

Bed Material Size Changes and Sediment Transport

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Kenneth G. Renard

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SEDIMENT transport rates and sediment yields are generally integral facets of water resource projects. In many ephemeral streams, design information to provide for sediment transport or storage is essentially nonexistent. This paper presents a method for estimating sediment design information and illustrates the importance of variations in streambed composition on sediment transport.

Size distributions and settling velocities of sediments encountered in streambeds vary widely. Thus, the fluvial behavior of sediment will depend on the spread of sediment sizes, in addition to mean size. In natural streams, complications arise in describing the sediments available for transport, because grain size varies from place to place and between bed and bank. Since rivers or streams are constantly sorting the sediment load, obtaining representative samples of the material available for transport is difficult during periods with or without flow.

In the highly influent stream channels, like these encountered in ephemeral streams of the Southwestern United States, sediment often moves in a stepwise manner because of transmission losses. Water from storms originating in the upper reaches of a watershed is often completely absorbed in the channel before reaching the outlet. Thus, the water absorbed in the streambed reduces the ability of the stream to transport the sediment removed from the land surface or from the channel itself. The sediment deposited on the streambed is later picked up by flow from subsequent local storms combined with upstream storms (also by runoff from unusually large storms) and moved until the water is again lost or until it

reaches a major reservoir where the sediment is deposited. Thus, the transport of a sediment particle is complicated by flow sequencing.

The dynamic behavior of alluvial streams in moving water-sediment mixtures is an extremely difficult problem in water resource development, because most of the energy dissipated at the streambed produces constantly changing bed form. The flow in the channel may be locally unsteady, with wide departures from uniform states. Bed deformation occurs from the movement of many sediment grains and results in the sediment transport by the flowing water. Given a water discharge and a sediment load, Maddock (1969) noted that the width, depth, velocity, and slope of a stream must be the result of mutual adjustments within a set of limits not yet defined in an acceptable manner. He further says:

The movement of sediment cannot be described by a simple function and the behavior of a load of a mixture of sand sizes is different from that for a load of uniform-sized sediment. There is considerably more uncertainty about pertinent relations when mixtures of sand sizes are involved because of the difference between the sediment sizes comprising the bed compared to the sediment in motion.

Investigations of sediment transport have often been confined to laboratory flumes where the availability of sediment is unlimited, depth and width are restricted, and sand size is uniform or sizes are uniformly distributed. Unfortunately, field conditions generally are not homogeneous and the sediment bed sizes vary widely. Thus, in many flow situations, the sediment sizes in the bed are quite different from those in transport. Generally, the bed contains more coarse sediment than does the material being transported.

The stream sediment load may be determined by the surface characteristics of the watershed and the intensity and duration of the storm causing the

flood. Before each runoff event, the surface usually has a certain amount of loose material that can be eroded and easily moved. Intense, short-duration storms bring into the stream system the most sediment for any total volume of flow.

The vegetation, especially grass, and the "riprap" armor coating of small and large pebbles and rocks on the hillslopes can also influence the sediment load delivered to the streams. Vegetation may prevent the raindrop impact from dislodging particles and also lower the velocity (and sediment-transporting capacity) of the overland flow.

The sediment discharge of the stream will not be immediately affected by the sediment load delivered. Although a deficiency of fine particles might exist and, therefore, sediment discharge be less if the overland flow were prevented somehow from delivering the usual sediment load, the stream characteristics would remain the same. The velocity, depth, width, particle shear, and sediment-transporting capacity still would be determined by the channel. The sediment load (other than that supplied by the overland flow) would be picked up from the bed (and banks) as usual. Not until the degradation changed the slope, and thus the velocity and sediment-transporting capacity, would the sediment discharge, especially of the coarser material, be drastically reduced. The same principle holds for an increase in sediment supplied to the stream system, except that aggradation will cause the bed level to rise to the level of the adjacent ground.

An additional problem in predicting ephemeral channel behavior is the inconsistent roughness across a particular section. During shallow runoff events, the bed may consist of a combination of dunes, antidunes, and flat bed for an individual cross section. Such roughness changes across the channel can result in marked changes in sediment discharge. Furthermore, the roughness changes across a channel vary during a runoff event and are often unique to that event.

