LONGITUDINAL PROFILES OF EPHEMERAL STREAMS
IN SOUTHEASTERN ARIZONA

by
Douglas Stuart Cherkauer

A Thesis Submitted to the Faculty of the
DEPARTMENT OF GEOLOGY
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

1969

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under the rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED:

Douglas A. Chabane

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

William B. Bull
William B. Bull
Professor of Geology

August 1, 1969
Date

ACKNOWLEDGMENTS

This project could never have been completed without the continual help and encouragement, in the field and with the drafting and typing, of my wife, Kathy. Mr. Thomas Maddock, Jr. initially suggested the topic for study, and his subsequent comments and ideas have been of great value. Dr. William B. Bull offered many useful and time-saving techniques and suggested important correlative investigations while serving as thesis director. In addition to these two men, Dr. John Sturgul reviewed the manuscript, making many valuable comments.

The Department of Geology and the University Computer Center provided the necessary computer time and program consultation.

TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS	vi
LIST OF TABLES	viii
ABSTRACT	ix
INTRODUCTION	1
Purpose	1
Location	1
Collection of Data	3
Presentation of Data	3
MEASUREMENTS	4
Selection of Parameters for Measurement	4
Map Measurements	5
Drainage Area	5
Channel Length	6
Channel Gradient	6
Concavity	6
Relief	7
Field Measurements	7
Channel Cross-section	8
Bed Material Size	10
Additional Field Parameters	12
Precipitation Index	12
GEOLOGIC AND HYDRAULIC CONDITIONS IN THE CHANNELS STUDIED	17
Whetstone Mountains	17
Mustang Mountains	21
Sierritas	26
Summary of Downstream Relations	32
INTERRELATIONS AMONG PARAMETERS LEADING TO A NATURAL SUBDIVISION OF DATA	36
CONCEPT OF THE EPHEMERAL STREAM PROFILE	44
Review of Pertinent Work on Longitudinal Profiles	44
Controls on the Longitudinal Profile	46
Significance of the Point of Concavity Change	48

TABLE OF CONTENTS--Continued

	Page
Summary	53
DEVELOPMENT OF EMPIRICAL EXPRESSIONS FOR THE PROFILES	54
TEST OF THE PROFILE EQUATIONS	63
CONCLUSIONS	71
REFERENCES	74
APPENDIX I	76
APPENDIX II	78

LIST OF ILLUSTRATIONS

Figure	Page
1. Index Map Showing Locations Mentioned in Text	2
2. Variation of Precipitation with Elevation in the Study Area .	14
3. Location Map for Streams and Stations in the Whetstone Mountains	18
4. Longitudinal Profiles (A) and Concavities (B) in the Whetstone Mountains	19
5. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Whetstone Mountains	20
6. Location Map for Streams and Stations in the Mustang Mountains	22
7. Longitudinal Profiles (A) and Concavities (B) in the Mustang Mountains	24
8. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Mustang Mountains	25
9. Location Map for Streams and Stations in the Sierrita Mountains	27
10. Longitudinal Profiles (A) and Concavities (B) in the Sierrita Mountains	30
11. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Sierrita Mountains	31
12. Relation of Mean Particle Size (A) and Width:depth Ratio (B) to Channel Gradient	37
13. Relation of Drainage Area (A) and Area:relief ² Ratio (B) to Channel Gradient	38
14. Relation of Channel Gradient at a Given Distance from the Divide to Basin Relief and Length	39
15. Relation Between Mean Particle Size and Width:depth Ratio . .	41

LIST OF ILLUSTRATIONS--Continued

Figure	Page
16. Relation of Cumulative Tributary Density to Channel Length and Concavity Change	49
17. Location Map for Streams and Stations in Catalina and Tucson Mountains	64
18. Comparison of Real and Predicted Profiles in Catalina Mountains	67
19. Comparison Between Real and Predicted Profiles in the Tucson Mountains	68

LIST OF TABLES

Table	Page
1. Elevation Zones for the Precipitation Index Values	15
2. Summary of Locations of Major changes in the Longitudinal Variation of Parameters and Their Relations to Bedrock . .	33
3. Relief:length Ratios of the Concavity Segments	40
4. Comparison of the Actual Channel Length from Divide to Concavity Change with Those Predicted from Cumulative Tributary Density	49
5. Comparison of Profile Concavity, Rate of Drainage Area Increase and Rate of Particle Size Decrease	52
6. Regression Equations Relating Drainage Area, A, Particle Size, D_{10} , Width:depth Ratio, W/D, and Gradient, S, to Channel Length, L	59
7. Comparison of Real and Predicted Concavities	61

ABSTRACT

The existence of two longitudinal profile segments of different concavity in ephemeral streams heading in the mountains of southeastern Arizona is shown to be related to the longitudinal variation of drainage area, A , bed material size, D_{mm} , and channel width:depth ratio, W/D . These parameters approximate discharge, sediment load and roughness, which have been found to control the profile in other regions, but were unavailable for this study.

Inclusion of basin relief, R , and lithology allowed development of statistically significant equations for both segments of streams draining granitic and sedimentary terrains:

Sedimentary concave:

$$S = \frac{(6.6 \times 10^{-5})R^{.80}D_{mm}^{.20}(W/D)^{.14}}{A^{.40}} \quad (1)$$

Sedimentary straight:

$$S = \frac{(1.4 \times 10^{-3})R^{.38}D_{mm}^{.26}}{A^{.19}} \quad (2)$$

Granitic concave:

$$S = \frac{(7.6 \times 10^{-6})R^{1.02}D_{mm}^{.28}(W/D)^{.22}}{A^{.51}} \quad (3)$$

Granitic straight:

$$S = \frac{(1.6 \times 10^{-3})R^{.42}D_{mm}^{.062}}{A^{.21}} \quad (4)$$

Profiles of streams with known lithology and relief in two additional mountain ranges were predicted from the equations with an accuracy within the limits of accuracy of the field and map measurements. Precipitation-elevation relations have no apparent effect on the accuracy of the predictions or on stream-profile concavity.

