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Variability of Sediment Removal in a Semiarid Watershed

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Field and documentary data from Walnut Gulch Watershed, an instrumented semiarid drainage basin of approximately 150 km² (57 mi²) in southeastern Arizona, show that 83% of the alluvium removed from the basin during a 15-year erosion episode beginning about 1930 was excavated from the highest-order stream. The amount of alluvium removed in the erosion episode would have been equal to a covering of about 4 cm (1.6 in) over the entire basin. The rate of sediment removal during the erosion episode was 18 times greater than the rate of present channel sediment transport. Production of sediment from slopes and channel throughput at present rates are approximately equal, and refilling will not occur under present conditions. The channel forms left by the massive evacuation of sediment impose controls on the spatial distribution of tractive force and total stream power that make renewed storage of sediment likely in only a few restricted locations. Modern instrumented records of a decade or more provide an inadequate perspective on long-term sediment movement.

INTRODUCTION

The geomorphologist and engineer share a common interest in the transport and storage of sediment in semiarid watersheds. Using theoretical deductions, the engineer has frequently attempted to predict the behavior of sediment transport systems, while the geomorphologist has frequently used field observations to inductively arrive at explanations for the process [*Shen*, 1979, p. 20/10]. The following paper represents an attempt to combine engineering and geomorphological perspectives on the sediment transport processes in channels of a semiarid watershed, Walnut Gulch in southern Arizona. Several studies have been completed there, and present day processes are well documented for several instrumented stations in the watershed [e.g., *Renard and Laursen*, 1975]. The emphasis in the present paper is on basin wide considerations of almost a century of process operation.

There are three basic research questions regarding the variation in sediment transportation in the Walnut Gulch Watershed. First, how has sediment transport varied through time? Short-term studies have provided estimates of the magnitude of present sediment transport processes on slopes and in channels which may be placed in a context when compared with century-long record. Second, what has been the spatial distribution of sediment removal during the last erosion episode when arroyo development occurred? Significant channel erosion and concomitant sediment removal occurred in the watershed during the major erosion episode that spanned most of the southwestern United States [*Cooke and Reeves*, 1976]. Third, what has that erosion implied for continued sediment transport? The channel morphology left by the catastrophic erosion episode represents a geometry that controls presently operating processes [*Cooke and Reeves*, 1976].

STUDY AREA

The Walnut Gulch Watershed is located in southern Arizona on pediment gravels, limestone, and igneous outcrops near the town of Tombstone (Figure 1). The drainage area above the lowest U.S. Department of Agriculture measurement site is about 150 km² (57.7 mi²). The rolling terrain of the basin has sandy and gravelly soils typical of the Basin and Range ge-

omorphic province [*Hunt*, 1974]. Geologic materials include Precambrian volcanics and tertiary alluvium [*Gilluly*, 1956; *Wilson*, 1962]. Elevation ranges from about 1220 m (4000 ft) to about 1890 m (6200 ft). The climate is semiarid with mean annual precipitation of about 35.6 cm (14 in) and mean annual temperature of about 17°C (63°F), with wide ranges for both variables [*Sellers and Hill*, 1974]. Precipitation falls mostly as rain from winter storms or sudden summer thunderstorms, so that the entrenched channels in the basin are usually dry. The vegetation in the basin is grass, shrubs, and brush.

Human impacts in the basin include the townsite of Tombstone and associated precious metal mines begun in 1877 [*Meyers*, 1956]. The mine shafts provided little surficial disturbance, but the waste materials from the shafts and from milling operations, active until about 1930, impacted limited areas of the landscape. A railroad serving the mining area and numerous cross-basin roads may have affected channel processes, especially through stabilizing the channel gradient by hardening road/channel intersections. In 1953 the U.S. Department of Agriculture began an intensive instrumentation program in the basin which included the installation of numerous concrete flumes in the channel system [see *Ferreira*, 1979]. The flumes resulted in further stabilization of established stream gradients. Cattle grazing has affected vegetation cover and related hydrologic/geomorphic processes since Spanish incursions from Mexico more than two centuries ago.

Stream channels of Walnut Gulch watershed were mostly narrow and shallow in the late 1800's and meandered across the upper surfaces of alluvial fills. Plat maps drawn in 1881 by the General Land Office Survey show cienegas (wide grassy meadows) in a number of flow areas, especially at junctions of valleys in the center of the basin. In the lower reaches of the trunk stream, the channel was wide, shallow, and sandy. Beginning in about 1930, residents of the area report that the channels of the entire drainage basin were entrenched and the cienegas were destroyed. Massive amounts of sediment were evacuated from the basin, as occurred in many streams of the semiarid and arid southwestern United States [*Cooke and Reeves*, 1976]. The entrenched channels remained in 1981, with small amounts of refilling, as observed elsewhere in the American southwest [*Emmett*, 1974; *Leopold*, 1976].

