overcome the flow resistance. The total resistance to the flow is the integral of the pressure distribution and shear distribution on the boundaries of bed and bank--resolved in the direction of the flow. The pressure distribution over the dunes in the bed and over rock outcrops and bank discontinuities is very important in determining the slope, but unless the bed goes flat at a high velocity, the pressures (as a first approximation) will be directly proportional to the square of the velocity.

If there were no sediment load and if the bed were inerodible, the depth and velocity would adjust for any flow so that the resolved pressure and shear distribution equalled the weight component of the flow "sliding down" the slope. However, the sediment load requires that there be some velocity to move the particles on the bed and even to "cast" them into the flow to be transported in suspension. The greater the sediment load, the greater the particle shear, velocity, and slope required. Larger sediment sizes also require greater particle shear, velocity, and slope.

For conditions near the critical for movement, a small increase in discharge velocity causes a large relative increase in sediment carrying capacity. Although velocities and sediment loads are high in desert streams, as the flow sinks into the bed the critical velocities are finally reached and movement of appropriate size classes cease. At higher discharges and velocities, this same change in velocity results in a greater change in sediment transporting capacity. This is because the particle shear increases as the square of the velocity, and the capacity for transport increases at least as the square of the particle shear.

Width is a delicate stream parameter, depending on the resistivity of the bank material and the shear on the banks, which, in turn, depends on the discharge, sediment load, and resistance to flow. Consider what would happen if the sediment load of a stream reach increased for the same discharge. The velocity would have to increase to increase the capacity for transport. This would also increase the shear on the bank. Consequently, the stream banks would erode, and the stream would become wider, the depth would decrease if the velocity were the same, and the particle shear would become greater. Therefore, there should be some width, depth, velocity (and slope) combination that would satisfy both the load and bank requirements.

The depth variable is also dependent on the other stream variables similar to the discussion for stream width. Depth affects particle shear slightly and may affect absolute dune size. Otherwise, depth combines with width to determine the cross-sectional area and thereby velocity and sediment transport capacity. However, the causal relation is the other way. The sediment load requires a particle shear, which is largely determined by the velocity, which then causes the bank shear, which determines the width, which, combined with the depth, gives the velocity. It is a circular relationship, but clearly the depth happens as the result of other more determining factors.

The watershed vegetation, especially the grass and the "riprap"-equivalent, armor coating of small and large pebbles and rocks on the hillslopes, can determine, in large measure, the sediment load delivered to the stream. Vegeta-