INTRODUCTION

Purpose

The longitudinal profiles of the ephemeral streams draining the mountains and alluvial valleys in southeastern Arizona are unusual. Rather than a constant rate of decrease of gradient downstream, or constant concavity, these profiles have one concavity from the divide to a point near the mountain front and another, much lower concavity below this point. This study was undertaken to determine whether the change in concavity is related to hydraulic and geologic conditions.

Location

The three mountain ranges studied, the Whetstones, Mustangs and Sierritas (Fig. 1), contain streams with segmented profiles. The Whetstone Mountains are located on the Benson, Arizona, quadrangle (1:62,500), some 45 miles southeast of Tucson. Streams on the east side of the range draining into the San Pedro River were studied. The Mustang Mountains are immediately south of the Whetstones, separated from them by Rain Valley. They are mapped on the Mustang Mountains and Elgin, Arizona, quadrangles at 1:24,000. Three streams with diverse orientations were measured. Two drain into the Babocomari River, and the third drains into Rain Valley. Both of these streams in turn flow into the San Pedro. The Sierritas are located on the Twin Buttes, Arizona, 1:62,500 quadrangle, 25 miles south of Tucson. Three main and four smaller streams draining east to the Santa Cruz River were studied.

FIG. 1. INDEX MAP SHOWING LOCATIONS MENTIONED IN TEXT.

Collection of Data

Measurements were made on accessible streams. Stations for measurement were selected arbitrarily along the length of each stream, but an attempt was made to space them uniformly within each profile segment. Generally, about the same number were established above and below the change in concavity. A longer spacing interval was used in the low-concavity segments since they are longer than the high-concavity segments. Figures 3, 6 and 9 show the station locations.

Field work was done during the winter and spring months of 1968 - 1969. In general, the full upstream segment and part of the downstream segment of each stream was walked, while the remainder was spot checked due to the long distance involved. Since the emphasis was on determining the cause of the concavity change, the field investigations were concentrated around the area of change. No stations were established more than six miles from the termination of the high-concavity segment. Data supplemental to field measurements were obtained directly from topographic maps.

Presentation of Data

The data was initially handled graphically, and most of the information for individual streams is presented in this manner. However, as the sample population and the number of variables increases, it becomes increasingly difficult to show the relations graphically. Consequently, the data was processed by a computer to get standard regression relations for the more complex situations.

MEASUREMENTS

Selection of Parameters for Measurement

Studies by Leopold and Maddock (1953), Wolman (1955), Leopold and Miller (1956), Hack (1957), Leopold and Wolman (1957), Miller (1958), and Brush (1961) have indicated that a stream's longitudinal profile is adjusted to discharge, velocity, sediment load, and channel roughness and shape as well as lithology, relief and climate. While many of these parameters can be readily observed in ephemeral channels, the relative infrequency of flow makes direct measurement of the hydraulic features, discharge, velocity, load and roughness, too difficult for a comprehensive, short-term study. Hence means for approximating flow parameters from the dry stage were sought. Leopold and Miller (1956, p. 23) cite a study by H. H. Hudson (unpublished) which shows a constant relation exists between drainage area and discharge in ephemeral streams: $Q \propto A^{.79}$. The exponent varies elsewhere between +.7 and +.8. In perennial streams, the relation is again very consistent, but with an exponent of about +1.0 (Leopold, Wolman and Miller, 1964, p. 251). Hence drainage area should be a good index of discharge.

This relation, however, is complicated by two factors. First, the climate in southeastern Arizona is directly dependent on elevation, so that a stream flowing from high mountains into a relatively low basin will receive more rainfall and probably more runoff in its headwaters than it will at lower points along its path. Secondly, when flow occurs

across the alluvial portions of a basin, water is lost by both infiltration and evaporation. The effect of the first factor will be included by relating precipitation and elevation, but the second is extremely difficult to determine from dry streams and will be discussed only qualitatively in this paper. Published studies of this phenomena include Babcock and Cushing (1942), Keppel and Renard (1962) and Renard and Keppel (1966).

Sediment load should also be related to drainage area, as the material available for transport increases with area. Leopold and Maddock (1953, p. 42) indicate that in channels with coarse bed material, such as those of the study area, roughness is largely a function of the size of material. Finally, the cross-sectional shape of the channel is related to roughness, velocity distributions and thus probable sediment load. Hence drainage area, precipitation, bed material size and channel shape will be substituted for the hydraulic parameters.

Map Measurements

Drainage Area

The drainage area upstream from each of the stations was measured from U.S.G.S. topographic maps using a compensating polar planimeter. This instrument is accurate to .01 square inches, or about .01 square miles on 1:62,500 maps and .001 square miles on 1:24,000 maps. Generally only one or two measurements were made as the instrument showed great consistency in the values measured. In most cases, variability due to measurement was less than 5%.

Channel Length

Channel lengths were measured directly from the topographic maps, allowing an accuracy to ± 100 feet on 1:62,500 maps and ± 50 feet on 1:24,000 maps. Measurement variability never exceeds 10% near the divide and is generally less than 2%.

Channel Gradient

Stream gradient was defined as the average channel slope between the point on the channel three to five contour lines above a station and the point an equal number of lines below the station. Inclusion of several contour intervals produces an averaging effect which smooths out some of the local variation and also reduces the error due to measurement. Since the gradient is simply fall, or vertical drop, divided by channel length, the error will be approximately the same as, or slightly larger than, that for channel length alone.

Concavity

The longitudinal profile of a stream is the relation between fall, H , and length, L . Gradient is simply the first derivative of the profile equation, dH/dL . Hack (1957) defined concavity as the exponent n in the power function relating gradient, S , and stream length, L , $S = kL^n$. Graphically, this is represented by the slope of the line formed when gradient is plotted against length on logarithmic coordinates. In essence, n is a function of the rate of change of gradient with length, dS/dL , the second derivative of the profile equation. Concavity, as used in this paper, will refer to n , the power function exponent. The errors due to measurement of both length and

gradient are thus included in concavity. However, the inaccuracy resulting from fitting a line to a scatter of points overrides these errors and limits determination of concavity to the nearest tenth.

Relief

Relief is defined as the difference in elevation between a specified point on a stream and the point where the drainage divide is met by extension of the stream's longest headward tributary. Relief was measured to the nearest 25 feet on 25 foot contour interval maps and the nearest 50 feet on those with contour intervals greater than 25 feet. The accuracy of the map elevations is well within these limits so, in effect, there is negligible measurement error involved in relief.