METHODS

Analysis of sediment removal during the erosion episode depends on knowledge of changing channel dimensions. The
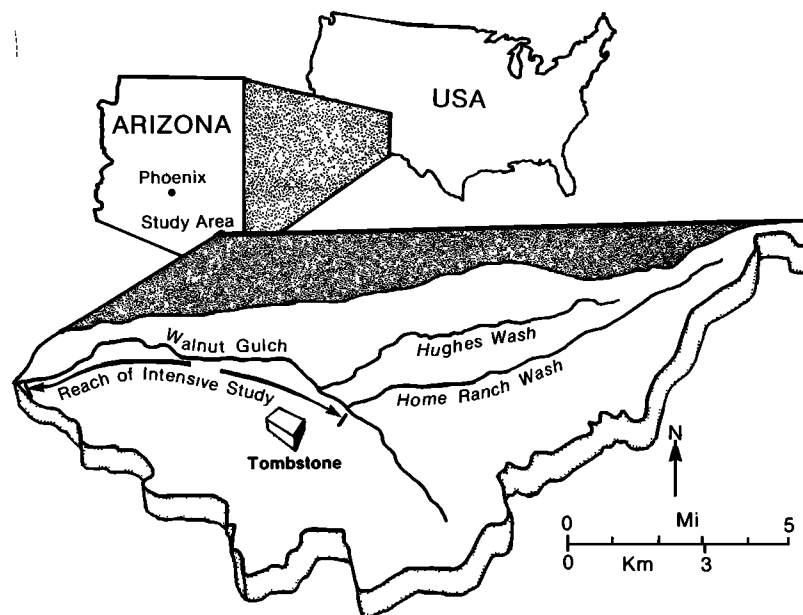
Fig. 1. Walnut Gulch Watershed, southern Arizona.

dimensions in turn provide the basis for the analysis of sediment volumes removed during the erosion episode. Field checks show that channel erosion during the past century is not likely to have incised bedrock but rather has excavated alluvial deposits. Therefore, if the dimensions of the small, pre-erosion channels and of the enlarged post-erosion channels are known at various cross sections, the differences between areas under the two cross sections represent the amounts of material eroded (Figure 2). Data for channel cross sections from the post-erosion period were available from 43 surveyed cross-channel profiles made in 1961 along a 13-km (8-mi) reach of the main stem of Walnut Gulch. The profile data are stored at the Southwest Rangeland Watershed Research Center in Tucson, Arizona. Data for the channel cross sections from the pre-erosion period were from the General Land Office Survey records made in 1881 and 1905, with the majority for the later date. Plat maps and surveyor's notes are available in the Phoenix, Arizona, office of the Bureau of Land Management for 55 cross sections scattered throughout the basin. Although more data would be useful, the historical record is limited.

The cross-sectional data for sediment removed by erosion were extended into the third dimension along channels

——— 1961 Surface   [:::] Bedrock   ▓ Alluvium

- - - - 1905 Surface   ▨ Alluvium Removed, 1905-1961

Fig. 2. Schematic diagram showing a typical cross section on the main stream of Walnut Gulch and illustrating the method of determining sediment volume eroded from the cross section. Not to scale.

throughout the basin. For an analysis of the channels of the entire basin, the data were organized according to the Strahler stream order method [Doornkamp and King, 1971]. The channel orders used were from a previous study by Murphy et al. [1977], permitting the calculation of the amount of sediment removed from an average cross section for each order. The total amount of sediment eroded from the system (which is seventh order) was represented by the function.

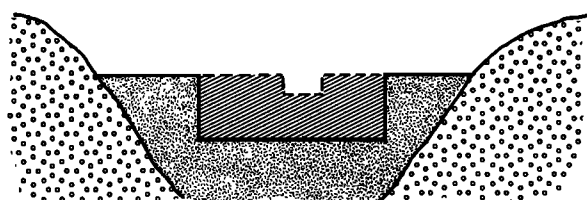$$S_t = \sum_{u=1}^{u=n} L_u \bar{S}_u \qquad (1)$$

where

S_t total volume of sediment removed from the basin channel system;

u stream order;

n maximum order;

L_u total length of streams of order u;

$\bar{S}_u$ mean cross sectional area of sediment removed by erosion on streams of order u.

Calculation of the total volume of sediment removed from the highest order stream was possible in greater detail than an overall average because of numerous cross sections on the main stream. The total reach was divided into 43 subunits, with each subunit centered on a measured cross section (see Figure 1 for the location of the reach of intensive study). The amount of sediment removed from the total reach then was

$$S_7 = \sum_{s=1}^{s=m} S_s L_s \qquad (2)$$

where

S_7 total sediment volume eroded from the seventh (highest) order channel;

s number of cross section;

m maximum number of cross section (43 in this case);

S_s cross sectional area of sediment removed from cross section s;

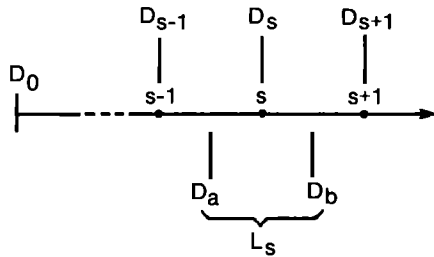L_s length of the subunit centered on cross section s.

Fig. 3. Schematic diagram defining factors used to calculate volume of sediment transported during the erosion episode on Walnut Gulch.

Each of the surveyed cross sections had two types of data: S_s, cross-sectional area of lost sediment and D_s, downstream distance of the cross section from an arbitrary starting point (Figure 3). The boundaries of each section were located halfway between the measured cross sections, so that the length of the end subunits required for the solution of (2) was

$$L_1 = D_1 + \frac{D_2 - D_1}{2} \qquad (3)$$

$$L_m = \frac{D_m - D_{m-1}}{2} \qquad (4)$$

Two measures supply potential process information in the following analyses. First is the concept of 'tractive force' suggested, named, and defined by DuBoys in 1879 [Bogardi, 1978, p. 80] where

$$\tau_0 = \gamma RS \qquad (5)$$

where

τ_0 mean tractive force, $N\ m^{-2}$,
γ unit weight of water $(9807\ N\ m^{-3})$;
R mean hydraulic radius, m;
S energy slope (must be assumed to be equal to bed slope in field applications).