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The author is: KENNETH G. RENARD, Research Leader, Southwest Watershed Research Center, Tucson, Ariz.

Data from the Walnut Gulch Watershed are used to illustrate sediment transport problems in ephemeral streams and to verify the conceptual model used to describe sediment transport with varying streambed material.

WATERSHED DESCRIPTION

Walnut Gulch, an ephemeral stream discharging into the San Pedro River in southeastern Arizona, drains a 58-square-mile watershed representative of much of the mixed brush-grass rangeland in southeastern Arizona and southwestern New Mexico. The watershed surface geology indicates an alluvial-filled area between igneous intrusive and sedimentary pockets. The lower two-thirds of the watershed is brush dominated and grazed year round, with very limited cultivation near the city of Tombstone. The watershed ranges in elevation from 4,000 ft at the outlet to slightly over 6,000 ft at the highest point in the Little Dragoon Mountains. Although some urban runoff occurs from the city of Tombstone, most runoff originates from the gently rolling low hills which form the natural grazed rangeland.

An intensive network of precipitation gages are operated to estimate inputs to the Walnut Gulch Watershed. The current network on approximately a 0.9-mile grid allows temporal and spatial quantification of the summer monsoon thunderstorms, which produce essentially all of the runoff. The mean annual rainfall at Tombstone (records from 1897) is 14 in. Rainfall is divided between a summer "monsoon" season, with thunderstorm precipitation producing about two-thirds of the annual total, and a winter season with frontal storms of long-duration and low-intensity.

Runoff from Walnut Gulch is measured with supercritical flow concrete flume-weirs (Gwinn 1970) designed expressly to measure heavily sediment-laden streams. From a hydraulic standpoint, the flume-weirs act similar to many geologic channel controls because they constrict channel width and control the channel elevation.

Suspended sediment samples are collected at two runoff measuring sites on the main channel of Walnut Gulch. At low discharges, depth-integrated samples are obtained by wading with a US D-48 hand sampler. During higher discharges, a US P-61 sampler is lowered from a cableway located 100 ft upstream from the runoff station. Because of the rapidly changing flow depths, samples from

the cableway are generally limited to a single central (or main flow) location in the flow cross section.

The sediment data collected at the outlet of Walnut Gulch show a tremendous scatter on a graph of concentration versus instantaneous water discharge. No significant correlation exists between the two variables when all data for a given year are lumped into one population. The data from an individual flow clarify the confusion, revealing a somewhat consistent pattern related to a hydrograph. Sediment concentration remains essentially constant on the rising limb of a hydrograph and decreases with the hydrograph recession. Thus, in the log-log graph usually used to develop sediment rating curves, the data appear as a series of side-by-side or superimposed 7's with the top of the 7 representing the concentration during the hydrograph rise (Renard 1972a), i.e., the concentration on the hydrograph rise is nearly constant and independent of the discharge.

One possible explanation for these concentration-discharge relations is that each runoff event is usually independent of the precipitation that caused previous flows, because the channel normally is dry between events. The channel bed, however, is influenced by sediment left by the preceding flow and the runoff source within the watershed. These factors may determine the bed material available for transport, as well as the bed geometry. Ephemeral stream flows in such areas normally lose water to the bed, and have lower potentials to move sediment because of these losses. The last material deposited on the bed during a flow recession is the finest material, which in turn is the first material picked up during the rising portion of the next flow. As the water discharge increases, the depth and bed shear increase, and coarser material is, therefore, suspended by turbulence associated with the hydrograph rise.

Although these phenomena are not included in commonly used sediment transport formulae, and the importance of such complete description may not be relevant for sediment yield, previous work (Renard 1972a) has shown that a combination of the Laursen (1958) sediment transport relation and the Manning equation provide many answers to sediment movement in ephemeral streams. The model developed does not describe all the observed flow intricacies, but lends insight to the overall stream behavior.