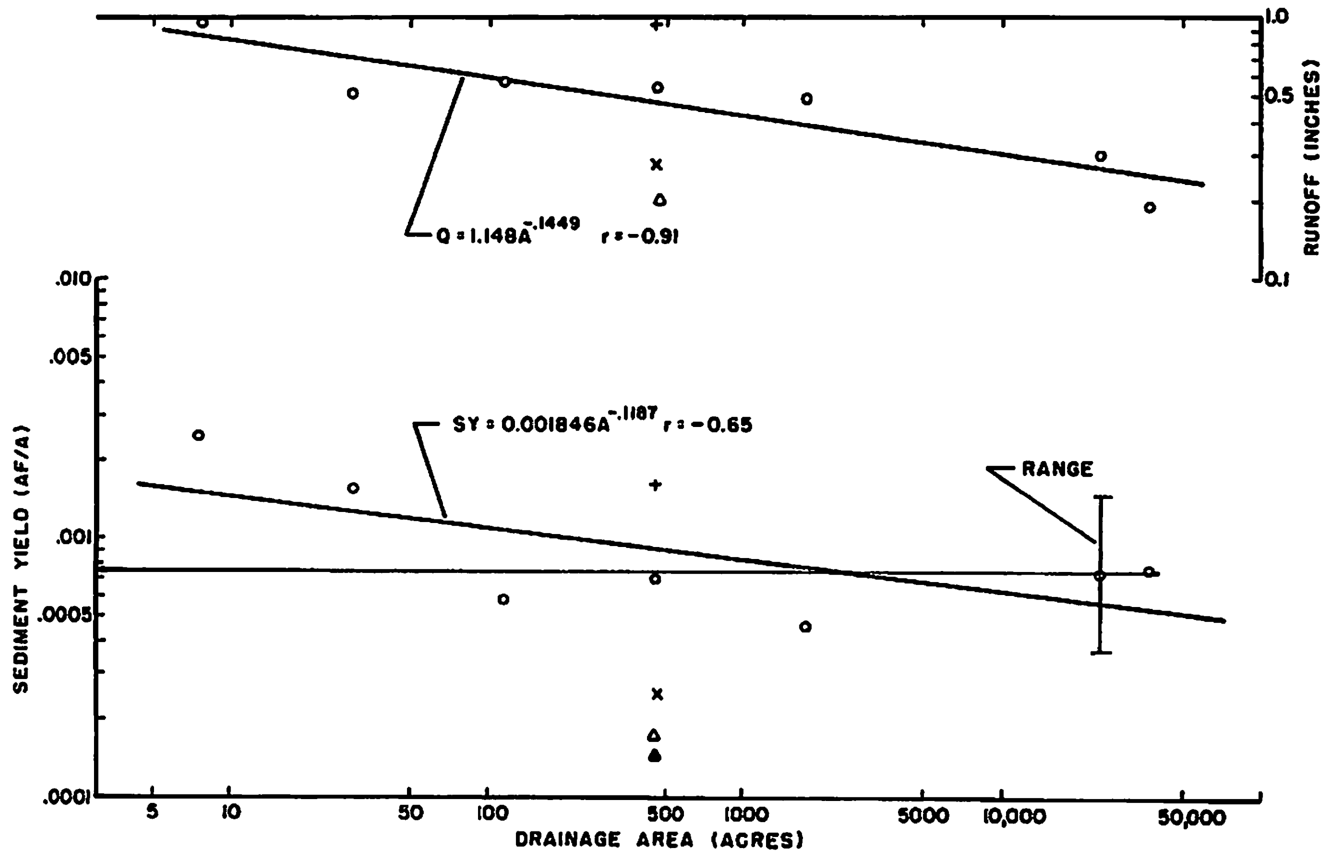

Figure 3. Average annual runoff and sediment yield as a function of drainage area for watersheds in southeastern Arizona, based on Walnut Gulch data and a runoff-sediment generation model.

tion may affect the opportunity for the raindrop impact to dislodge particles and also affect the overland flow velocity (and sediment transporting capacity).

The sediment discharge of the stream will not be overwhelmingly affected by the sediment load delivered--at least not immediately. Although there may be a deficiency of fine particles and, therefore, a lesser sediment discharge if the overland flow were prevented somehow from delivering the usual sediment load, the stream characteristics would be the same as before. The velocity, depth, width, particle shear, and sediment-transporting capacity would be as before and as determined by the channel. The sediment load not supplied by the overland flow would be picked up from the bed (and banks) as usual. Not until the degradation changes the slope, and thereby the velocity, and thus the sediment-transporting capacity, will the sediment discharge, especially of the coarser material, be drastically reduced. The same kind of argument holds for an increase in sediment supplied to the stream system, except that aggradation building up the slope will result in the bed level rising to the adjacent ground level.

Deposition

Deposition also is an important part of the sedimentation process and causes serious economic losses throughout much of the intermountain western United States. For example, necessary sediment storage pools behind irrigation and flood control reservoirs both add to the cost and destroy the esthetic value of the reservoir for recreation. Backwater conditions above reservoirs often lead to deposition in the approach channel, which may increase flooding because of decreased channel capacity and may increase water losses because of increased wetted perimeter in an area already suffering from water deficiencies.

Deposition in irrigation canals or in irrigated fields may also result in economic loss. Examples of such problems are almost limitless.

Lustig (5) concluded: "There is a great deficiency of information on basic climate, geomorphic and hydrologic data, in addition to a lack of adequate maps of several kinds. Because of these deficiencies a legion of unsolved problems exists. ....We need more data than currently exist on processes and rates of processes, on the relative importance of wind and water, on the magnitude and frequency of winds, precipitation, and runoff and on the precise relationships between landforms and climatic and geologic factors."

Although the discussion to this point sounds discouraging, hopeful possibilities can be pointed out. Coupling sediment production and transport to analytical watershed (hydrologic) models should produce worthwhile results in the near future.

An Analytical Sediment-Yield Model

I (*10*) recently coupled a sediment transport relationship to a stochastic runoff model and tested it on data from the Walnut Gulch Experimental Watershed (*9*) in southeastern Arizona. The runoff-sediment transport model used the Diskin and Lane (*1*) stochastic runoff generating model with the Manning open channel flow relation and the Laursen (*4*) sediment transport relation. The work showed that although about 3 feet of water were lost per unit area of channel wetted on the lower 6.8 miles the Walnut Gulch stream, the sediment transport was very near equilibrium to maintain the slope and width presently encountered. The model, which is very sensitive to the bed material mean size as well as the total size distribution, predicts decreasing sediment yield per unit watershed area as shown in figure 3. The figure represents averages based on 10 years of synthetic data. The actual computations in the model are performed on an individual storm basis and thereby preserve the nonlinearities of the water discharge concentration relation. The model was tested with suspended sediment sample data on two watersheds at Walnut Gulch. All runoff data for this conceptual scheme would be produced from summer air-mass thunderstorm.

