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Dynamic Behavior Model of Ephemeral Stream

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Introduction

In an ecology-conscious society, sedimentation processes must be an integral part of efforts to design, construct, or maintain watershed conservation facilities. However, because sedimentation is a perfectly natural phenomenon, efforts to reduce sedimentation rates must include site conditions and existing rates. Engineers and scientists responsible for maintaining the land resource require information about how natural channels react to various inputs and how inputs are transformed in transporting sediment to downstream points. Understanding stream behavior is a complex problem that has tormented the designer for years.

Two tendencies are apparent in an ephemeral stream channel: (1) To be *concave down* due to discharge loss by infiltration through the normally dry channel alluvium; and (2) to be *concave up* due to more flow downstream than upstream because of tributary inflow. Thus, in addition to variations in sediment transport in perennial streams, with ephemeral streams, the uncertain temporal and spatial precipitation variability plus transmission losses further complicate predicting their behavior. For a given water discharge and sediment load, the stream width, depth, velocity, grain size, and slope result from mutual adjustments. As Rubey (13) stated: "If discharge, head, grain size, and sorting are considered the controlling factor, then velocity, slope, width, and depth of channel are dependent variables that are affected not only by the independent variables, but also by one another."

Stream and Channel Behavior Example

The practical objective of sediment transport studies in an alluvial channel involves understanding the factors affecting sediment discharge at unmeasured locations. The behavior of an ephemeral stream with respect to its ability to transmit the water and sediment load is a dynamic situation that can be predicted

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by studying the extreme hydrologic variability that produces the water and the channel system heterogeneity, both of which alter the hydraulic factors of the flow itself. To illustrate this complexity, we used a storm on the Walnut Gulch Watershed.

Walnut Gulch Experimental Watershed Description.—Walnut Gulch contains

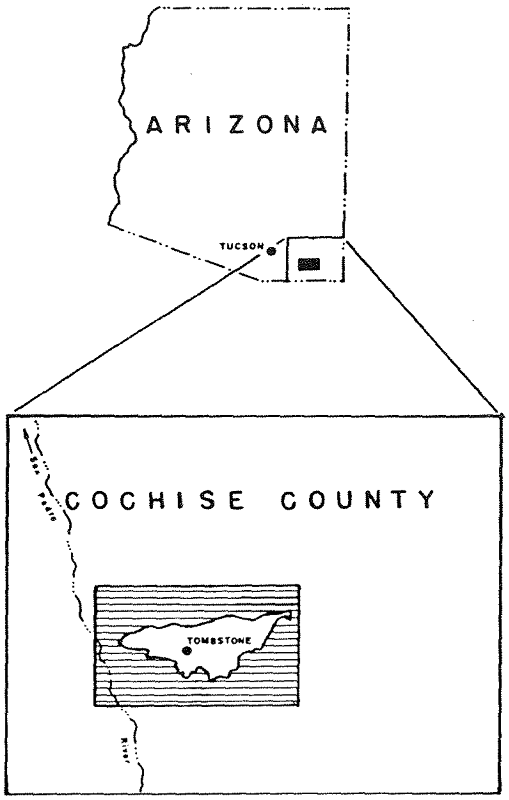

FIG. 1.—Location of Walnut Gulch Experimental Watershed, Southeastern Arizona

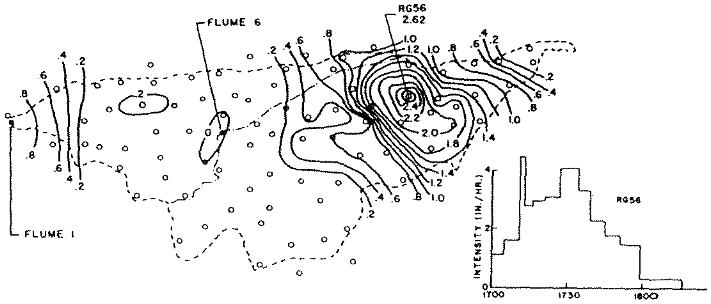

FIG. 2.—Walnut Gulch Isohyetal Map [0.2-in. (5-mm) Increments] and Hyetograp for September 11, 1964 (1 in./hr = 25.4 mm/hr)

an ephemeral stream located in the San Pedro River drainage in southeastern Arizona (Fig. 1). This portion of Arizona is quite homogeneous in landforms and climate and most major streams have headwaters in mountains that subsequently traverse alluvial slopes before intersection major streams, e.g., the San Pedro. The climate is subhumid at higher mountain elevations and gradually

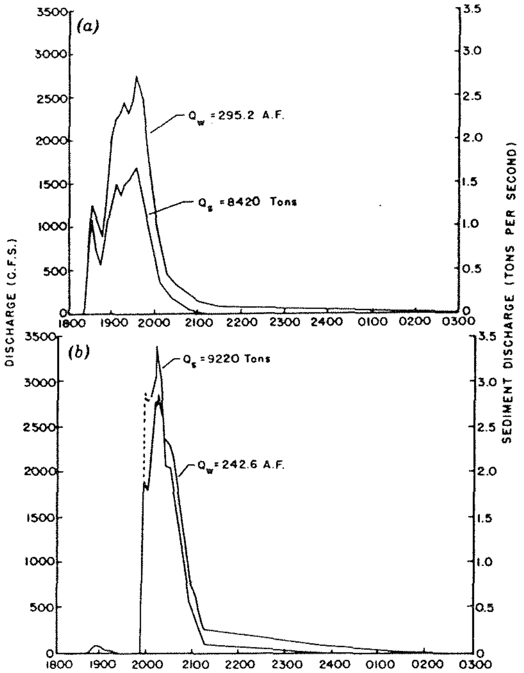

FIG. 3.—Hydrograph and Sediment Discharges for September 11, 1964, Storm at Walnut Gulch: (*a*) Flume 6; (*b*) Flume 1 (1 ton = 907.2 kg; 1 cfs = 0.028 m^3/s; 1 acre-ft = 1,233 m^3)

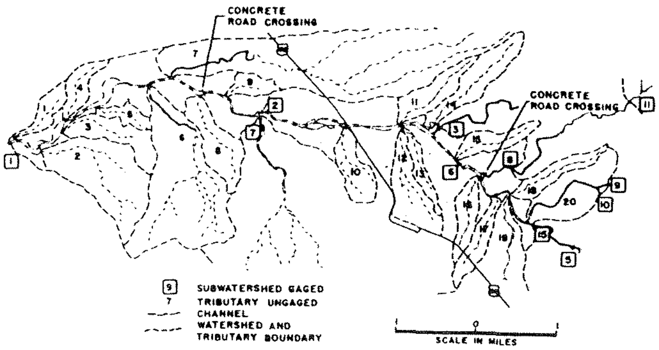

FIG. 4.—Main Channel and Major Tributaries of Walnut Gulch between Flumes 5 and 1 (1 mile = 1.61 km)

changes to semiarid in the basins between major mountain blocks.