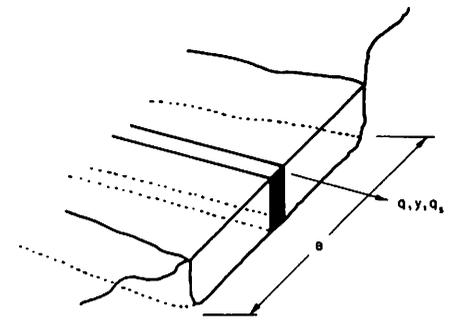


FIG. 1 Sketch of a typical channel segment showing the water discharge (q), depth (y), and sediment discharge (q_s) per unit stream width.

MANNING-LAURSEN CONCEPTUAL MODEL

Stream width, a sensitive parameter in stream behavior, depends upon the ability of the bank material to resist shear, which in turn depends upon the discharge, sediment load, and flow resistance. For example, if the sediment load of a stream reach increased for the same discharge, velocity would have to increase before the transport capacity could increase. A velocity increase would increase the shear on the bank, which in turn would widen the stream. At the same time, the depth would decrease if the velocity were the same and particle shear would increase. Therefore, some width, depth, and velocity (and slope) combination should satisfy both the load and bank requirements.

For wide shallow channels, such as are characteristic of many ephemeral streams in the Southwestern United States, where the channel traverses alluvial fill, the flow may be insensitive to bank conditions. For width-depth ratios greater than 25, the error involved in assuming that the hydraulic radius equals the flow depth is less than 5 percent. Thus, an important simplification can be made for routing flows by performing the hydraulic computations per unit stream width. Schematically, an increment of stream is shown in Fig. 1.

The basic equations used in the conceptual model are the Manning equation and the Laursen sediment transport relation. For the conceptual stream (Fig. 1), equations are:

$$q = Q/B = Vy = \frac{1.49}{n} y^{5/3} S_o^{1/2} \quad [1]$$

where

- q = discharge per unit width, cu ft per sec per ft
- Q = total discharge, cu ft per sec

- B = flow width, ft
- V = average velocity, ft per sec
- y = depth of flow, ft
- S_o = bed slope, ft per ft

The Laursen sediment transport formula is given as:

$$\bar{C} = \sum p_i \left(\frac{d}{y}\right)^{7/6} \left(\frac{\tau_o'}{\tau_c} - 1\right) f\left(\frac{\sqrt{\tau_o/\rho}}{w}\right) \quad [2]$$

where

- \bar{C} = the mean concentration of total sediment, percent by weight
 - p = bed material fraction of diameter d; $\sum p_i = 1.0$
 - d = diameter of sediment particle, ft
 - y_i = depth of flow, ft
 - τ_o' = boundary shear stress associated with sediment diameter
 - τ_o = boundary shear or tractive force at the stream bed = $\gamma y S_o$
 - τ_c = critical tractive force for the beginning of sediment movement
 - γ = mass weight of water, lbs per cu ft
 - ρ = density of water, slugs per cu ft or lb per sec² per ft⁴
 - f = function
- and
- w = fall velocity of sediment, ft per sec

Laursen showed in solving the Manning formula and the Strickler expression for n as a function of the sediment diameter ($n = 0.034 d^{1/6}$), that:

$$\tau_o' = K V^2 \left(\frac{d}{y}\right)^{1/3} \quad [3]$$

where $K = \frac{1}{30}$ and $d = D_{50}$.

The critical tractive force can be obtained as:

$$\tau_c = Cd \quad [4]$$

where from the Shields diagram $4 \leq C \leq 16$.

The function term (equation [2]) was determined graphically by writing straight line equations for segments of the curve given in Laursen's paper (an "S" shaped relation is presented on a log-log graph). For the digital computer solutions used in all the computations, a linear interpolation scheme was developed using logarithms of the data for straight line segments of the original graph.

Fall velocity for the sediment was computed using a similar logarithmic interpolation scheme for data present in Fig. 5 in Report No. 4 of the Interagency Sedimentation Project (1941).

The instantaneous sediment discharge for a given water discharge, assuming a bulk dry sediment weight of 100 lb per cu ft, was obtained from:

$$Q_s = Bq_s = \frac{\bar{C}qB}{265} \quad [5]$$

where Q_s = total volumetric sediment discharge, cu ft per sec.