The instantaneous water discharge versus sediment concentration relationship at the outlet of Walnut Gulch is shown in figure 4. A wide scatter is indicated by the sediment sampling program at this station and may depict the dynamic behavior of such streams responding to the variable hydrologic conditions as well as to sampling errors. Figure 5 shows how the bed material composition varies at the sediment sampling site after each runoff event. The samples have been observed to fit a log normal distribution, which simplifies their quantification. Figure 5 shows that the material in the bed available for transport varies widely from flow to flow, probably in some as yet undefined relation to the area within the watershed producing the runoff.

Figure 4 illustrates the effect of changing

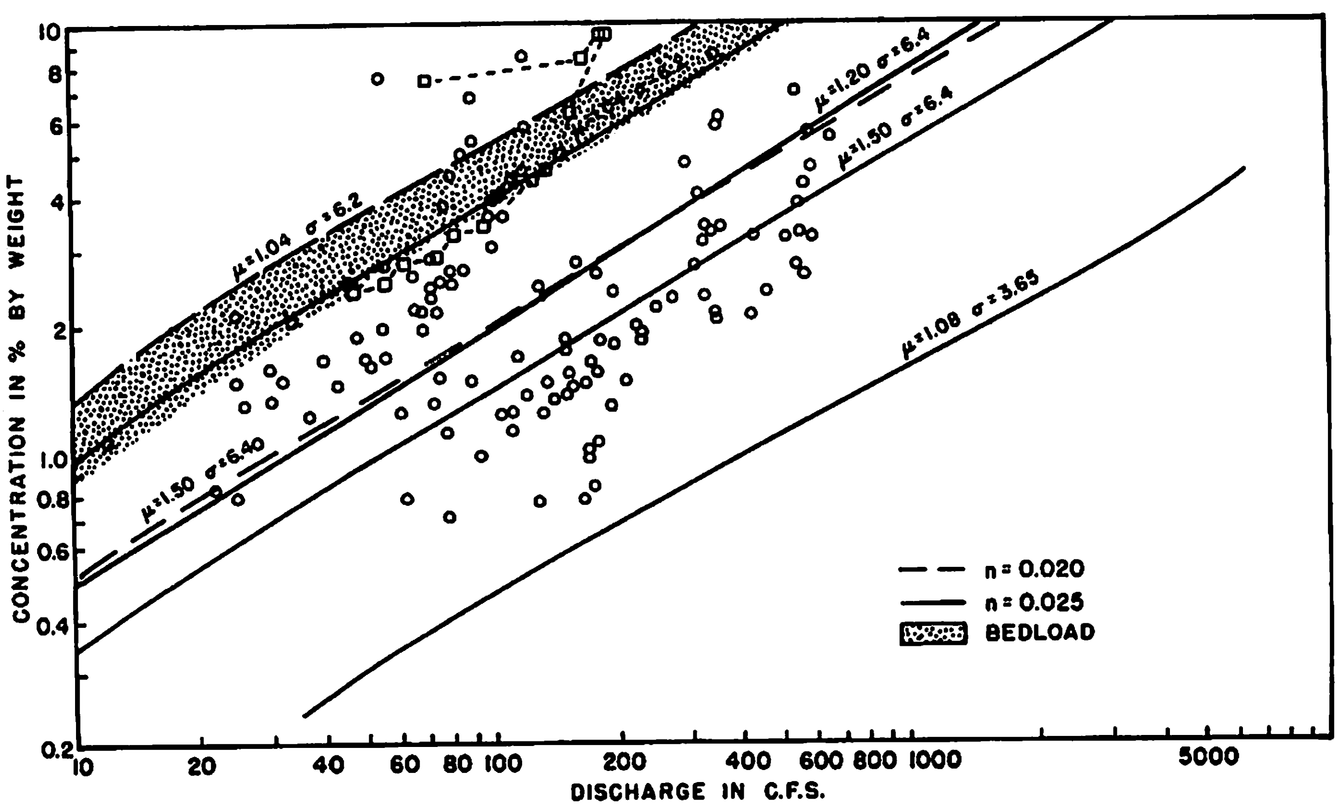

Figure 4. Sediment concentration versus water discharge at flume 1, Walnut Gulch. Circles are instantaneous values obtained by sampling in 1970, and squares connected by a dashed line represent the typical pattern associated with an individual runoff event. Solid and dashed lines are predicted values using the Laursen transport relation for various size distributions given by the mean and standard deviation shown.