The 58-sq mile (150-km^2) Walnut Gulch Watershed is representative of much of the mixed grass-brush rangeland in southeastern Arizona and southwestern New Mexico. The watershed is grazed year round with cultivation limited to small areas in the city of Tombstone, Ariz. The watershed consists of gently rolling low hills with elevations ranging from 4,000 ft (1,200 m) at the outlet to slightly over 6,000 ft (1,800 m).

In addition to a runoff-measuring network, a 90-gage precipitation network measures the precipitation inputs to the watershed. The mean annual 14-in. (360-mm) rainfall measured (11,14) in Tombstone is divided between a summer "monsoon" season (characterized by thunderstorm precipitation producing about two-thirds of the annual total) and a winter season (characterized by long-duration low-intensity storms).

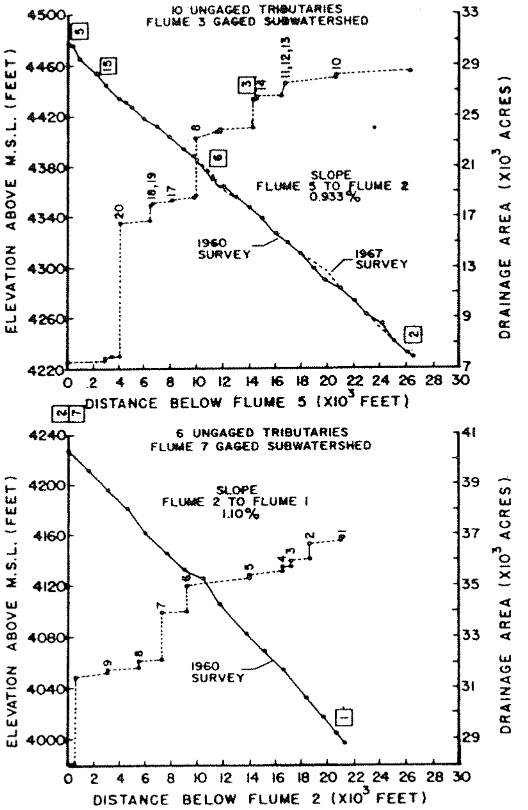

FIG. 5.—Streambed Longitudinal Profile and Drainage Area Changes with Channel Distance below Flumes 5 and 2 (See Fig. 4 for Locations of Watersheds and Tributaries; 1 acre = 4,047 m^2; 1 ft = 0.305 m)

Precipitation, Runoff, and Sediment Discharge.—The September 11, 1964, thunderstorm on the upper portion of Walnut Gulch is presented in Fig. 2 to show precipitation variability. The hyetograph for the gage at the storm center shows a maximum intensity of over 4 in./hr (100 mm/hr) near the storm center. The rain gages, located on an approx 0.9-mile (1.4-km) grid, show the steep precipitation gradient generally measured in such thunderstorms. The small storm near the watershed outlet began about the time the storm ended on the upper end and produced a small flow at the outlet (Flume 1) before the flow from the upper drainage reached the outlet.

Runoff resulting from this storm was measured at Flume 6 [the upper 36.7 sq miles (95.1 km^2)] and at Flume 1 (the watershed outlet), by critical depth flumes (2). The hydrographs for these two sites are shown in Figs. 3(*a*) and 3(*b*). The storm resulted from a late summer moisture influx from a tropical storm off Baja California. Heavy thunderstorms occurred on each of the 2 days preceding this event, leaving the channels quite wet. Still, 52.6 acre-ft (64,900 m^3) of water were lost in the 6.8-mile (11-km) channel reach between these flumes with the peak discharge remaining nearly constant. Additionally, the three hydrograph peaks at Flume 6 were attenuated to essentially one peak at Flume 1.

At both flumes during this event, suspended sediment samples were collected with a depth-integrating sampler lowered from a cableway approx 100 ft (30 m) above each flume. This sampling revealed 8,420 tons (7.64×10^6 kg) of sediment at the channel upper end with 9,220 tons (8.36×10^6 kg) leaving at the watershed outlet. Thus, although only 82% of the runoff at Flume 6 was discharged at the watershed outlet, suspended sediment deposition in the channel from previous events, plus inflow from this event, left the channel reach.

Walnut Gulch Channel.—Such storms, plus those originating in the lower portions of Walnut Gulch, have resulted in a channel reach that is remarkably uniform and appears to be graded and in equilibrium (7,8). The streambed slope at most places in the main channel is 1% with only minor deviations, mostly related to geologic controls.

Fig. 4 shows the main Walnut Gulch channel and the major tributaries between Flume 5 and the watershed outlet (Flume 1). For this main channel reach, bed-slope profiles were made with transit and stadia surveys and the alluvial bed was sampled above each confluence. The bed material samples were obtained at equal increments from the surface 2 in. (50 mm) since this was hypothesized as the material most readily transported.

Fig. 5 shows the slope uniformity on the main channel with a break associated with the granodiorite intrusion near Flume 2 [4 miles (6.4 km) above the watershed outlet]. Thus, the average slope for the 27,000 ft (8,200 m) above Flume 2 is 0.93%, whereas that below the flume is 1.10%. Fig. 5 also shows major tributary confluences and the resulting increase in contributing watershed area. Such increases explain the slight slope deviation, like that associated with tributary 6 for the channel reach below Flume 2. This tributary apparently discharges a heavy sediment load, causing deposition and creating a small mound on the channel profile 10,000 ft (3,000 m) below the flume. The 1967 and 1960 surveys deviated slightly above Flume 2. This assumed temporary deviation resulted from agregate borrow connected with highway construction.