STREAM BED MATERIAL

The streambed material is the sediment available for transport in an individual runoff event. Most of the finest size fractions (i.e., clays and some silts) are washed into the stream by the overland flow, as well as being available in the bed. Stream channels and banks usually produce most of the coarser sediment transported.

In many ephemeral streams of the Southwestern United States, the sediment supply available for transport in the streambed is limitless. In some instances, the bed or banks or both are composed of geologically consolidated materials which rather than limiting sediment supply, tend to control channel gradients and alignment (Fig. 2).

Bed material sampling on Walnut Gulch has shown that the size distribution can generally be described by a log normal relationship. Minor deviations from the straight line theoretical relationship have been observed in the coarse size fraction, but because this material moves less frequently, the errors in sediment movement prediction are undoubtedly small relative to other assumptions. With the bed material following the log normal distribution, the size distribution can be expressed by two parameters, the geometric mean size (the size for which 50 percent is finer) and the geometric standard deviation determined graphically as:

$$\sigma_g = \frac{D_{84.1}}{D_{50}} = \frac{D_{50}}{D_{15.9}} \quad [6]$$

where $D_{84.1}$ is the size for which 84.1 percent of the material is finer, D_{50} is the size for which 50 percent of the material is finer, etc.



FIG. 2 This conglomerate bank on Walnut Gulch has some undercutting but has not caved much. The bank controls the stream alignment and partially the width. The alluvium visible in the picture varies from fine silts and sands to cobbles larger than 5 cm.

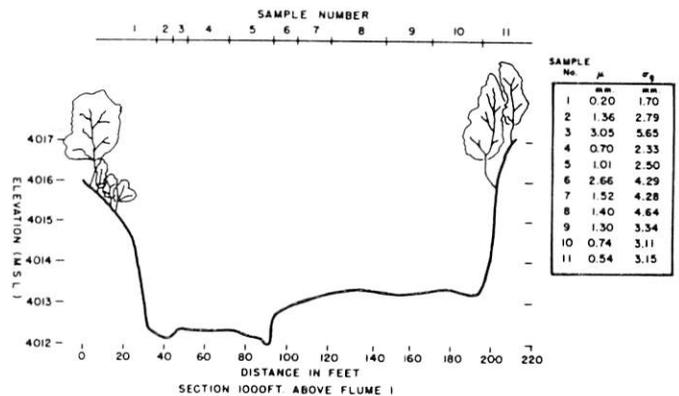


FIG. 3 A typical cross section near Flume No. 1 on Walnut Gulch. The trees on the banks are mesquite with some white thorn brush. μ and σ_g are the mean and standard deviations obtained at each of the sample sites shown for the section.

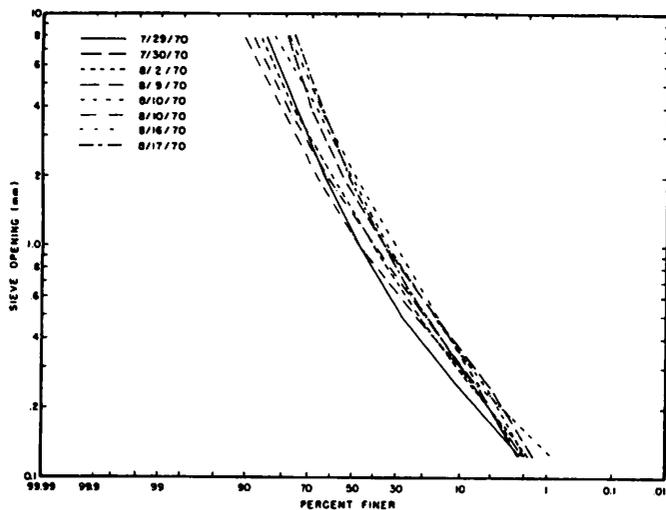


FIG. 4 Bed material size distributions for various dates at the Walnut Gulch outlet.