It is perhaps misleading to refer to the DuBoys value as tractive force since it is not a force in the physical-mathematical sense, but the term and equation are widely accepted [Bogardi, 1978, p. 83]. The geomorphic significance of tractive force is that it is directly related to the competence of stream flow over a wide range of particle sizes (recent reviews by Baker and Ritter [1965] and Church [1978]). The units for tractive force (e.g., as shown by Church [1978, p. 756]) are the same as the units for shear stress (as given by Stelczer [1981, p. 18]).

The second measure of potential process is total stream power, the amount of power expended by flowing water per unit length of channel. As defined by Bagnold [1966, 1977] it is

$$\Omega = \gamma QS = \tau_0 VW = \gamma RSVW \qquad (6)$$

where Ω is total stream power in N, V is mean velocity of flow in m s^{-1}, W is width of flow in meters, and other symbols as before. The geomorphic significance of total stream power is that it is directly related to total sediment discharge, that is, stream capacity assuming a constant supply of sediment (see GRAF [1971] for a review).

Church [1978] found that the critical tractive force for very loose sediment was

$$\tau_c = 1.78\ d \qquad (7)$$

where τ_c is critical tractive force in Newtons per meters squared and d is the median particle diameter in millimeters. The importance of critical tractive force to the present study is that tractive force generated by some flows may be insufficient to move commonly found particle sizes in some reaches of the channel.

RESERVATIONS

The results of the investigation of spatial and temporal variation of sediment transport must be viewed with certain constraints in mind. The channel dimensions for the period before the erosion episode are from the notes of surveyors who were more concerned with township survey than with stream channels. General Land Office surveys that can be checked in other areas by independent evidence have proven reliable in some cases but not in others [Cooke and Reeves, 1976]. The records in the Walnut Gulch area appear reasonable in light of photographic evidence and recollections of long-time residents [Hastings and Turner, 1965].

Also, the original surveys do not provide samples of channel dimensions as frequently along the main stream as do later surveys. The lack of depth information at many cross sections in the older surveys required the use of depth dimensions calculated from allometric relationships established from known cross sections [Bull, 1975; Graf, 1979], further reducing the precision of the data. Channel dimension data from the old surveys represent a definite improvement over qualitative estimates, however.

The estimate of sediment removed during the erosion episode involved comparison of the pre-erosion channels with those surveyed in 1961. Most of the erosion probably occurred during events of intense precipitation in the early 1930's and early 1940's (precipitation data published by Cooke and Reeves [1976, pp. 65–79]). An implicit assumption was made that after the episode of erosion was completed (by 1945 at the latest), no channel enlargement occurred. This assumption was probably not strictly met, and some bank or bed scour probably occurred after the erosion episode and before 1961. The amount of material involved, however, is not likely to have altered the calculations appreciably because there were few significant precipitation episodes during the period [see Cooke and Reeves, 1976, pp. 70–72].

In the comparison of rates of process, average yearly values were used for convenience, but actually the processes are discontinuous, and year to year variation is substantial. Along the channel, periods of scour and fill alternate with each other. The average rates of sediment yield from slopes do not take into account climatic variability but submerge such variability in long-term averages. Sediment production rates are likely to have been significantly different in the period prior to the erosion episode when the vegetation cover was different in many parts of the basin. Variation in human-induced changes, such as road building, mining, and grazing of cattle, also limit the extension of estimates of production of sediment from slopes.

SPATIAL VARIATION

The total amount of sediment removed from the channels was enough material to cover the basin to a depth of 4 cm (1.6 in). The values reported in Table 1 show that the major portion of sediment removed from the channels of Walnut Gulch Watershed was removed from the highest-order channel. Despite the great numbers of lower-order channels, the relatively

TABLE 1.   Sediment Volumes Removed During Erosion Episode, Walnut Gulch Watershed, Southern Arizona

Stream Order	Stream Number	Mean Stream Length, m	Mean Drainage Area, km²	Mean Cross-Sectional Area, m²	Mean Individual Volume, m³	Total Volume, m³	Volume, % of Total
1	6134	96	0.01	0.1	10	61,300	1
2	1373	190	0.03	0.2	38	52,200	1
3	257	508	0.13	0.8	406	104,000	2
4	58	1,306	0.50	2.4	3,134	182,000	3
5	15	2,430	1.95	7.3	17,739	266,000	4
6	3	5,712	7.62	22.2	126,806	380,000	6
7	1	13,051	146.52	*	*	5,100,000	83
Total						6,150,000	100

Table values in the final column are rounded.
*Mean values replaced by detailed survey data.

small amount of material removed from each one results in low amounts of sediment being eroded from them in total. Whether or not these results are typical of semiarid watersheds remains to be seen, because data are not available for comparison. In a similar analysis of basins in a humid region, J. C. Knox (University of Wisconsin, Madison, personal communication) found that most of the sediment lost from channels in an erosion episode came from the lower-order streams.

The spatial variation of erosion is directly related in budgetary fashion to a comparison between total stream power and the amount of sediment supplied to the channel system. It is impossible to construct a complete time series of sediment supply from surrounding slopes, but the channels are excavated into unconsolidated materials, either alluvium deposited by the stream in its geologically recent configuration or basin fill shed from surrounding mountains. Therefore, throughout the period of interest sediment supply has exceeded transport capacity, and spatial variation in form is attributable to spatial variation in transport capacity or total stream power.

The Walnut Gulch case probably differs from the southwestern Wisconsin example because of the particle sizes involved. In Wisconsin, sediments are from fine-grained loess soils (Figure 4) so that they are carried in suspension and bedload is not a large proportion of the total load (*Schumm* [1977] reviews river

transport types and regions). In Walnut Gulch much of the sediment is coarse continental alluvium carried by the streams as bedload. The particle size d_{84} for the alluvium is in the 4.0- to 8.0-mm range [*Osterkamp et al.*, 1982]. Field investigation revealed many particles 25 mm or larger in medium diameter. In lower orders depth of flow is insufficient to generate the high values of tractive force (or competence) required for transport.