The main channel alluvial material sampled above tributary and main channel confluences had particle diameters describable by a straight line on logarithmic probability paper (Fig. 6). This log-normal distribution simplifies the description of the material, which can be described by a mean (μ) and standard deviation

(σ). The bed material variability along the channel is appreciable. It was observed that the material mean size decreased as watershed area increased while the standard deviation decreased. Except for correlations between μ and σ, their highest correlation coefficient was associated with drainage area.

Conceptual Sediment Transport Model

The correlation of the instantaneous water discharge versus sediment concentration, for all samples collected within a year, is only slightly above zero with the concentration at any water discharge varying by about one order of magnitude. Examining the data from flow to flow reveals a fairly consistent pattern with respect to the individual hydrographs. Thus, on a log-log graph,

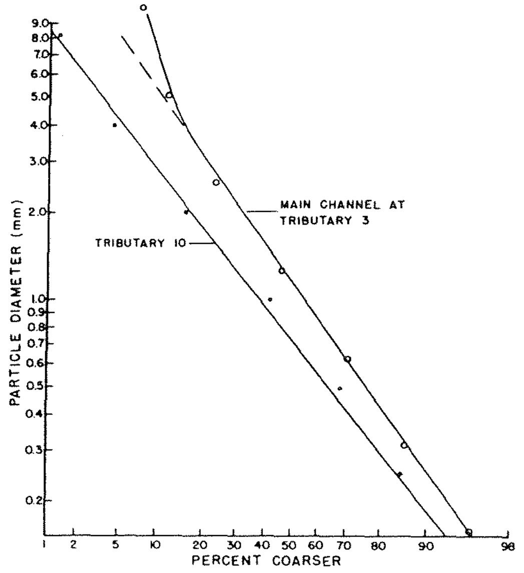

FIG. 6.—Logarithmic-Normal Particle Size Distribution of Two Typical Bed Samples on Walnut Gulch Watershed (1 mm = 0.039 in.)

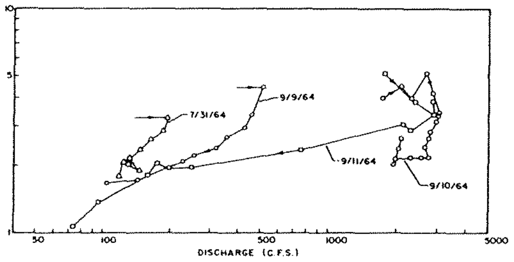

FIG. 7.—Suspended Sediment Concentration Versus Discharge for Walnut Gulch Flume 1 for Four Storms in 1964 (1 cfs = 0.028 m³/s)

the data appear as a series of side by side and superimposed sevens with the top portion of the seven as the concentration on the hydrograph rising portion (Fig. 7).

Possible explanations for these concentration-discharge relations are: (1) Concerning precipitation, each runoff event is quite independent of the previous flows; (2) when the bed is dry, the sediment to be transported is the residual sediment from preceding flows plus the new predominantly fine material produces from the runoff source area; (3) ephemeral streams are continually losing water to the bed, which reduces the power of the stream to move sediment; (4) usually the last material deposited on a flow recession is the finest size material, which can readily be picked up by subsequent rises in flow; and (5) as discharge increases the depth and bed shear increases, the coarser material is placed in motion and even suspended by the turbulence associated with the hydrograph rise.

The Laursen (5) transport relation was used to provide answers to the sediment movement process as an insight to ephemeral stream behavior. For analytic simplifications, the stream cross section was assumed rectangular. Although this assumption has limited application, ephemeral streams are often wide and shallow with width-depth ratios greater than 50. The error (12) for assuming depth equals hydraulic radius is less than 5% as long as the width-depth ratio exceeds 15.

For each stream width increment, the water discharge per unit width can be given by the Manning equation as:

$$q = Vy = \frac{1.49}{n} y^{5/3} S_o^{1/2} \quad \ldots\ldots\ldots\ldots (1)$$

in which q = discharge per unit width ($L^3/T/L$); V = average velocity (L/T); y = depth of flow (L); S_o = bed slope (L/L); and n = Manning coefficient. The Laursen sediment transport formula is given as:

$$\bar{C} = \sum_i P_i \left(\frac{d_i}{y}\right)^{7/6} \left(\frac{\tau_o'}{\tau_c} - 1\right) f\left(\frac{\sqrt{\frac{\tau_o}{\rho}}}{w}\right) \quad \ldots\ldots\ldots\ldots (2)$$

in which $\bar{C}$ = mean instantaneous total sediment concentration, as a percentage by weight; P_i = bed material fraction of diameter d ($\Sigma P_i = 1.0$); d = diameter of sediment particle, in feet; y = depth of flow, in feet; 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; ρ = density of water, in slugs per cubic foot or pounds per second squared per foot^4; f = function of the term; and w = fall velocity of sediment, in feet per second.

Using the Manning formula and the Strickler expression (assuming uniform roughness) for n as a function of the sediment diameter, it can be shown that:

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

in which $K = 1/30$; and $d = \mu$ = mean sediment size. The critical tractive force can be obtained as:

$$\tau_c = Cd; \quad 4 \leq C \leq 16 \qquad (4)$$

The function term in the formula can be determined by writing straight-line equations for segments of the graph given in Laursen's paper (5). For the digital computer solutions, a linear interpolation scheme was developed using logarithms of the data for straight-line segments of the original graph. The fall velocity for the sediment was computed using a similar logarithmic interpolation scheme for the data presented in Fig. 5 of the Interagency Sedimentation Project (9).