Field Measurements

Field measurements were made at the stations chosen from the maps. An attempt was made to select a representative 100 foot reach from a straight section of the channel near the map locality. If pool and riffle patterns were found, equal numbers of each feature were included in the section. Where the channel alternated between a single channel and braided reaches, the section chosen included both features. For convenience in fully braided reaches, the section with the narrowest islands was chosen to allow continuity in channel width measurements. Since the actual field measurements were rarely made at precisely the map point, a small location error is added to the measurement error of channel length.

Channel Cross-section

To measure a channel cross-section, one must first define that channel's banks in a way that will be valid for other streams. If a dominant flood level, similar to the bankfull stage of perennial streams, exists in a channel, it should leave distinct traces on the vegetation and alluvium of the banks. Because of their lower frequency, higher floods would be represented by less distinct traces, while smaller, more frequent floods would leave traces below the bankfull level which would be destroyed by a bankfull flood. A pronounced flood level does exist on the banks of all the streams studied, but it becomes progressively harder to trace upstream. In general, the most common marker is the level of vegetative flood debris caught on brush or wedged between rocks on the banks. Since the material floats, it must mark the water surface at some time during the flood.

The significance of the floating debris lines is supported by the frequency of occurrence of other indicators at the same level. Abrupt changes in vegetation density or type occur at the flood-debris level. Often less resistant plants such as mosses or fine grasses grow above this level, but not below it. Bank materials commonly show significant changes here also. Below the flood-debris level, fine sand and other obvious fluvial deposits occur frequently, while above it few can be found. In addition, there may be a color change in the fine material composing the banks which agrees with the flood debris. Upstream, as these indicators become less frequent, certain cacti appear to be useful markers. In particular, the agave seems unable to survive below the bankfull level. Defined on the basis of these indicators, the

bankfull level shows no particular relation to terraces. It can occur at a terrace level, above it, below it, or occasionally, between two terraces. However, at stations where the bankfull stage occurs at a terrace level, the coincidence remains consistent throughout the reach studied.

Once bankfull stage was defined independently on each bank, a line was stretched taut between the two points perpendicular to the direction of flow. As a final check on the validity of the bankfull position, the line should be level in straight reaches. Width was measured to the nearest half foot, and depth was measured to the nearest inch at one foot intervals along the line. If the channel was braided, then the line was stretched continuously across all channels perpendicular to the overall direction of flow. Those channels in which flow occurred at bankfull stage were measured and total channel width was the sum of the individual channel widths. Generally, three cross-sections were measured at arbitrarily chosen points at the upper and lower ends and the middle of the 100 foot reach. Average depth and the width:depth ratio were computed for each cross-section. The mean value of width, depth and width:depth ratio for the reach is simply the average of the values at each point. Variance of means made on reaches where more than three cross-sections were measured indicated a sample of three generally had a variation of 15% about the mean. Increasing the sample size would decrease the error, but not significantly until many more cross-section measurements were added. Since this study deals only with very gross relations, greater accuracy was not deemed necessary, and the sample size was set at three.

Bed Material Size

Particle size distribution was determined using the sampling method set forth by Wolman (1954). A grid was established in the channel bed by making a series of pacing traverses. At every second stride, a sample was taken by picking up the first particle touched when the fingers were extended over the toe of the boot. The intermediate axis was measured and recorded. When one traverse was completed, the next was run in the opposite direction and parallel to it, two strides away. To minimize the sampling error due to oriented distributions of material, traverses were run perpendicular to the arrangement of material sizes on the bed. Thus if channel configuration was essentially pools and riffles, the traverses were run parallel to the channel banks. On the other hand, channels which were dominated by gravel bars or boulder trains parallel to flow were sampled with traverses perpendicular to the banks. This procedure reduced the possibility of weighting the sample toward gravel, as an example, by making one entire sampling traverse along the length of a gravel bar.

Since the material in most streams has a log-normal distribution, it is most convenient to record the intermediate axis in a logarithmic classification. The Wentworth phi-scale was used as it is the most common and generally reduced the distribution to a normal one. The phi size is defined as $-\log_2 D_{\text{mm}}$ where D_{mm} is the particle's diameter in millimeters (Folk, 1965, p. 25).

Particle size is thought to be related to both channel roughness and sediment load. Both would be most closely related to the particles

on the surface of the channel bed. Wolman's method was chosen because it allows relatively quick, easy and accurate sampling of this very feature in coarse material, and does not require transporting heavy samples to the lab. Roughness might be controlled mainly by the coarse fraction of the bed material, represented by ϕ_{84} , the 84th percentile, or size larger than 84% of the particles. On the other hand, the material size most representative of that being moved during a flood would most likely be a mean size, since the majority of material on the stream bed is transported. Mean size, defined by Folk (1965) as $(\phi_{16} + \phi_{50} + \phi_{84})/3$, and ϕ_{84} were determined for each station. It was found that there was almost a constant ratio between the two size parameters. Only in the farthest upstream reaches does this ratio change, owing to the poorer sorting of material there. In addition, the deviations from the ratio of the size parameters show no significant relations to the other parameters. It was concluded that the two size measurements are probably functions of the same controls and are not both necessary. Consequently, only the more general mean particle size will be considered later in the paper.

Variation of means indicates that a sample of 100 particles would give a mean accurate to within 10% at most of the stations measured, while a sample of 50 is accurate to within 18%. The increase in accuracy which would result from a sample larger than 100 was not deemed necessary for the general nature of this study. Thus a sample size of 100 particles was generally used. In cases of extremely good sorting, or where the channel bed had very small areal extent, only 50

particles were measured. As a result, error of measurement never exceeds 18% and is generally about 10%.

Additional Field Parameters

Channel gradient in each 100 foot reach was also measured in the field using a Brunton compass as hand level. The resulting slopes showed greater variation than the map measurements, but in general there was good agreement between the two. No trends were found between the deviation of field gradient from map gradient and the other channel parameters, so the deviation apparently reflects only the relative inaccuracy of the hand-level method. Consequently, map gradient was used to represent the gradient at each station.