The large amounts of sediment eroded from the highest-order of the channel network (as shown in Table 1 and Figure 5) direct attention to a detailed analysis of the main stream of Walnut Gulch. A plot of cross sectional area of sediment removed by erosion against downstream distance in the trunk stream (Figure 6) shows that the amount of material removed first increases and then decreases downstream. General explanation of the trends in Figure 6 depends on sediment supply, tractive force, and total stream power.

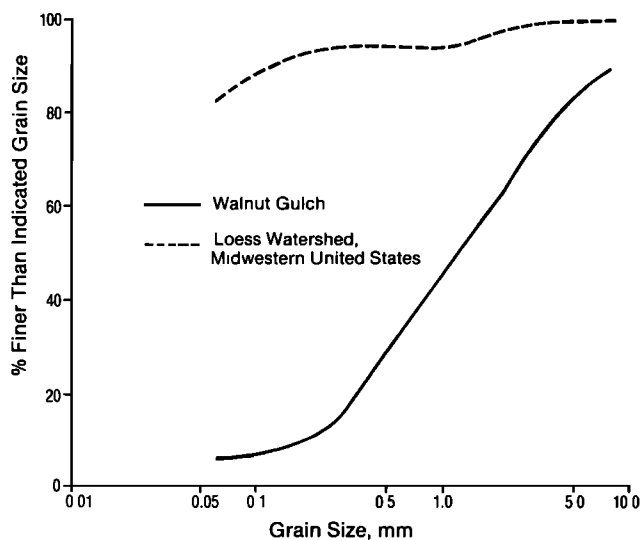As stated previously, sediment supply has exceeded transport

Fig. 4.   Particle size analyses for the channels of the main trunk of Walnut Gulch and a typical loess watershed in the midwestern United States.
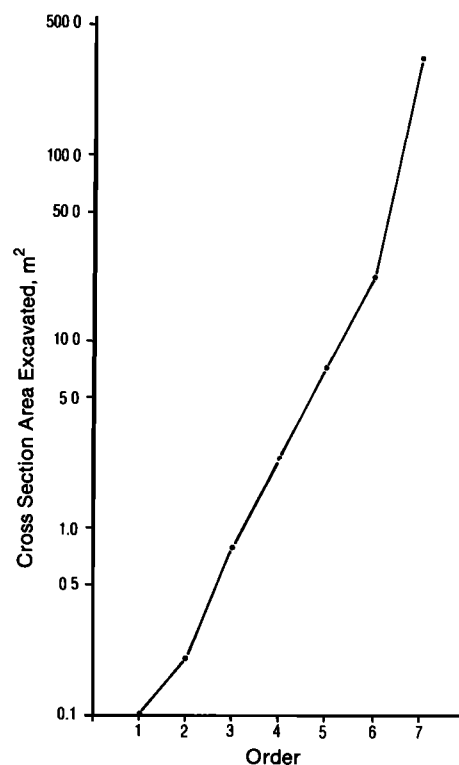

Fig. 5.   Distribution by stream order of mean area of channel cross section excavated by erosion in channels of Walnut Gulch Watershed.
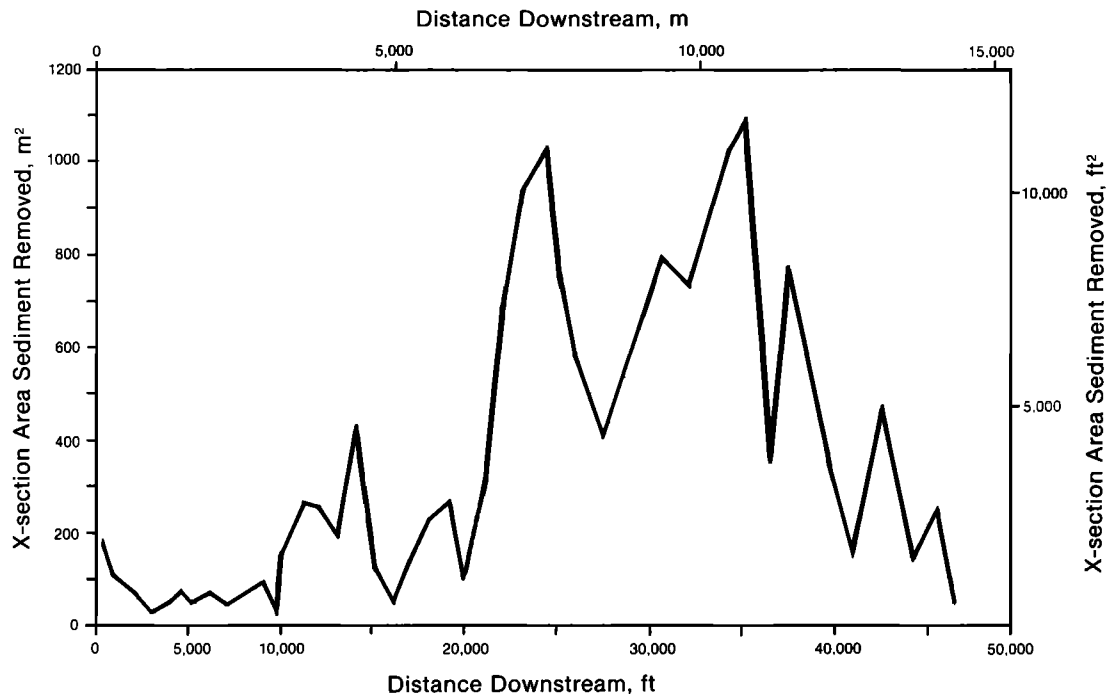
Fig. 6. Downstream distribution of area of channel cross section excavated by erosion on the main stream of Walnut Gulch. See Figure 1 for the location of this intensively studied reach.