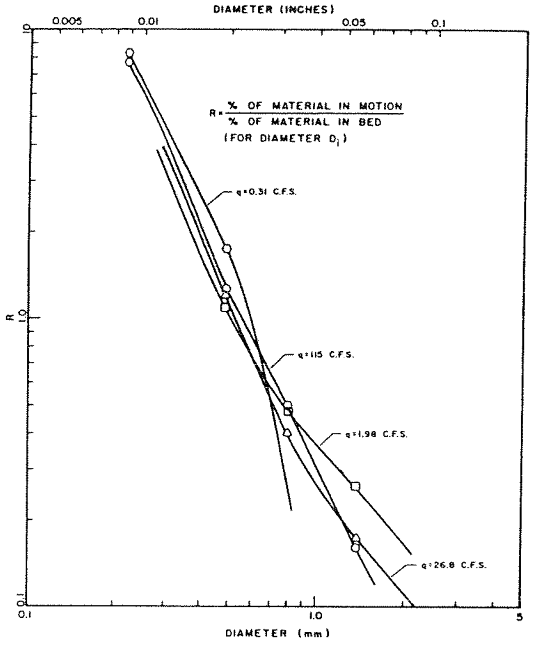

FIG. 8.—Ratio of Sediment in Motion to Composition of Bed Material for Various Sediment Sizes and Water Discharges, per Unit Width, Based on Laursen Transport Relation and Flume 6 Data

The instantaneous sediment discharge for a given water discharge can be obtained from Eq. 5, assuming a bulk dry sediment weight of 100 pcf (1,600 kg/m^3):

$$q_s = \frac{\bar{C}q}{265} \qquad (5)$$

Assuming that the Laursen relation correctly indicates conditions in the stream, the ratios of grain sizes predicted in motion to the material of the same size deposited in the bed are shown in Fig. 8. Fig. 8 shows that although the bed might contain large amounts of the larger sizes, the transport relation predicts that only a small portion of this material is moved. This condition persists regardless of the instantaneous discharge.

PHYSICAL CHARACTERIZATION AND SIMULATION OF STREAM REACH

To quantify the dynamic behavior of a stream, a relationship must be available to estimate the tributary contributions of runoff and sediment. Analysis of tributaries intersecting the main channel included counting the streams by order (3,15) on 1:12,600 contact aerial photographs. Then the measured tributary intersections were fitted to Poisson, geometric, and binomial distribution functions. The minimum least-squares criteria for the normalized data indicate good agreement using a geometric distribution function given as:

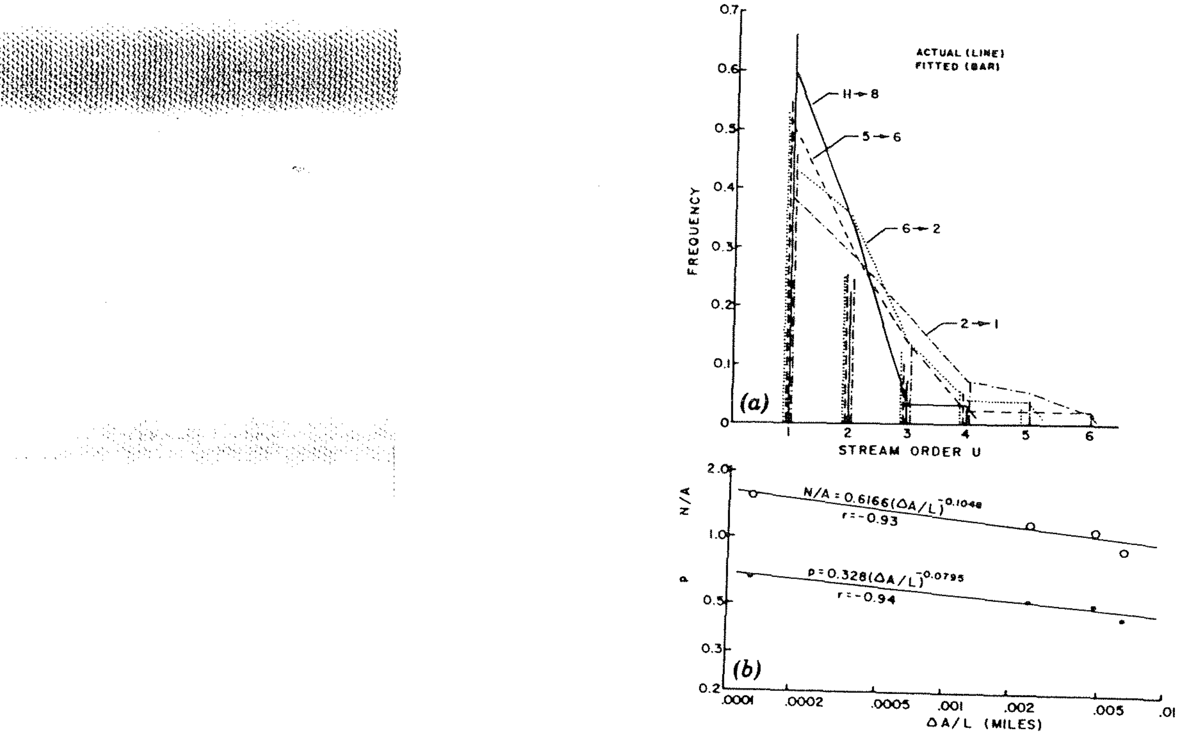

FIG. 9.—(*a*) Geometric Probability Distribution (Bar Graphs) of Stream Orders for Four Walnut Gulch Channel Reaches and Measured Distribuitons for Same Reaches (Line Graphs); (*b*) Parameters of Geometric Probability Distribution Versus Drainage Area Changer per Unit Channel Length (A = Drainage Area, in square miles, at End of Channel Reach L, in miles; N = Number of Stream Channel Intersections; p = Probability of Intersection; 1 mile = 1.61 km)

$$F(U) = (1 - p)^{(U-1)} p \quad \quad (6)$$

in which $U = 1, 2, 3, \ldots x$, the stream orders; and p = the occurrence probability.

The agreement obtained in this manner is shown in Fig. 9(*a*) for four separate channel reaches on Walnut Gulch.