Gross estimates of the density of vegetative cover on the regional slope, channel banks and bed were made at each station. In addition, qualitative observations comparing the size and distribution of material on the banks to that on the bed were recorded.

Precipitation Index

Studies in the Catalina Mountains by L. J. Battan and C. Green of the Department of Atmospheric Physics at the University of Arizona indicated a close relation between precipitation and elevation during summer rainstorms. In southeastern Arizona, summer rainfall is more plentiful and intense than that in any other season. Monthly precipitation in July and August exceeds three inches on the average at the stations studied by Green and Sellers (1964, p. 13) while it is only about one inch in the winter months. As a result, most flows in the streams studied probably occur in the summer. All available summer

precipitation data for sites close to the study area were plotted against elevation. These data included precipitation information from the University of Arizona's Santa Rita Experimental Range (Green and Martin, 1967) and Green and Sellers' (1964) data from the Apache Powder Co. and Elgin, Benson, Canelo, Fairbanks, Fort Huachuca, Patagonia and Tombstone, Arizona (Fig. 1). Several of the precipitation gages in the towns have been moved throughout the years to points of different elevations, giving additional reference points. Total rainfall for July and August of each year was divided by 62 to give average daily precipitation comparable to the Battan and Green data. The results were plotted against elevation on a log-log scale (Fig. 2). This plot shows a relation exists such that $\log \text{ precipitation} = -3.53 + .70 \log \text{ elevation}$ where precipitation is given in inches/day and elevation is in feet. The correlation coefficient of .83 has a significance of 99.5%. The data are listed in Appendix I.

The Catalina points are dispersed throughout the mountains, so an attempt was made to determine if any difference in precipitation occurred due to the location with respect to the mountain mass. Points on the north and south sides of the range are differentiated on figure 2 and there is no trend apparent to this writer. Consequently it was decided that elevation is a major factor in controlling precipitation and the agreement of towns around the study area with the data from the Catalinas and Santa Ritas implies this is a regional relationship. It would appear to be a valid assumption that a similar relation exists in the mountains of the study area.

FIG. 2. VARIATION OF PRECIPITATION WITH ELEVATION IN THE STUDY AREA

A precipitation index was derived from the relation shown in figure 2. The precipitation value at 3250 feet was arbitrarily equated with 1.0 and all other elevations were given corresponding values (Table 1). The purpose of the index was merely to make the figures easier to handle. However, the proper index for a station is not that for the station's elevation. All runoff at a station comes from points of higher elevation and thus higher precipitation.

Table 1. Elevation Zones for the Precipitation Index Values

Bounding elevations (inclusive)	Precipitation index	Bounding elevations (inclusive)	Precipitation index
7000 - 6600	1.7	4499 - 4000	1.2
6599 - 6000	1.6	3999 - 3500	1.1
5999 - 5500	1.5	3499 - 3100	1.0
5499 - 5000	1.4	3099 - 2600	0.9
4999 - 4500	1.3	2599 - 2100	0.8

A more valid index value would be that for the elevation which divides the area draining to a station in half. Since half the area receives more precipitation and half receives less, this mid-area index should approximate the mean index for the drainage area. The dividing elevation can be estimated by eye from the map to the nearest 100 or 200 feet depending on the contour interval. As a test of this method, the area within a basin between each pair of accented contour lines was measured. From these values the elevation dividing the drainage area in half was computed for each station. The mean precipitation index obtained was the same as the estimated value in each case.

The error inherent in the precipitation index cannot be evaluated here. The rainfall data for the various points were made on different instruments, by different observers, at different intervals of time, and all have different periods of record. In addition, no points actually within the drainage basins studied were available, and the simplifying assumption is being made that the precipitation which effects discharge at a point is essentially the average precipitation for the entire area draining to that point. However, the index is of such a general nature that a deviation of ± 1 allows a range of over 1000 feet in elevation. In most cases, this should be an adequate range of deviation to include the controlling precipitation, and it is generally less than a 10% variation on the precipitation index.

GEOLOGIC AND HYDRAULIC CONDITIONS IN THE CHANNELS STUDIED

Stations in the washes are identified with a six figure code, such as W15200. The letter is the first letter of the name of the mountain range, in this case, Whetstone. The first digit is a number arbitrarily assigned to each stream within a range, and the final four digits are the elevation of the station. In cases where stations on tributaries have been used, the final digit will be replaced by a "T". The rates of change of drainage area, particle size and width:depth ratio with channel length refer, as does the rate of change of gradient with length, to the exponent of length, L , in relations of the form $A \propto L^p$, $D_{\text{med}} \propto L^q$, and $W/D \propto L^r$. When the exponent is positive, the parameter increases downstream. All the measurements referred to in this section are listed in Appendix II.

Whetstone Mountains

Of the three streams studied (Fig. 3), Whetstone 1 drains limestone and sandstone, while Whetstone 2 and 3 drain granitoid igneous rocks. The sedimentary rocks fracture into blocks up to three meters in diameter. Along its lower reaches, Whetstone 1 flows through coarse alluvium derived from these rocks which contains fragments with a maximum size of about a meter. Caliche cementing is common in the channel banks. The channel is never braided and is entrenched between W15400 and W14480 with a maximum depth of 35 feet at W14780.

FIG. 4. LONGITUDINAL PROFILES (A) AND CONCAVITIES (B) IN THE WHETSTONE MOUNTAINS

Fig. 5. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Whetstone Mountains

A, B and C show the variation with channel length of drainage area, particle size and width:depth ratio respectively. The location of the concavity change is superimposed on A, and that of the downstream limit of bedrock exposed in the channel, labelled "lowest channel bedrock", is placed on B to show the relation of these features to the longitudinal change of drainage area and particle size.

FIG. 5. CHANGE OF AREA, PARTICLE SIZE AND WIDTH:DEPTH RATIO WITH CHANNEL LENGTH IN WHETSTONE MOUNTAINS

The granitoid rocks generally fracture to fragments larger than ten centimeters, which in turn weather to particles of four to eight millimeters. As a result, the bed material shows a noticeable bimodality toward the head of both Whetstone 2 and 3. Local intrusions by small dikes of more massive, finer-grained rock are more resistant to weathering than the granitic rocks. The alluvium below the mountains on both streams is finer-grained than in Whetstone 1. Braiding is the dominant channel form downstream from W24200 and W34200. Entrenchment is minor on Whetstone 2, but is as much as twenty feet on Whetstone 3, between W34720 and W34400, and at W33800 where the channel is cutting through a pronounced bluff paralleling the San Pedro River.