capacity throughout the past century and is not a variable in this discussion. Generally, as higher orders are considered, the 10-year discharge at any one cross section increases, channel slope exhibits relatively small declines, and width increases dramatically (Figure 7). The interaction of discharge and width, however, causes a decrease in depth from sixth to seventh order (Figures 6 and 7). The amount of material excavated from the upper reaches of the network is relatively small where depth of flow is insufficient to entrain the basin materials. In midbasin areas, tractive force (competence) is sufficient to entrain materials and the channel is wide enough to permit high values of total power (capacity), so large amounts of material were lost. In the lowest reaches, the channel became so wide that depth of flow and tractive force declined and limited the amount of material lost by erosion. Transmission losses, unaccounted for in this analysis, also depleted available discharge and tractive force, as well as total stream power [Renard, 1970; Lane et al., 1980].

The final distribution of erosion is modified by a variety of local influences extending a few hundreds of meters along the channels in a variety of locations. These local phenomena represent variability in bank resistance so that the general trend of changing amounts of channel erosion in the downstream direction, as shown in Figure 6, is imperfect. At downstream distance 8230 m (27,000 ft), a minimum of erosion indicates that relatively small amounts of material were removed in comparison to adjacent channel areas. The area of the reduced sediment loss is spatially coincident with surface outcrops of Schieffelin Granodiorite (Tertiary) and Naco Limestone (Permian). These highly resistant materials cause more narrow, deep, and steep channel morphology than the Tertiary-Quaternary alluvial materials that dominate the other reaches of the main stream (for a geologic map of the basin, see U.S. Department of Agriculture [1970]). Channels through the resistant section contained less alluvium for potential erosion than other nearby reaches.

Other specific details of the spatial distribution of sediment

removal include a peak of sediment removal near 4000 m (about 14,000 ft). Sedimentary materials in the reach are dominated by fine-grained, easily entrained materials, so that the arroyo left after the erosion episode was significantly wider and deeper in this reach than in nearby reaches. The wide fluctuations in amount of material removed from the lowermost reaches result from the influences of geologic structure and the nature of the sediment transport process itself. In some instances, areas where little erosion occurred had stored little sediment initially because the channel was eroding through exposed resistant strata. In such places the channel was relatively narrow, deep, and had a steep gradient. Other fluctuations in the amount of sediment removed from the lowermost reaches reflect masses or pulses of sediments moving through the system. Because the sediments are moved by discontinuous events, these pulses are probably temporary features.

TEMPORAL VARIATION

The amount of material eroded from channel storage areas during the erosion episode can be placed in a temporal context by comparison with data collected in other studies of Walnut Gulch. Comparisons are possible for channel storage on a several-thousand-year scale and on a scale of a few years during the post-erosion period for sediment from slopes and channels.

Although large volumes of materials are involved in the recent erosion episode (about 6.2×10^6 m^3), the volume is small in comparison to the amount of alluvium remaining beneath the channels. A well in the lower reach of the main stream channel revealed that alluvium extended to a depth of 29 m (95 ft) below the surface of the modern channel [Renard, 1977]. Therefore, based on survey data of channel cross sections at a similar site nearby and assuming continuity of subsurface conditions, the episode of erosion removed only about 15% of the alluvial materials stored in the lower reaches. Even allowing for substantial entrenchment of the channel and lesser depths of alluvium upstream, the amount of material removed
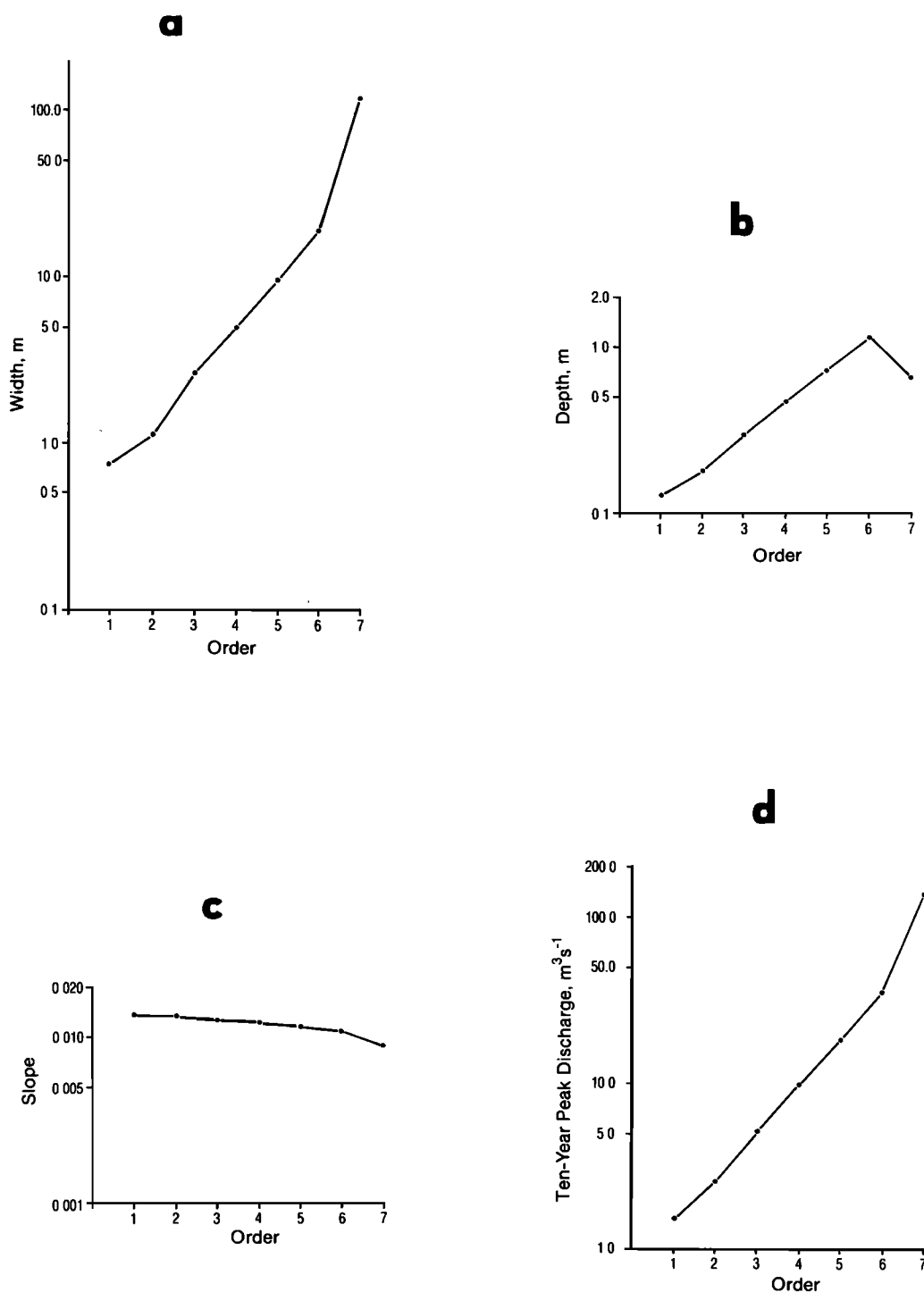
Fig. 7. The distribution by stream order of mean values of hydraulic parameters in channels of Walnut Gulch Watershed. A, width; B, depth; C, channel bed slope; D, magnitude of calculated 10-year peak discharge.