Bed samples were collected from the alluvial bed in Walnut Gulch by sampling the surface 2 cm at equal increments across the section above Flume No. 1 (the outlet of the watershed) (see Fig. 4). The materials from each increment site were combined into a composite for the entire cross section. Subsequently, each combined sample was remixed in the laboratory and an approximate 1,200-g sample removed using a mechanical sample splitter. Each sample so obtained was analyzed with standard sieves to obtain the size distribution.

No effort was made to sample bed composition variation that might be encountered with depth. Because the scour relationships during individual flow events are unknown, surface sampling only may result in a sizeable error. It seems likely that the vertical composition variation may be similar to the transverse variation at the channel surface. The large standard deviations at most sampling sites indicate this surface variation (Fig. 3). The composite sample standard deviation was about twice as large as that for an individual sample in the few tests made.

Vanoni et al. (1961) listed typical values of the mean and standard deviations of log normal distributions of natural river beds in various places around the world (generally perennial streams). The values of μ and σ_g on Walnut Gulch are considerably larger than most of the values listed by Vanoni et al. (1961). The Walnut Gulch bed samples are characterized as coarse material (most samples had 50 percent of the material larger than 1 mm) with a wide particle size range between the largest and finest fractions.

The dynamic behavior of the stream

cross section, the transverse sediment size distribution changes, and the bed material size distribution changes during the passage of an individual runoff event, all contribute to the problem of modeling sediment transport in an ephemeral stream. A trapezoidal channel was used in the computer model (Fig. 1) to describe a cross section in the prototype (which is more like the section shown in Fig. 3).

Fig. 3 also shows that the bed material deviates appreciably across the section. For the total cross section, the geometric mean grain size is 1.1 mm with a standard deviation of 6.2 mm (determined by equidistant surface sampling). Although no size variability pattern is discernable in the figure, the finest material generally is at the lowest cross section points and adjacent to the banks.

Using average size distribution and a rectangular channel may underestimate the depth, and thus the velocity, which account for most of the sediment transport. Thus, the concentration may be low because of the depth, velocity, and size distribution estimates.

Changes in bed material composition may be appreciable from one flow event to another. Fig. 4 illustrates the composition variability at the outlet of Walnut Gulch for samples collected after most of the runoff events in 1970. The data tabulated are presented in Table 1 with flow information and the sediment size distribution.

In an effort to predict bed composition changes from one flow event to another, the data in Table 1 were examined using multiple regression techniques. The simple correlation matrix of Table 2 shows that a significant positive correlation exists between the mean and

TABLE 1. 1970 FLOW DATA AND BED MATERIAL SIZE

Flow date, 1970	Begin time, military	Flow		Bed material	
		Q _p (peak), cfs	V (volume), a.f.	μ , mm	σ_g , mm
Beginning values					
7/20	2045	710	47.8	1.10	6.18
7/25	1648	70	3.1		
7/29	1443	74	2.3	1.20	3.75
7/31	2246	178	10.5	1.65	3.37
8/1	2031	<1	<0.1		
8/1	2359	1.82	15.9		
8/2	2324	194	7.6	1.40	3.50
8/9	0559	49	4.9	1.10	2.75
8/10	0410	94	10.3	1.70	3.80
8/10	1655	12	0.4		
8/10	1847	335	33.5	1.35	3.14
8/16	2307	614	56.4	2.05	4.02
8/17	1930	350	51.1	1.80	4.19

standard deviation terms for the log-normal distribution. The mean for the storm event in question (μ_n) and that from the previous event (μ_{n-1}) were essentially uncorrelated. Intuitively, it had been hoped that such a relationship might be present. Similarly, the standard deviation (σ_{g_n}) for the storm event in question and the standard deviation of the last previous event ($\sigma_{g_{n-1}}$) also were uncorrelated.

Multiple linear regression analysis of the data produced the following equations:

$$\mu_n = 0.112 + 0.342 \sigma_g + 0.00085 Q_p \dots \dots \dots [7]$$

$$(r^2 = 0.742)$$

and

$$\sigma_g = 1.894 + 1.091 \mu_n \dots \dots \dots [8]$$

$$(r^2 = 0.552)$$

Substituting equation [8] into equation [7] gives:

$$\mu_n = 1.212 + 0.00136 Q_p \dots \dots \dots [9]$$

These equations were then used as input to a computer model developed and evaluated in previous work (Renard 1972a, Renard 1972b, and Renard and Lane 1974) and described here as the

TABLE 2. CORRELATION MATRIX FOR TERMS USED TO PREDICT THE MEAN GRAIN SIZE.