Figure 4, showing the longitudinal profiles and the relation of gradient to channel length, indicates the location of the concavity change in each wash. Figure 5 portrays the longitudinal variation of drainage area, particle size and width:depth ratio, with lines drawn to indicate the trends of change. Generally, the rates of change are not constant throughout the entire length of the stream. In all cases, the data from tributaries fits well within the scatter of points, indicating a similarity of relations with the main streams.

Mustang Mountains

All three washes (Fig. 6) that were studied in the Mustang Mountains drain sedimentary and volcanic rocks. Mustang 1 begins in limestone and at M15200 flows into alluvium which appears to be an alluvial fan. The limestone fractures to fairly large fragments and generally resists weathering. Below M15200 the stream crosses

FIG. 6. LOCATION MAP FOR STREAMS AND STATIONS IN THE MUSTANG MOUNTAINS.

a rhyolite outcrop, flowing on the rhyolite-alluvium contact. The rhyolite content of the bed material barely reaches 20% as the alluvium is essentially all limestone. In this area the rhyolite is generally massive, breaking into large fragments, although it is sometimes highly fractured.

The drainage area of Mustang 2 is dominantly limestone with minor sandstone. Coarse fragments are prevalent. At M25050, the main stream is cutting through a small fan which originates in one of the tributaries to the north. The main channel ends on the surface of a small, heavily vegetated fan at 4860 feet elevation. At its upper end, the fan has a width of 74 feet and a mean particle size of 6.5 millimeters, significantly smaller than the 25 millimeters found at M24900, the nearest station upstream. At a distance of about 225 feet downfan, the width has increased to 95 feet and the mean size to 35 millimeters.

Mustang 3 drains areas of limestone, rhyolite and mudstone. The limestone is typically resistant, but the rhyolite ranges from highly fractured to massive and the mudstone is quite weak. At M34900, a major tributary enters which carries primarily limestone. The left bank of the stream, the side from which the main branch comes, is 90% rhyolite, while the right side is only 60% rhyolite, with the remainder being limestone and sandstone. In the bed, the boulders are 60% rhyolite, while the gravel is only 40% rhyolite. The percentage of rhyolite in both decreases rapidly downstream and at M34800 the bed material is 60% limestone and only 25% rhyolite. Apparently the limestone is more resistant than the rhyolite.

FIG. 7. LONGITUDINAL PROFILES (A) AND CONCAVITIES (B) IN THE MUSTANG MOUNTAINS

Fig. 8. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Mustang Mountains

A, B and C show the variation with channel length of drainage area, particle size and width:depth ratio respectively. The location of the concavity change is superimposed on A, and that of the downstream limit of bedrock exposed in the channel, labelled "lowest channel bedrock", is placed on B to show the relation of these features to the longitudinal change of drainage area and particle size.

FIG. 8. CHANGE OF AREA PARTICLE SIZE AND WIDTH: DEPTH RATIO WITH CHANNEL LENGTH IN THE MUSTANG MOUNTAINS

The alluvium in the banks of the lower reaches of these streams is dominantly coarse limestone and commonly is cemented with caliche. It generally contains more fines than the bed material. No braiding occurs, probably due to the large material size. Entrenchment is minor on Mustang 2. Mustang 1 is incised ten feet at M15100 and M14700, but very little elsewhere, and the bed of Mustang 3 is five to ten feet below the regional surface throughout most of its length.

Figure 7 portrays the concavity change on the profiles and on the gradient-length relations. The longitudinal variations of parameters are shown on figure 8. Again, the rate of change of each parameter generally changes abruptly at some point along the channel profile.

Sierritas

On the Sierrita streams (Fig. 9) caution was taken to avoid selecting stations in areas affected by the damming of stock tanks. The filling which occurs upstream is generally obvious in the field. Overflow from the tank will be sediment-free and will tend to remove the finest bed material and decrease width:depth ratio and stream gradient by trenching. If no overflow occurs, the channel downstream will receive water only from precipitation below the dam. Streams heading below the mountains, analogous to those heading below the dams, show similar particle sizes and gradients but slightly smaller width:depth ratios than their counterparts heading in the mountains. Thus, the tanks' effect on the measured parameters appears to be small. In either situation below the dam, the effects of the tank disappear rapidly

FIG. 9. LOCATION MAP FOR STREAMS AND STATIONS IN THE SIERRA MOUNTAINS.

downstream and are generally gone after the first major tributary entry.

Immediately below the tank on Sierrita 1 at 4700 feet, the channel cuts ten to twenty feet into bedrock. S14525 is located between this incision and the first major downstream tributary. Three stations were measured at the junction with this tributary, one above the intersection on the main stream, S144MT, another on the tributary, S1444T, and the third on the main stream below the junction, S14440. Particle size increases from S14525 to S144MT, and then decreases below the junction, while the material in the undammed tributary, is the same size as at S14525. Had removal of fines occurred, it should have been more effective at S14525 than S144MT and a reversal of the sizes found would be expected. Furthermore, the drop in width:depth ratio between S14750 and S14525 reflects the influence of the bedrock outcrops and not the manmade dam, for it has similar values on the undisturbed tributary and the main stream above the junction. Thus the effect of the tank does not extend downstream in this channel. Indeed, the effects of short-term features such as the tanks may not be great enough to be noticed at all in the gross relations sought in this study. The locations of the other tanks are shown on figure 9.

The Sierrita channels are flowing across a bedrock pediment. Bedrock crops out in the channel walls and on the interfluvies well downstream from the last channel outcrops. No effect on particle size and other features was noticed.

Bedrock is generally phaneritic igneous. Sierrita 1 and 2 flow through areas mapped by Lootens (1965) as primarily quartz monzonite and

granodiorite. Some finer units include welded tuff breccias, fine leucogranites and tourmaline granites. All fracture to fragments up to a half meter, but the coarse-grained rocks weather rapidly to four to eight millimeter fragments, while the others are more resistant. The bedrock is dominantly coarse leucogranite (Lootens, 1965) in Sierrita 3. At S35000 this stream is structurally controlled, flowing parallel to a major joint system.