in the erosion episode accounted for only a minor portion of the total amount still stored in the basin.

Local accounts indicate that most of the catastrophic channel erosion occurred within a 15-year period commencing about 1930. The erosion process was inconsistent from one year to the next, but the overall average rate of sediment transport from channel storage was about 434,000 m³ per year. Studies by *Renard* [1972] and *Renard and Laursen* [1975] show that during the post-erosion period the yearly average of sediment output from the entire basin was about 24,100 m³. The rate of

sediment removal during the erosion episode therefore was 18 times the rate observed after the episode.

Sediment contributions to the channels from surrounding slopes under conditions of the post-erosion period are about equal to the amount of material transported through the channels. In recent work, *Simanton et al.* [1977, 1980] and *Renard* [1980] have calculated that 20,000 to 25,000 m³ of material are eroded from the basin slopes. Given the accuracy of the estimates and variable lengths of record, the annual slope erosion can be considered identical to the annual channel
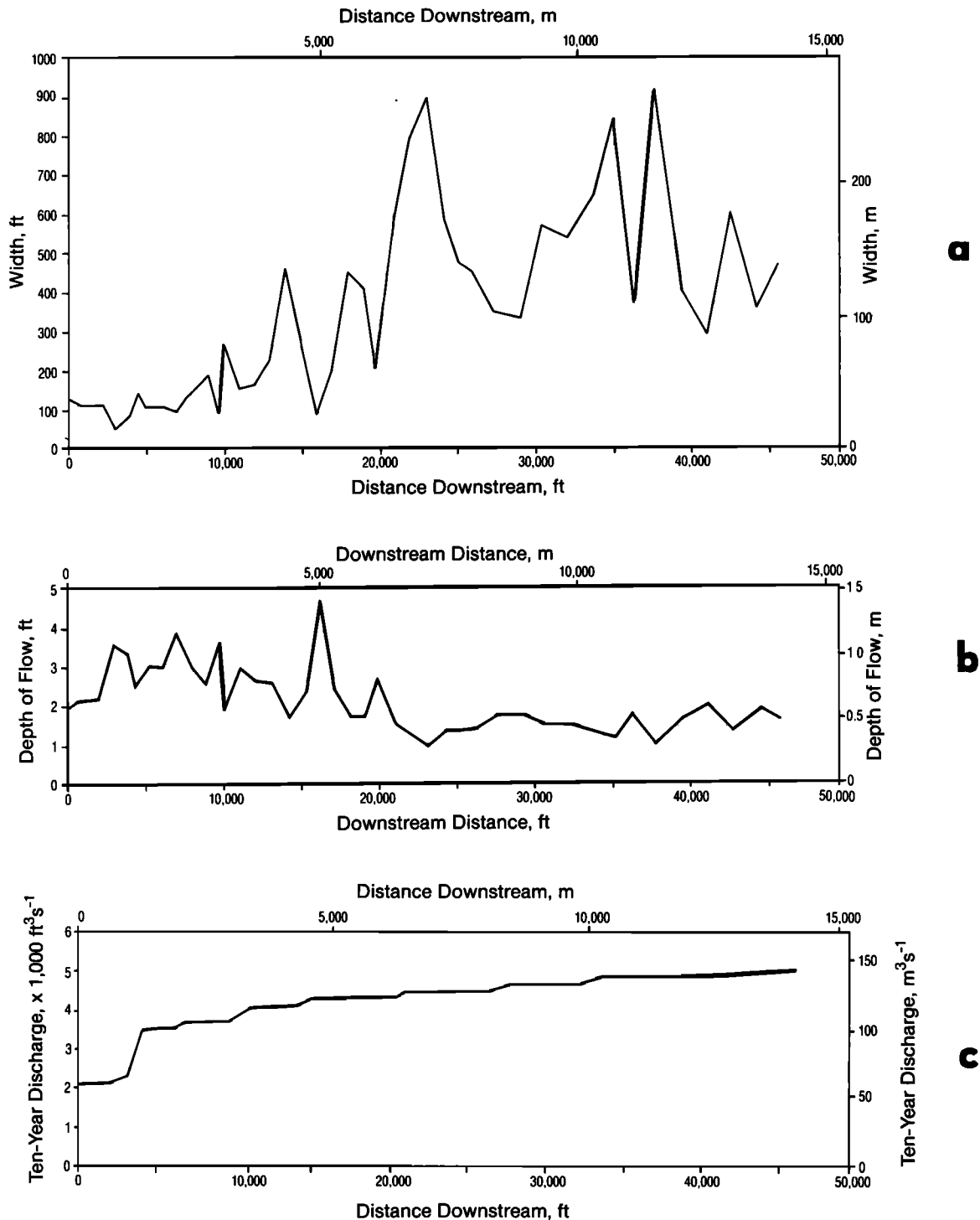
Fig. 8. Downstream distribution of hydraulic variables in the main trunk of Walnut Gulch Watershed. A, width; B, depth; C, magnitude of the 10-year peak discharge. Channel bed slope relatively invariate and not plotted.