	Q _p	μ_{n-1}	σ_g	μ_n
Q _p	1.00	0.399	0.483	0.741
μ_{n-1}		1.00	0.138	0.115
σ_g			1.00	0.743
μ_n				1.00

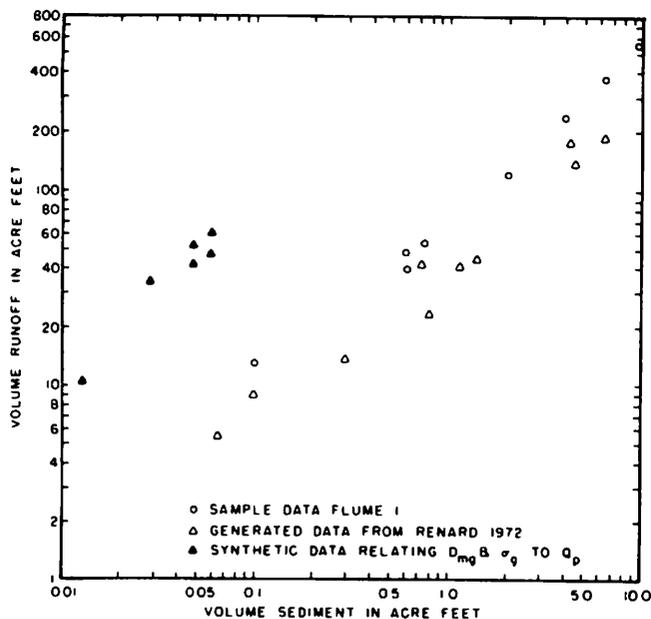


FIG. 5 Comparison of the synthetic sediment volumes with sample volumes for Flume No. 1 on Walnut Gulch.

conceptual model. The 1970 flow events were used as inputs to the sediment model. Figs. 5 and 6 show the results of this endeavor and compare data from actual sampling with data generated from earlier work and from the Walnut Gulch sampling program. There is no agreement of the peak sediment discharge and the storm volumes obtained by equations [8] and [9]. The actual sample data can be matched much closer using a μ of 1.10 mm with a σ_g of 5 mm as illustrated in the earlier work.

The prediction equations for μ and σ_g represent the total cross section, whereas at lower discharges, the sediment available for transport is that available in the lowest parts of the cross section (Fig. 3) where the sediment gener-

ally has a smaller mean diameter. At these low points in the cross section, the shear is greatest and thus the largest concentration of sediment would be expected.

Fig. 7 illustrates the sediment size distributions used for the 1970 storm computations for the data in Figs. 5 and 6. Although the variation in sizes at the finer fractions show greater scatter in the actual data (Figs. 4 and 7), the predicted curves generally have the same range as the actual values.

To illustrate the magnitude of the changes in bed material composition on sediment transport, the mean grain diameter and standard deviation in the log-normal distribution were sequentially varied to produce the results shown in Table 3. The values in the table repre-

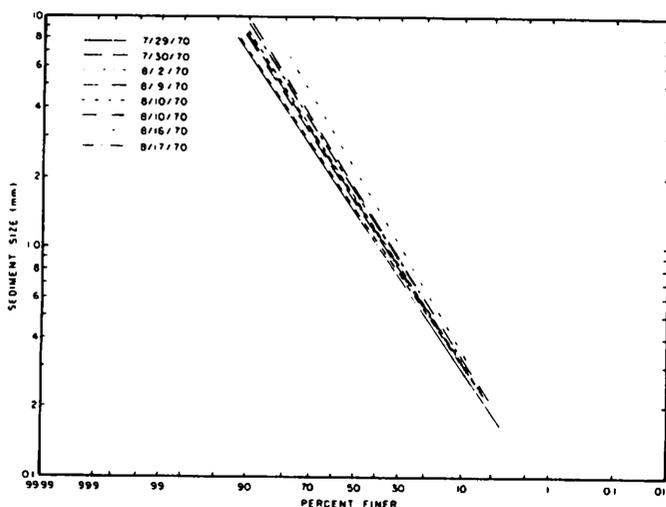


FIG. 7 Predicted bed material distributions using equations [8] and [9].