Braiding is the dominant channel form between S14250 and S14000, from S25000 to S24000 and at S34250. Elsewhere there is generally only one channel. No entrenchment occurs along Sierrita 2. Sierrita 1, on the other hand, is undergoing active trenching at present at S15000, probably because additional sediment resulting from a local burn has filled the channel. Incision of ten to twenty feet has occurred in bedrock between S14750 and S14525, with the stream remaining deeply entrenched to S14250. Sierrita 3 shows incision of fifteen feet at S34500, which decreases in both directions.

As in the other ranges, the profiles and concavity, together with longitudinal rates of change of parameters have been drawn (Figs. 10 and 11). Sierrita 5, 6 and 7, three smaller drainages heading below the mountain front, were examined to determine how such streams would relate to those heading in the mountains (Fig. 9). These data are plotted on figures 10b, and 11a, b and c. Individually, each station fits relatively well into the scatter of points on each plot, except on gradient versus length where they are removed. This anomaly will be explained in a subsequent section.

FIG. 10. LONGITUDINAL PROFILES (A) AND CONCAVITIES (B) IN THE SIERRITA MOUNTAINS

Fig. 11. Change of Drainage Area, Particle Size and Width:depth Ratio with Channel Length in the Sierritas

A, B and C show the variation with channel length of drainage area, particle size and width:depth ratio respectively. The location of the concavity change is superimposed on A, and that of the downstream limit of bedrock exposed in the channel, labelled "lowest channel bedrock", is placed on B to show the relation of these features to the longitudinal change of drainage area and particle size.

FIG. 11. CHANGE OF AREA PARTICLE SIZE AND WIDTH:DEPTH RATIO WITH CHANNEL LENGTH IN THE SIERRITA MOUNTAINS

All three streams flow in alluvial material derived from granitic rocks. Streams 5 and 6 do have some bedrock cropping out in the walls of the stream valley, parts of the Sierrita pediment. However, none occurs in the stream bed. Braiding occurs only at S63500, and only at the same station is bank material very different from bed material, being noticeably coarser.

If these four stations were considered as being on a single stream, the concavity and rates of change of drainage area, particle size and width:depth ratio with channel length would be similar to the downstream segments of the other streams. Concavity would be $\sim .1$.

Summary of Downstream Relations

The change in concavity (Figs. 4, 7 and 10) and the changes in the rate of variation of parameters with channel length (Figs. 5, 8 and 11) already have been noted. Table 2 summarizes the most important of these features. The concavity of the profile of each stream changes from high upstream to low downstream. In eight of the nine cases, this change coincides closely with a change in the drainage area-channel length relation (Table 2). Drainage area increases more rapidly with length in the high-concavity segments than in the low (Figs. 5a, 8a and 11a). The one anomalous case, Mustang 3, results from the entrance of a major tributary about one-half mile downstream from the concavity change, causing the higher rate of increase of area to be maintained downstream beyond the concavity change.

The rate of decrease of particle size downstream also shows a tendency for change (Figs. 5b, 8b, and 11b). In eight of the nine

Table 2. Summary of Locations of Major Changes in the Longitudinal Variation of Parameters and Their Relations to Bedrock

The letters p and q refer to the exponents in $A \propto L^p$ and $D_{mn} \propto L^q$.

Stream	Concavity: upstream downstream	Location of concavity change (feet from divide)	Location of change of p (feet from divide)	Location of lowest channel bedrock (feet from divide)	Location of change of q (feet from divide)
Mustang 1.	[-1.9 -.6	4200	4200	4100	No change
Mustang 2	[-2.4 -.4	4200	4200	4600	4400
Mustang 3	[-1.0 -.6	6000	9000	5950	5700
Whetstone 1	[-1.2 -.6	13500	12500	15000	15000
Whetstone 2	[-1.2 -.7	11000	11000	6550	6500
Whetstone 3	[-1.2 -.1	10000	10500	15250	16000
Sierrita 1	[-1.1 -.3	12000	13000	12700	12700
Sierrita 2	[-1.0 -.8	7500	7200	4300	4000
Sierrita 3	[-1.0 -.2	11000	11000	7500	7000

streams, particle size decreases more slowly and/or more consistently below the last outcrop of bedrock downstream than it does above it. The ninth stream, Mustang 1, shows essentially no difference in particle size decrease above and below the last bedrock. The rate of decrease below the bedrock tends to be smaller in granitic channels than in those draining sedimentary and volcanic rocks.

The coincidence of the particle size and concavity changes depends on the location of the last outcrop relative to the concavity change (Table 2). These two points coincide in four of the nine channels, Mustang 1, 2 and 3, and Sierrita 1. Of the remaining five, three streams, Whetstone 2 and Sierrita 2 and 3, change concavity below the last bedrock. The last outcrop occurs downstream from the concavity change on both Whetstone 1 and 3, although the distance separating the two points in Whetstone 1 is less than 1000 feet. This distance could easily represent only the error inherent in the location of the concavity break. The location of a station within the possible range of location has probably only accented the inaccuracy that exists elsewhere as well.

Considerable variation of concavity occurs within both the high-concavity and the low-concavity segments, but the two sets of values have no overlap (Table 2). Part of the variation, particularly that of the high-concavity segment, results from lithologic differences. In the streams in sedimentary rocks, the highest concavities correspond to the most resistant lithology, limestone, while the lowest occurs in the stream with substantial rhyolite. The consistency of concavities in the granitic channels probably indicates the similarity of lithologies.

With the exceptions of Mustang 2 and Whetstone 3, width:depth ratio increases downstream to a maximum value within the low-concavity segment, below which it decreases (Figs. 5c, 8c and 11c). Whetstone 3 is anomalous in that the profile becomes convex where it appears the maximum value would occur. Thus a more general feature is that width:depth ratio actually tends to decrease with diminishing gradient in the downstream segment. This feature is probably related to an increasing sediment concentration downstream as discharge is lost to infiltration. Either a smaller width:depth ratio, steeper gradient, or both, is necessary to carry the load.