transport of 24,100 m³. If the present rates of sediment production from slopes and throughout were to be maintained, the material excavated from the basin during the erosion episode would not be replaced.

IMPLICATIONS FOR PRESENT PROCESSES

The spatial distribution of sediment removal left behind channel forms that have important implications for continuing processes. Because the vast majority of sediments in the semi-

arid streams of Walnut Gulch are transported as bedload and because in the main channel large amounts of sediments remain available for entrainment, tractive force and total stream power represent reasonable indicators of the ability of the channels to transport sediment [*Graf*, 1971]. When these measures are calculated for the discharge of the 10-year flood along Walnut Gulch (flood data from previous work, published in part by *Knisel et al.* [1979] and *Reich and Renard* [1981]), the resulting distributions show that present conditions are different from
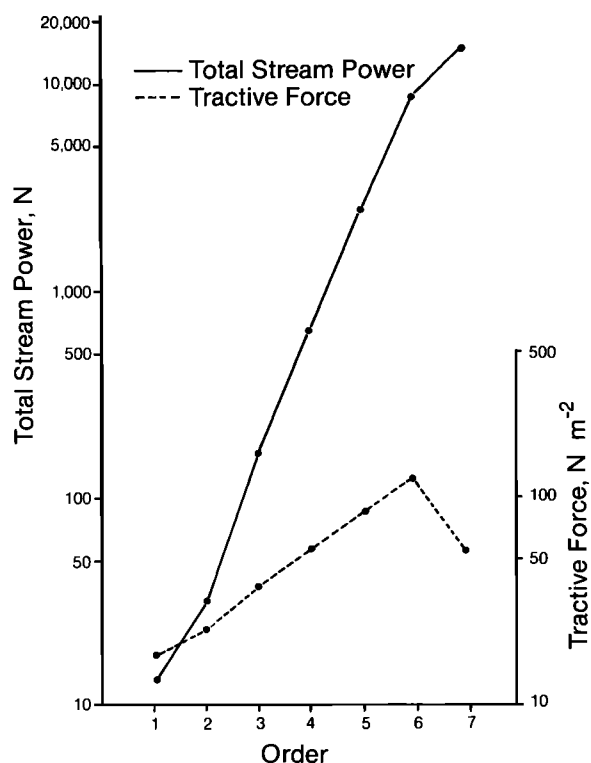
Fig. 9.   Distributions by stream order of mean values for tractive force and total stream power for channels of Walnut Gulch Watershed.

those prior to the erosion episode (see Graf [1982] for a detailed analysis from a different area). Figures 7, 8, and 9 show the spatial distribution of hydraulic measures.

Under conditions of the post-erosion period, total stream power increases consistently with increasing order (Figure 9). Tractive force also increases with increasing order until the highest or seventh order is encountered (Figure 9). Dramatic increases in width and concomitant declines in depth serve to limit tractive force and competence (Figure 7). The largest particles in the channel may therefore be carried in midbasin areas, but in lower reaches they may not be transported because of lower levels of tractive force. Renard and Laursen [1975] noted the fine characteristics of sediment transported in the lower reaches as opposed to upstream areas, a further

indication that the coarse particles are not entrained in the lower reaches. The large particles require almost 45 N m² tractive force for motion (from (7) and 25-mm particles), and as shown in. Figure 9, this critical level is not attained in some reaches.

In the main trunk of Walnut Gulch, downstream trends in tractive force are much different after the erosion period than they were before (Figure 10). An erratic but general decline in tractive force in the downstream direction replaced a marked downstream increase. It appears likely that the largest particles in the stream sediments can be carried in the upper reaches but not the lower reaches of the trunk stream, while the reverse was true before arroyo development.

In the trunk, total stream power increased in the downstream direction more rapidly before the erosion episode than after (Figure 11). The post-erosion system lacks the steep gradients in total power found in the pre-erosion system, resulting in more throughput of sediments in midbasin area at present. In the more recent channel system, well-defined boxlike channels (which replaced wide shallow swales) produce higher levels of total power in the upper reaches of the main stream because before arroyo development the channel could not contain all the water in the 10-year flow.