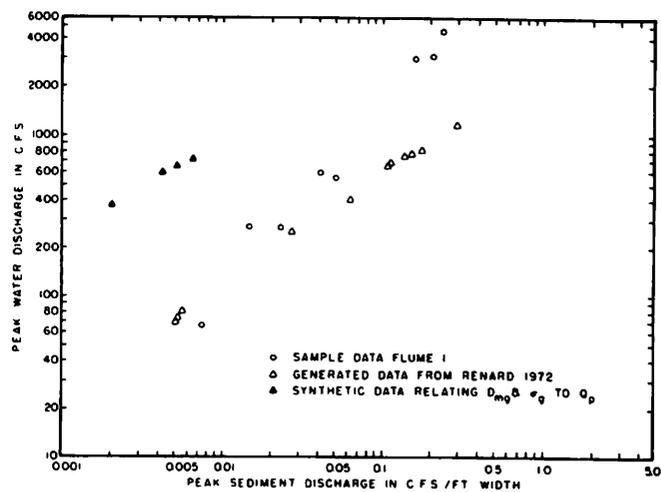


FIG. 6 Comparison of the peak water and sediment discharges between the synthetic and sampled data at Flume No. 1 on Walnut Gulch.

sent the predicted sediment yield for a storm on September 10, 1967, which had a peak discharge of 4,650 cfs and 361 acre-ft of runoff (the largest storm measured on Walnut Gulch with sediment sampling throughout the flow). With the predictions of equations [8] and [9], the suspended sediment yield for this storm would be 2.32 acre-ft. The sampling program at this station indicated the suspended sediment yield was 4.55 acre-ft.

The distribution of sizes (as indicated by the standard deviation) has a marked effect on the predicted material in transport. For example, when the mean grain size was doubled from 1 mm to 2 mm (for a standard deviation of 2.0 mm), a 73 percent reduction in suspended sediment was predicted, (Table 3), whereas when the standard deviation was doubled from 2 to 4 mm (for a mean value of 1.0 mm) the predicted suspended sediment yield increased almost 1,000 percent.

Although the bed material might contain a large amount of larger size material, Laursen's transport relation predicts that only a small percentage of this material is being moved. The condition persists regardless of the instantaneous discharge. Thus, it is imperative to ac-

(Continued on page 1010)

TABLE 3. SEDIMENT YIELD FOR A STORM AT THE OUTLET OF WALNUT GULCH FOR VARIOUS ASSUMED BED SEDIMENT SIZE DISTRIBUTIONS.

σ_g	μ					
	1.0	1.1	1.3	1.5	2.0	2.5
Acre - ft						
2.0	0.84	0.69	0.49	0.37	0.23	0.26
3.0	2.69	2.24	1.51	1.10	0.58	0.35
4.0	8.02	5.80	3.95	2.60	1.42	0.82
5.0	18.60	15.10	8.57	5.32	2.80	1.73
6.0	28.90	24.30	15.80	10.80	5.07	2.98

Sediment Transport

(Continued from page 1005)

curately know the distribution of the smaller sediment sizes indicated by the standard deviation.

SUMMARY

Experience with an ephemeral stream such as Walnut Gulch indicates that the Laursen sediment transport relation provides a good estimate of the sediment concentration if the bed material composition is known. Because the bed composition changes between flow events, long-term sediment yields are hard to predict unless some historical data are available about the bed material.

Because the finest fractions of the bed material are those most easily trans-

ported, it is especially important to accurately estimate the fine fraction of the size distribution. If the bed material can be expressed by a log normal distribution (described by a mean and a standard deviation), doubling the mean grain size resulted in a 73 percent reduction in the predicted sediment transport whereas the predicted suspended sediment yield increased almost 1,000 percent when the standard deviation was doubled from 2 to 4 mm.

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