Width:depth ratio is less consistent in the low-concavity segment, partly due to the occurrence of braiding. This channel form does not occur in the sedimentary channels with coarse bank material.

Precipitation also decreases regularly downstream. This feature, however, results from precipitation's relation to elevation and the fact that the streams flow downhill.

INTERRELATIONS AMONG PARAMETERS LEADING TO A NATURAL SUBDIVISION OF DATA

It would be valuable to determine whether the data can be grouped in a more useful manner than by individual streams. One means to this end is to look for factors which reduce the scatter on the plots of variables, particularly those including stream gradient, the primary measure of the stream profile involved. The plots of gradient against length (Figs. 4b, 7b and 10b) and drainage area against length (Figs. 5a, 8a and 11a) indicate that if the data is separated on the basis of concavity segments, some of the scatter will disappear.

Figures 12a and 12b show the scatter is quite large on the gradient-particle size and gradient-width:depth ratio relations. Imposing lithology by differentiating sedimentary and volcanic points from granitic points cuts the scatter almost in half on each plot. Separation into concavity segments, where concave stands for high-concavity and straight for low-concavity, adds a slight improvement.

The gradient-drainage area relation (Fig. 13a) shows a scatter which is not eliminated by application of either lithology or concavity segments. In fact, the granitic points form a band in the center, enclosed by points from sedimentary-volcanic channels. This phenomena is a function of relief. Whetstone 1, with the greatest relief, has the steepest gradient for a given area, while the Mustang streams, with the lowest reliefs, show the gentlest slope for a given area. It was found by trial and error that gradient varies most closely with A/R^2 , where R is the total relief for the profile segment in which a point is

FIG. 12. RELATION OF MEAN PARTICLE SIZE (A) AND WIDTH: DEPTH RATIO (B) TO CHANNEL GRADIENT. DOTTED LINES SEPARATE LITHOLOGIES

FIG. 13. RELATION OF DRAINAGE AREA (A) AND AREA:RELIEF² RATIO (B) TO CHANNEL GRADIENT

located. Figure 13b shows the improved fit, and also the effect of imposing the profile segments on the relation, for the pronounced bend in the scatter field coincides with the change in concavity.

The effect of relief on the area-gradient relation is strictly geometric. Table 3 shows that the relief:length ratios are quite similar for the same segment on different streams. Thus the profiles are concave-upward arcs below the hypotenuses of similar right triangles (Fig. 14).

Fig. 14. Relation of Channel Gradient at a Given Distance from the Divide to Basin Relief and Length

The figure shows that at a given distance "x" from the divide, the gradient in the stream with the greater relief, (A), will be steeper because the chosen position is relatively higher in the profile. The situation is the same when the area is substituted for length, as area increases with length at a constant rate in each concavity segment.

The relation of width:depth ratio to particle size (Fig. 15) indicates a separation of points due to lithology. However, this separation is merely a result of the coarser material and lack of braiding existing in sedimentary streams, for the scatter is not reduced by imposing lithology on the plot. Actually, the relation of

Table 3. Relief:length Ratios of the Concavity Segments

Stream	High-concavity segment			Low-concavity segment		
	Total Length (feet)	Total Relief (feet)	Relief: Length Ratio	Total Length (feet)	Total Relief (feet)	Relief: Length Ratio
Mustang 1	4200	1025	.24	12100	350	.029
Mustang 2	4200	1075	.26	8200	275	.034
Mustang 3	6000	1050	.18	13700	350	.025
Whetstone 1	13500	2500	.19	66500	1400	.021
Whetstone 2	11000	1550	.14	39300	1100	.029
Whetstone 3	10000	1550	.16	42000	1250	.030
Sierrita 1	12000	1250	.10	69200	1800	.026
Sierrita 2	7500	1100	.15	78300	1900	.024
Sierrita 3	11000	1150	.10	73600	1750	.024
Sierrita 5	-----	-----	---	9500	250	.029
Sierrita 6	-----	-----	---	13300	350	.026
Sierrita 7	-----	-----	---	16000	400	.025

FIG. 13. RELATION BETWEEN MEAN PARTICLE SIZE AND WIDTH: DEPTH RATIO

these parameters appears to be continuous across lithologic boundaries. Introduction of profile segments produced little effect either.

Three stations on tributaries above the break in concavity on their trunk streams, and five on those below it are shown on figures 12a, 12b, 13a, 13b and 15. All are in granitic bedrock areas. Only in three instances do they show a marked difference from the other stations. On plots of gradient and width:depth (Fig. 12a), gradient and area (Fig. 13a) and width:depth and particle size (Fig. 15), the tributaries which enter below the mountain front fall out of the normal scatter field. Addition of relief moves them into the main field of gradient versus A/R^2 (Fig. 13b). The remaining two plots indicate these streams have a somewhat smaller width:depth ratio than the streams which head in the mountains. The three stations on tributaries entering above the concavity change fall within the scatter on all plots. It appears that the relations which exist among the parameters are the same on main stream and tributary with the exception of those involving width:depth ratio on tributaries wholly below the mountains. Consequently, the scatter on plots cannot be attributed to a difference in basin size or order, and the relations which exist among parameters are not due simply to the overall similarity of the streams sampled. The tributary data will henceforth be included with the other stations.

The scatter of the plots is reduced primarily by the introduction of lithology and profile segments. Relief shows an important effect, but since the field of possible reliefs is infinite, any useful separation of points would involve arbitrary grouping. No natural grouping is apparent, so relief is not considered a valid parameter

for classifying the data. In addition, there are indications that concavity is a more sensitive index of lithology than is the classification of rock type used here. However, the streams chosen for this study happen to flow through rocks which fit best into the two very broad lithologies used. Subdividing the sedimentary rocks into limestone, sandstone and mudstone, for instance, would apparently produce better relations, but would require many additional sample sites in each lithology. The general nature of this study did not warrant detailed analysis of the effect of lithology on profiles and the sampling done is inadequate to extend it to that end. Thus the twofold division of lithology is all that will be undertaken.

In conclusion, the data show a natural fourfold subdivision, the high-concavity and low-concavity profile segments of sedimentary-volcanic streams, abbreviated sedimentary concave and sedimentary straight, as well as granitic concave and granitic straight. Introduction of this classification of data to log-log plots of the parameters measured significantly reduces scatter. Appendix II provides a detailed list of the data used in this section.