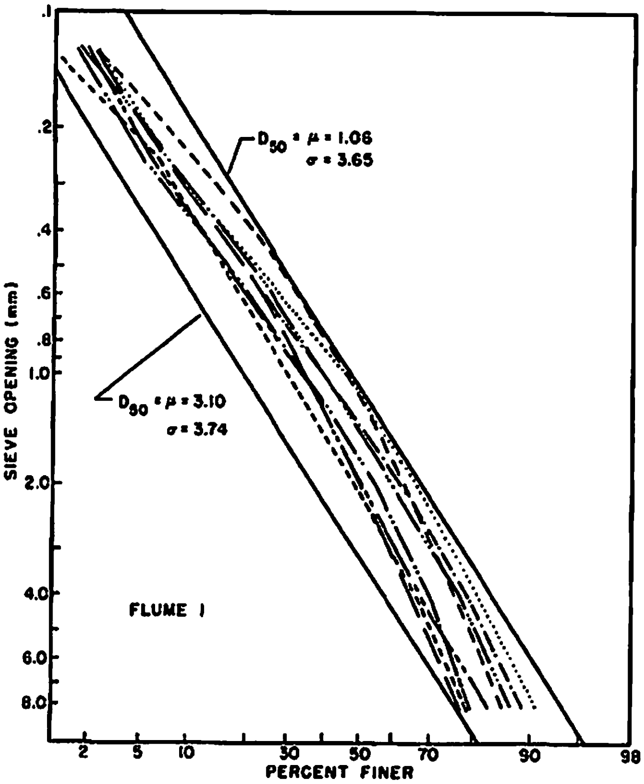

Figure 5. Bed material size distribution variation above flume 1 during 1970 summer runoff season.

the roughness (Manning n value) in the model as well as the sediment size distribution of the bed material. Reducing the roughness from 0.025 to 0.020 in the model predicted about the same concentration change as decreasing the mean size from 1.50 millimeters to 1.20 mm while keeping the standard deviation constant. Figure 4 further illustrates the magnitude of the bedload portion in the concentration relation. The shaded portion in the figure shows the bedload concentration (that sediment moving in close contact with the streambed) to be about equal to changing the roughness from 0.020 to 0.025 for the 1.04-mm mean grain size (*u*) and 6.2-mm standard deviation (*n*). The predicted lines pretty well encompass the sampling points, with the exception of a few points in the upper left. These high values are probably associated with irregularities in the cross section, which was described analytically as rectangular. At low discharge the flow seldom covers the entire bottom width, and, therefore, the particle shear in the real world is probably higher than the predicted value.

Variability, such as that explained in figures 4 and 5, was used in the runoff-sediment generating model for a 23,000-acre watershed to produce the sediment discharge range shown for the lower line in figure 3.

It is apparent that sediment yield is sensitive to runoff variations. To illustrate the effect, the bed material sizes were kept constant and the generated runoff events both increased and decreased from the values shown for a 450-acre watershed in the relationship of figure 3. The sediment yield variability corresponding to the runoff variability produced is appreciable. To further illustrate the model's sensitivity for bed material sediment-size distributions, the mean grain size for the open triangle symbol in figure 3 for watershed size was increased from 1.40 mm to 1.54 mm with the sediment yield reduction as shown. Under most conditions, the sediment transport probably adjusts in some selective process with particle shear changes associated with the runoff variability. The composition at any time, therefore, undoubtedly is changing in response to the rate at which the material is being supplied from sediment sources during various hydrologic events.

Conclusions

Sediment problems in the southwestern United States are primarily related to the climatic and physiographic variability of the region and increasingly to the land use in the region. Quantification of such variability is a gargantuan task, with the solution rather unwieldy in an analytic sense. The Soil Conservation Service has recognized this need and emphatically requested additional effort in the Agricultural Research Service. If present investigation levels are not increased, certainly the problem will plague design people ad infinitum because increasing activity in the region (in the form of land demand) will create new problems faster than existing ones are solved.

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