To complete the model for tributary intersections, the frequency parameter, p, and the number of intersections, N, were related to physically measurable watershed characteristics. The relationship [Fig. 9(*b*)] that relates these terms to the drainage area increase per unit channel length, $\Delta A/L$, seems physically realistic. The occurrence probability for small values of $\Delta A/L$ states a more peaked distribution, i.e., numerous small tributaries are involved (the drainage area associated with any tributary would be small). Likewise, as the drainage area increases or as the channel reach length decreases, higher order streams

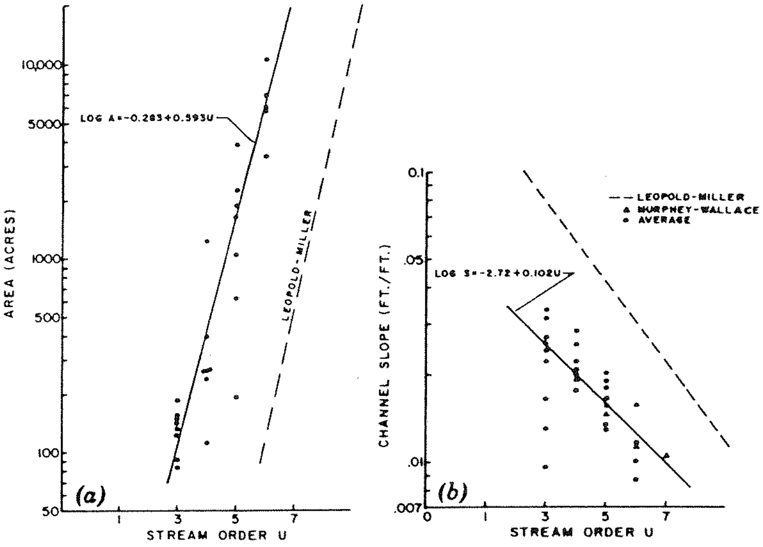

FIG. 10.—(*a*) Drainage Area Versus Stream Order for Walnut Gulch Main Channel Tributaries; (*b*) Channel Slope Versus Stream Order for Walnut Gulch Main Channel Tributaries (1 acre = 4,047 m²)

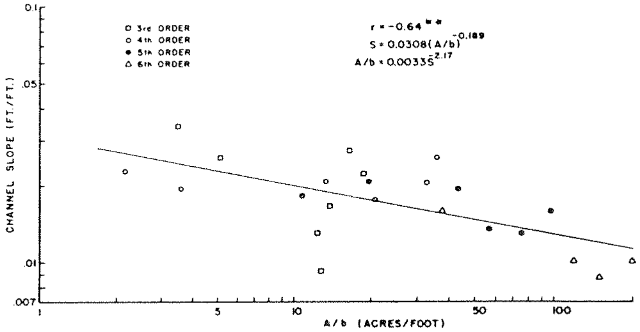

FIG. 11.—Channel Slope Versus Area per Unit Channel Width from Tributaries to Main Channel of Walnut Gulch (1 acre/ft = 13,270 m²/m)

join the channel reach and a corresponding decrease occurs in the intersection number for the reach in question.

The stream reach simulation also required the determination of the drainage area, slope, and channel width associated with each tributary. The results of this effort are shown in Figs. 10(*a*), 10(*b*), and 11. Although the scatter in Fig. 10(*b*) is great, arithmetic averages of the data for each stream order defined a reasonably straight line. Data from Murphey and Wallace (10) for other Walnut Gulch portions were included. Their data, plus the similar slopes obtained for the Leopold and Miller (6) data, lend confidence to the scheme. Variations like those shown herein are probably associated with the complexities of landform evolution. The existence of nonerodible (on other than a geologic time scale) outcrops in some tributaries may cause steep slopes, whereas their absence may reduce the average slopes. Another large variation source involves the site at which the determinations are made. For example, if the site for which the slope is determined is immediately below the confluence of two like-numbered streams (the next higher number is then adapted), the drainage area may be the minimum value for such a stream order, and the slope may be changing from a steeper lower order slope to the more gradual higher order slope.

The displacements associated with the Leopold and Miller (6) work in New Mexico may be explained partly by map scale (Leopold-Miller second-order stream is probably equivalent to the first order used herein) and partly by differences in the structural geology of the watersheds involved.

The stream width versus order number correlation was higher on an arithmetic scale than for any of the other single independent variables (i.e., area and slope). However, the average width for the fourth and fifth-order streams was approximately the same. Accordingly, the relationship shown in Fig. 11 was developed. As is common in geomorphic relationships, the variability is great but may be truly indicative of the conditions in arid and semiarid areas.

A stochastic ephemeral runoff model (1,4) was used to generate the tributary inflow as an alternative to a rainfall-runoff model. The model used was based on Walnut Gulch data and generates intermittent and independent runoff events. Two variables are used to describe the runoff season: (1) Date at the beginning of the thunderstorm season; and (2) the number of runoff events at a watershed outlet per season. The temporal runoff event position is described by: (1) Event time within a day; and (2) the interval between events. Each runoff event is then described by a random variable for the runoff volume. Then the peak discharge is related to the volume. The random variables were described by distributions that were related to drainage area.

SEDIMENT TRANSPORT MODEL VERIFICATION

For streams like Walnut Gulch, sediment transport verification is difficult due to inherent high stream velocities and rapidly changing discharge. Depth-integrated samples collected at a single cross section are available for many storms at Flumes 6 and 1, but often they do not include sampling during the entire hydrograph. Bed material composition and roughness changes during a flow event present measurement difficulties and are not available.