One of the most important implications of the spatial variation of sediment removal is that it imposes a particular spatial control on subsequent fluvial processes. The channel morphology left after the erosion episode dictates the likely foci of erosion and deposition. Since sediment is readily available, those reaches with sharply declining tractive force and total power are likely deposition sites, while those with sharp increases are likely erosion sites. The placement of one or a limited number of recording instruments is therefore likely to provide an inaccurate or misleading representation of the true nature of processes along the main stream. The temporal variation of sediment removal also makes limited recorded data difficult to interpret, since such data are useful in a predictive sense only until the next catastrophic adjustment.

The calculations reported here rely on flow generated by the 10-year flood, which has a magnitude too small to substantially affect the channel morphology of the network within the span of a single event. The continued movement of materials from low-order streams and storage in high-order streams might in time alter the spatial arrangements of tractive force and total stream power, but the role of high-magnitude events in such a
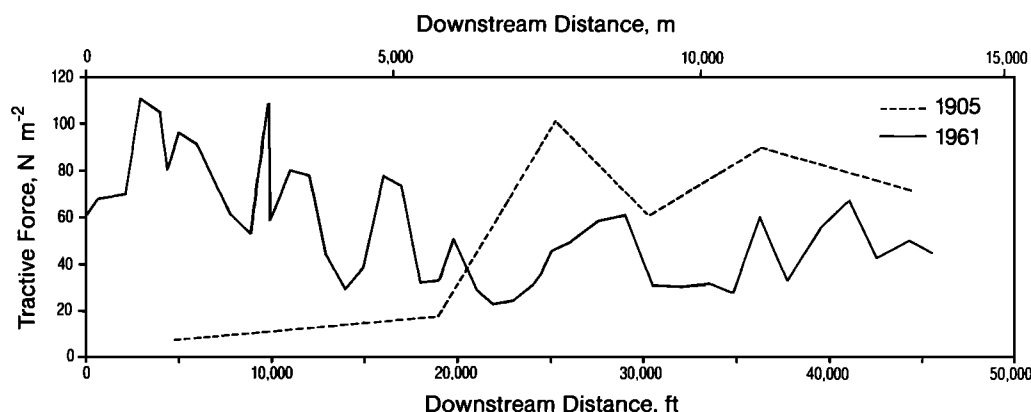

Fig. 10.   Downstream distributions of tractive force for the main trunk of Walnut Gulch. See Figure 1 for location of this intensively studied reach. For reference purposes the largest common particles have critical tractive force levels of about 45 N m⁻².
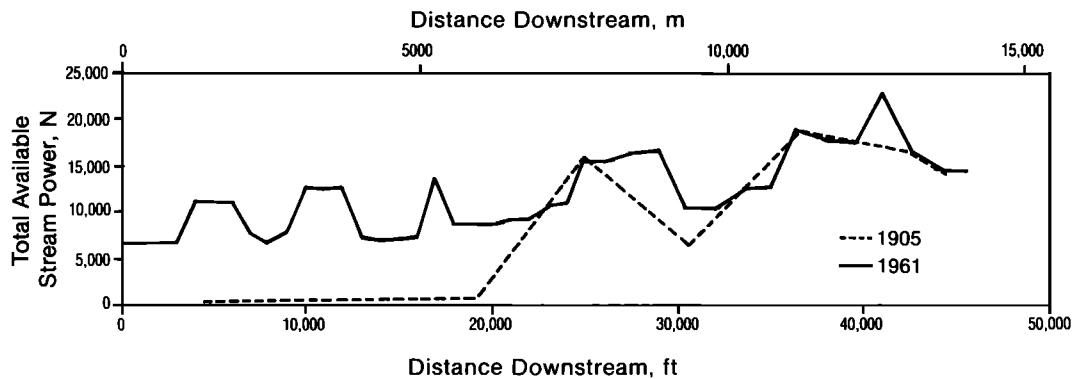
Fig. 11. Downstream distributions of total stream power for the main trunk of Walnut Gulch. See Figure 1 for location of this intensively studied reach.

scheme is unknown. The 100-year event, for example, might completely change the present system and establish new spatial arrangements over a short period.

CONCLUSIONS

Tentative answers are possible for the basic research questions. First, rates of sediment transport during the erosion episode were about 18 times greater than channel sediment transport rates or production of sediment from slopes during the post-erosion period. The precipitation record [Cooke and Reeves, 1976, pp. 70–73] shows at least two remarkable years of intense precipitation during the episode. Second, during the erosion episode beginning about 1930 the majority of sediments evacuated from the basin were eroded from the highest-order stream. At cross sections along the length of the highest-order segment, the amount of sediment removed increased in the downstream direction to a maximum and then declined, a distribution reflecting the conflicting influences of variation in discharge and channel width. Third, the arroyo forms left by the erosion episode control the distribution of tractive force and total stream power so that renewed storage of sediment is likely in only a few limited areas.

A geomorphological perspective on the sediment transportation processes on the Walnut Gulch watershed as outlined above indicates that short-term analyses of the processes produce accurate but imprecise views on the processes that are not comprehensive. Process rates obtained from instrumented portions of the basin during the past three decades cannot be extended spatially or temporally without risk of substantial error. Without the short-term analyses, the longer-term geomorphologic perspective provides a highly generalized view lacking in detail, especially with respect to presently operating processes. Evidence from the Walnut Gulch Watershed suggests that the prudent watershed analyst is one who employs a judicious mixture of engineering and geomorphic approaches to basic and applied research.

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