Fig. 12 shows the depth-integrated samples collected at Flume 1 during 1970. The concentration scatter encountered for a given water discharge is similar

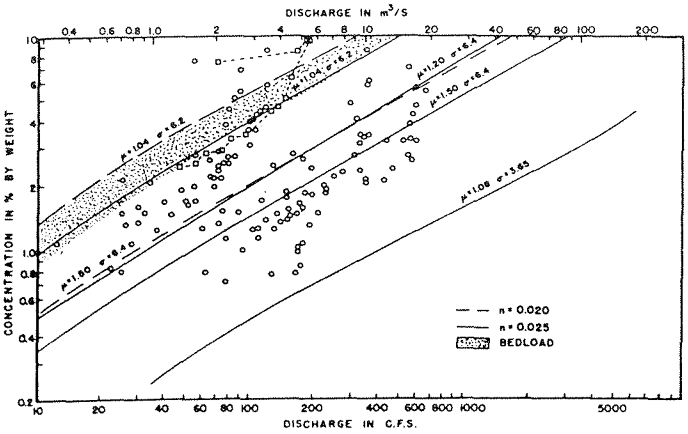

FIG. 12.—Instantaneous Concentration-Discharge Variations at Flume 1 on Walnut Gulch and Laursen Relation for Various μ, σ, and n Values (Connected Concentration line between Individual Squares Shows Typical Seven Pattern for Samples Collected During July 30, 1970, Storm; Shaded Area Show Effect of Bed-Load Discharge on Concentration)

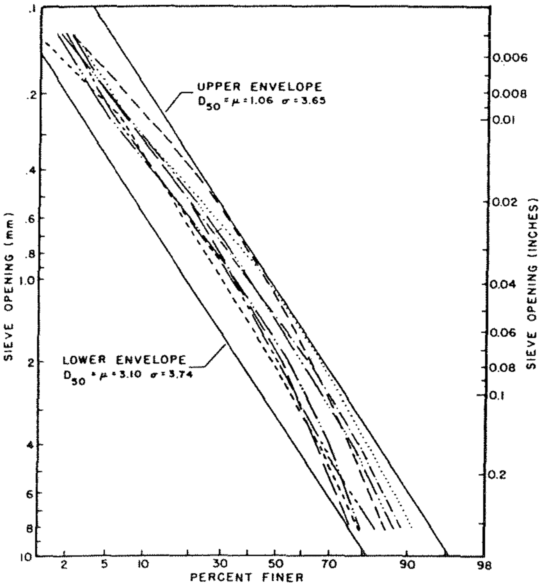

FIG. 13.—Bed Material Size Distribution Variation During 1970 at Flume 1 of Walnut Gulch

to that measured in other years. The lines in Fig. 12 show the predicted relationship for a rectangular channel using the Manning-Laursen relation. The mean grain size, μ, and standard deviation, σ, listed for each line are the parameters of the log-normal probability distribution used to describe the bed material. Readily apparent in Fig. 12 is concentration sensitivity to differences in the bed material and the difference associated with changing the Manning roughness, n. The shaded portion in the upper left-hand corner demonstrates the concentration magnitude from bed load for the combination of $\mu = 1.04$ mm (0.041 in.), $\sigma = 6.2$ mm (0.24 in.), and $n = 0.020$.

Fig. 13 shows the bed material composition variability at Flume 1 obtained by sampling after each runoff event. Such wide variations in bed material are sufficient to account for the sampling variability encountered in Fig. 13. Generally, the slope of the line is different from the limit lines, indicating more fine material or more material in the distribution extremes. For example, the $\mu = 1.06$ and $\sigma = 3.65$ line produced a predicted concentration relationship in Fig. 12 that was below the values obtained by sampling. Accurately describing the fine fractions is very important because they contribute most of the material being transported (Fig. 8).

Several interesting observations regarding grain size and hydraulic roughness can be made in Fig. 12. For example, reducing the mean grain size from 1.5 mm (0.059 in.) to 1.2 mm (0.047 in.) increased the predicted concentration at 100 cfs (2.80 m^3/s) from 1.5 wt% to 1.9 wt%. Similarly, decreasing the roughness, n, from 0.025 to 0.020 increased the concentration from 1.2 wt% to 1.5 wt%. Decreasing the roughness from 0.025 to 0.020 and increasing the mean diameter from 1.2 mm (0.047 in.) to 1.5 mm (0.059 in.) kept the predicted concentrations about the same. Subtracting bed load from the total concentration with $n = 0.020$, $\mu = 1.04$, and $\sigma = 6.2$, had the same effect as increasing the roughness to 0.025.

Digital computer programs were developed to perform all the computations involved. The lower 6.8 miles (11 km) of the Walnut Gulch channel were simulated to examine the stream behavior from runoff and sediment transport for a 10-yr period. The actual sediment volume associated with individual hydrographs was computed using a triangular hydrograph. When the peak discharge per unit width, Q_p/b, was less than 1 cfs/ft (0.09 $m^3/s/m$), the concentration was computed for the peak discharge only. When Q_p/b was greater than 1 cfs/ft (0.09 $m^3/s/m$) but less than 10 cfs/ft (0.93 $m^3/s/m$), the concentration was computed at the hydrograph peak and at one-half the peak value and the resulting sediment discharge graph was integrated to obtain the volume. When Q_p/b exceeded 10 cfs/ft (0.93 $m^3/s/m$), the sediment discharge corresponding to the hydrograph peak, as well as at one-third and two thirds of the peak discharge, was obtained. The scheme, although not faithfully reproducing the prototype condition, minimized the computing time while preserving some of the nonlinearities involved in the sediment discharge computation.

Fig. 14 shows the agreement between the peak runoff and sediment discharge and between the runoff and sediment volumes for selected events. Fig. 14 again shows the sensitivity of the model to variations in the bed material size distribution. Interestingly, the bed material size distribution that best fits a peak sediment load does not necessarily give the best agreement for total sediment volume in the flood. Although the results are acceptable, more field data would undoubtedly permit improving the relationships.

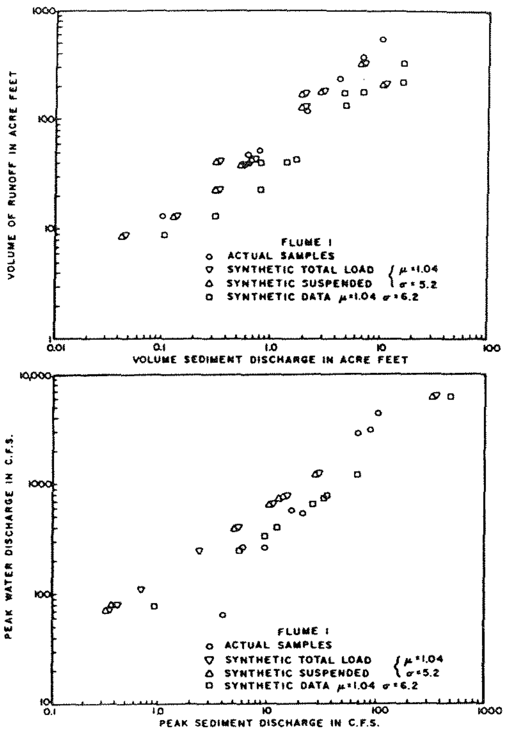

FIG. 14.—Selected Events on Walnut Gulch at Flume 1 with Different Bed Material Size Distributions Using a Log-Normal Probability Relationship Quantified by Mean Diameter (μ) and Standard Deviation (σ): (*a*) Comparison of Synthetic and Actual Peak Sediment Discharges; (*b*) Comparison of Synthetic and Actual Sediment Yields (1 cfs = 0.028 m^3/s; 1 acre-ft = 1,233 m^3)

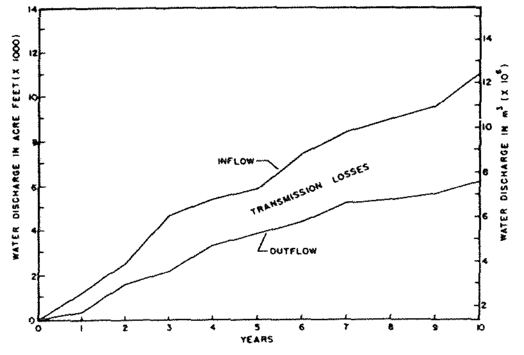

FIG. 15.—Cumulative Inflow and Outflow of Water in 36,200-ft (11,000-m) Channel Reach Using Runoff Generating Model (Difference between Two Lines Represents Transmission Losses in Alluvial Channel)

Channel Behavior from Water and Sediment Inputs

Synthetic runoff and sediment data from both the tributaries and the main channel for the 36,200-ft (11,000-m) channel reach between Flumes 6 and 1 were added for all storms. Interestingly, considering just the upstream and downstream stations showed that a single large storm in each year produced a large part of the runoff and a still larger portion of the annual sediment discharge.

The cumulative water inflow from the tributaries and the upstream end of the channel reach exceeded the outflow (Fig. 15), with the difference being transmission losses. As expected, the 480 acre-ft/yr (5.9×10^5 m^3/yr) average loss was highly variable. Assuming the true population statistics are preserved by the synthetic data, the loss represents 13.3 acre-ft/1,000 ft (53.6 m^3/m) of channel or about 3.8 ft (1.2 m) of water per unit area wetting [assuming an average channel width of 100 ft (30 m)].

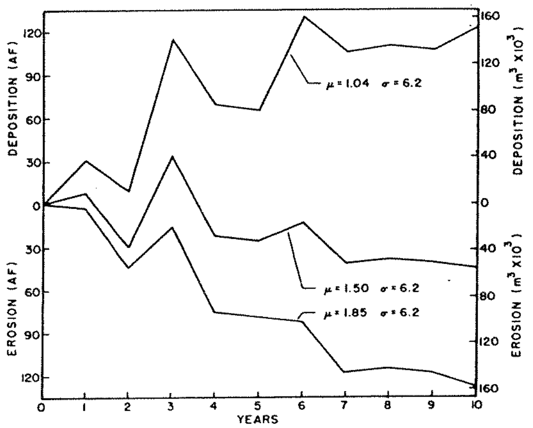

FIG. 16.—Cumulative Erosion and Deposition in 36,200-ft (11,000-m) Channel Reach Using Runoff-Sediment Transport Model (Shows Differences in Sediment Continuity Obtained by Changing Mean Sediment Size (μ) and Standard Deviation (σ) at Upstream End of Simulated Reach

Cumulative erosion or deposition are presented in Fig. 16 for the simulated channel reach. Although highly variable inflow and outflow values occur yearly, the average erosion or deposition (based on the extreme size distributions at Flume 6, shown as the upper and lower graphs) was approx 12 acre-ft/yr (15,000 m^3/yr). Converted to a uniform depth for the reach, it represents approx 0.096 ft/yr (0.029 m/yr) or approx 1 ft (0.3 m) in 10 yr. Such uniform values would not be expected because bank scour would reduce the bed erosion and man's activity, e.g., aggregate borrow operations, would limit the supply in deposition situations. The middle line in Fig. 16, which represented bed material size encountered just below Flume 6, shows that the channel is very near equilibrium. In actual flows, the bed mean size and range (as indicated by the standard deviation) is probably varying appreciably not only in the main channel but in each tributary as well.

Channel Changes

Early inhabitants of the Walnut Gulch area stated that the main channel was much narrower about the turn of the century. The explanation may involve the following. Stream bank shear is roughly porportional to the square of the velocity. Assuming the velocity erodes the banks and widens the channel, this additional bank sediment will be distributed over the stream bottom (assuming that the sediment available exceeds the stream transport capacity). The stream width increase offsets the depth decrease and the cross-sectional area remains essentially unchanged.

The tendency for wide shallow channels also may involve the transmission losses. Because water loss to the streambed reduces the water available to move sediment, the general tendency is for the bed to aggrade or fill up. This phenomenon, plus that mentioned previously, tends to convert a deep narrow channel to a wide shallow channel until the valley floor is level (transverse to the flow direction). A new storm subsequently cuts a new narrow channel through the fill from some downstream elevation control and the entire process repeats itself.

Conservation efforts to reduce erosion have been quite successful in some physiographic provinces. Present economics for rangeland areas greatly limit the erosion control efforts, although brush-to-grass conversion has been demonstrated to reduce sediment yield on areas like Walnut Gulch. Therefore, it is interesting to speculate what might happen if the sediment production to the stream suddenly became less. On Walnut Gulch, for example, the slope would be largely controlled by geologic outcrops and by the confluence elevation of Walnut Gulch and the San Pedro River. Thus, the slope probably would not change appreciably, but the roughness might increase because the fine sediment supply would decrease, thus changing the energy gradient. An increase in roughness with a coarser sediment also might alter the bed form and the sediment discharge. Thus, the sediment not immediately available for transport from tributary inflow would be scoured from the bed and banks until a "new" gradient was established.

Similarly an increase in sediment supply should produce aggradation, assuming the sediment supply exceeded transport capacity. Aggradation would persist until a new slope, roughness, and velocity established "new" grade conditions. Bed composition is very important, and if only fine additional sediment is supplied, the stream might not change appreciably from the width, depth, slope, roughness, and velocity to reach a new system of equilibrium.

Conclusions

The sediment transport model postulated, incorporating a stochastic runoff model with a deterministic sediment transport relationship, is especially geared to handle the temporal and spatial variability encountered in Southwestern thunderstorms. The model incorporates tributary watersheds to a channel reach based on geomorphic parameters and thereby generates the entire storm input-output sequence to a stream reach.

The Laursen sediment transport relation used with the Manning open channel flow relationship in a rectangular channel predicted sediment discharge that agreed closely with values obtained by sediment sampling on the Walnut Gulch Experimental Watershed. The relationships proved to be very sensitive to the bed material size distribution and to the roughness term used in the Manning relation. The finer materials make up by far the largest portion of the total sediment in motion. For coarse streambeds with wide range in sediment size, like those encountered on Walnut Gulch, the larger material is essentially at rest although a significant amount is available for transport.

The runoff-sediment generating scheme based on a runoff relationship developed by Diskin-Lane produced synthetic data that, when checked with limited field data, appeared to agree quite well. When the model data were totaled to simulate the lower 36,200 ft (11,000 m) of Walnut Gulch, it indicated the reach is approximately in equilibrium. Again however, the delicate sensitivity of the sediment load to the bed material size distribution and the spatial and temporal variability to the streambed preclude predicting long-term trends without data to verify the streambed composition. Further research seems warranted to define these streambed composition changes so that the distribution can be varied in the model in a predictable manner related to flow conditions or stochastically to include variability, such as that encountered in the prototype.

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APPENDIX.—REFERENCES

1. Diskin, M. H., and Lane, L. J., "A Basinwide Stochastic Model for Ephemeral Stream Runoff in Southeastern Arizona," *Hydrological Sciences Bulletin*, International Association of Scientific Hydrology, Vol. 17, No. 1, 1972, pp. 61-76.
2. Gwinn, W. R., "Calibration of Walnut Gulch Supercritical Flumes," *Journal of the Hydraulics Division*, ASCE, Vol. 96, No. HY8, Proc. Paper 7479, Aug., 1970, pp. 1681-1689.
3. Horton, R. E., "Erosional Development of Streams and Their Drainage Basins: Hydrophysical Approach to Quantitative Morphology," *Geological Society of America Bulletin*, Vol. 56, 1945, pp. 273-371.
4. Lane, L. J., and Renard, K. G., "Evaluation of a Basinwide Stochastic Model for Ephemeral Runoff," *Transactions*, American Society of Agricultural Engineers, Vol. 15, No. 2, 1972, pp. 280-283.
5. Laursen, E. M., "The Total Sediment Load of Stream," *Journal of the Hydraulics Division*, ASCE, Vol. 84, No. HY1, Proc. Paper 1530, Jan., 1958, pp. 1531-1536.
6. Leopold, L. B., and Miller, J. P., "Ephemeral Streams—Hydraulic Factors and Their Relation to the Drainage Net," *United States Geological Survey Professional Paper No. 282-A*, Washington, D.C., 1956.
7. Leopold, L. B., Wolman, M. G., and Miller, J. P., *Fluvial Processes in Geomorphology*, W. H. Freeman and Co., San Francisco, Calif., 1964.
8. Mackin, J. H., "Concept of the Graded River," *Geological Society of America Bulletin*, Vol. 59, 1948, pp. 463-512.
9. "Methods of Analyzing Sediment Samples," *Report 4*, by the Interagency Sedimentation Committee, Interagency Sedimentation Project, St. Anthony Falls, Hydraulic Laboratory, Minneapolis, Minn., 1941.
10. Murphey, J. B., and Wallace, D. E., "Annual Progress Report," Research Center,

Agricultural Research Service, United States Department of Agriculture, Tucson, Ariz., 1971.

11. Renard, K. G., "The Hydrology of Semiarid Rangeland Watersheds," *Agricultural Research Service Publication ARS 41-162,* United States Department of Agriculture, 1970.
12. Renard, K. G., "The Dynamic Structure of Ephemeral Streams," thesis presented to the University of Arizona, at Tucson, Ariz., in 1972, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
13. Rubey, W. W., "Geology and Mineral Resources of the Hardin and Brussels Quadrangles (in Illinois)," *United States Geological Survey Professional Paper No. 218,* Washington, D.C., 1952.
14. Sellers, W. B., *The Climate of Arizona,* University of Arizona Press, Tucson, Ariz., 1960.
15. Strahler, A. N., "Quantitative Analysis of Watershed Geomorphology," *Transactions,* American Geophysical Union, Vol. 38, 1957, pp. 913-970.

11315 DYNAMIC BEHAVIOR MODEL OF EPHEMERAL STREAM

KEY WORDS: Analytical techniques; **Ephemeral streams; Erosion; Hydraulics; Hydrology;** Mathematical models; **Open channel flow;** Predictions; **Sedimentation; Sediments;** Water resources

ABSTRACT: Ephemeral stream hydraulic features are dynamic and respond to the variable streamflow available to move sediment. Streamflow varies both from the runoff-producing storms and transmission losses that decrease the runoff volume and peak. The channel profile in an ephemeral stream tends to be concave up because of the transmission losses and concave down because there is more flow downstream due to tributary inflow. These phenomena were modeled for the main channel of the Walnut Gulch Experimental Watershed using a geomorphic approach to describe the channel and its tributaries and a hydraulic-hydrologic model for the runoff-sediment movement. Runoff and sediment transport were synthesized using the Diskin-Lane stochastic runoff model with a deterministic sediment transport relationship using the Manning and Laursen equations.

REFERENCE: Renard, Kenneth G., and Laursen, Emmett M., "Dynamic Behavior Model of Ephemeral Stream," *Journal of the Hydraulics Division,* ASCE, Vol. 101, No. HY5, **Proc. Paper 11315**, May, 1975, pp. 511-528