CONCEPT OF THE EPHEMERAL STREAM PROFILE

The data presented thus far show that channel gradient is, in fact, related to drainage area, channel length, particle size and width: depth ratio as well as to lithology and relief. What role does each play in determining the shape of the profile? Does precipitation have any effect? Are these relations valid in other mountain ranges?

To serve as an answer to these questions, a model of the longitudinal profile will be developed from the relations observed in the three mountain ranges. This model will be used to predict profile form in two additional mountain ranges, the Catalina and Tucson Mountains, to test its generality. These two ranges were chosen for their lithologies and proximity to Tucson, but also because they extend to elevations well below those found in the three ranges studied. As a result, the precipitation in the lower reaches should be substantially lower than in the original nine streams.

Review of Pertinent Work on Longitudinal Profiles

A complete review of the development of thought on longitudinal profiles was presented by Woodford (1951). The ideas which have been incorporated in this paper start with Shulits (1941), who developed an equation for the profile relating it to the downstream decrease in particle size. Mackin (1948) contended particle size was not the sole control on gradient, but that rather discharge, sediment load and particle size are all important.

However, stream gradient has two important dimensions, its absolute value, the actual slope at a point, and its concavity, the relation between the slope at a point and slopes at points up and downstream. The controls on each dimension need not be completely interrelated, so it is important to look at both. Using data from gaging stations throughout the western United States, Leopold and Maddock (1953) concluded that the absolute slope is imposed on a channel by the events which determine the vertical and horizontal distances through which it must flow. The profile which connects the two fixed end points is an adjustment to the discharge, sediment load, particle size and relative erodibility of banks and bed.

Later workers have essentially agreed with this point of view. Wolman (1955) argued that in Brandywine Creek, Pennsylvania, slope could not be adjusted simply to carry the particle size supplied, because velocity increases downstream, indicating other factors are adjusting also. He concluded that gradient on any given reach is primarily a function of the discharge and sediment load supplied to that reach. Hack (1957) found in the Shenandoah Valley that $S = 18(M/A)^{0.6}$, where S is channel gradient in feet/mile, M is median particle diameter in millimeters, and A is drainage area in square miles. Area represents discharge in his relation. In addition, the concavity of a profile is greater when the particle size decreases downstream than when it remains constant. He felt, however, that slope was not entirely a function of particle size and drainage area, noting particularly that streams in areas of similar geology adjusted their profiles in the same manner. Miller (1958), in his study of high mountain perennial streams in

New Mexico, pointed out that a combination of geologic factors may have more control on slope than hydraulic factors. Brush (1961), in his work with perennial streams in Pennsylvania, decided that bedrock influences a channel's slope and its position in space. He concluded that bedrock is one parameter absent from Hack's relation. The studies of Leopold and Miller (1956) in ephemeral channels below the mountain front in New Mexico showed relations among hydraulic and geometric parameters similar to those found in perennial streams. They indicated that for a given rate of increase of velocity or depth downstream, concavity would be highest when roughness decreased most rapidly downstream.

More recently, Schumm (1963, 1968) has emphasized that a stream may also adjust its longitudinal profile laterally by changing the sinuosity of its course. Streams with a higher ratio of suspended load to bed load, a ratio controlled by channel shape, will tend to be more sinuous than those with low ratios. The increased sinuosity increases channel length, thus decreasing the gradient and affecting the profile.

Controls on the Longitudinal Profile

The present study indicates that while similar relations exist in ephemeral channels draining from the mountains to the alluvial valleys as do elsewhere, the picture of the longitudinal profile is complicated by the existence of the concavity change. Lithology, relief, base level and climate are imposed upon each stream system. The importance of the first two has already been inferred from figures 12, 13 and 15. Lithology, or more generally geology, which also includes structural effects such as fracturing, controls the particle size

available for transport, the resistance of material to erosion and, to some extent, channel shape. These three factors, together with the outcrop pattern, are the primary controls of channel roughness.

Tectonics control the vertical and horizontal distances through which each stream must move by imposing the heights of and distances between mountain ranges. A range's height above the surrounding valleys is actually its total height minus the thickness of the alluvial fill on its flanks. Both are functions of tectonics. The amount of fill coming from each range bordering a valley, again a tectonic function, determines the location of the through-flowing stream which serves as local base level in each valley. The location of the local base level together with the distance between ranges controls overall stream length. The relief:length ratios thus determined are listed in Table 3.

Climate is a function of elevation, as precipitation increases and temperature decreases with increasing height. The amount of moisture, together with prevailing temperature, controls weathering and thus sediment production. Precipitation also provides the stream with discharge. Thus both the amount of material available for transport and the amount of water available to transport it, the sediment load and discharge, can be expected to vary with elevation.

Normally, then, relief and base-level location control absolute slope by imposing two end points on a stream, while concavity reflects the adjustment of the profile to lithology and climate. It is unlikely that sinuosity is an important factor in the concavity of the profiles studied as the coarseness of the bed material and width of the channels

imply bed load is the dominant load type everywhere. The profiles studied, however, have a third important point, the concavity change.

Significance of the Point of Concavity Change

The frequency of tributary entry into the main stream changes at the concavity change. A parameter called the cumulative tributary density was developed by dividing the number of tributaries between the divide and each station by the channel length to the station in thousands of feet, giving the average number of tributary entries per thousand feet. Figure 16 shows this parameter plotted against channel length in two selected streams. Note that the relation upstream from the concavity break is highly variable, but with a general trend toward increasing density downstream. Below the concavity change, the tributary density shows a consistent decrease. Note also the close proximity of the concavity break to the start of the final decline of cumulative tributary density. Table 4 shows that the coincidence of these two points is a general feature. The deviations are generally within the limits of accuracy of the location of both points. This idea is supported by the tendency for the greatest errors to occur on those streams where the stations are most widely spaced. The increased distance between points reduces the accuracy in locating the changes.

The change in tributary distribution implies a change in drainage pattern and density and basin shape. Below the concavity change, the tributaries tend to run more parallel to the main channel and thus to intersect it less frequently. The basin, in turn, is more elongate parallel to the main channel below the concavity change than it

Table 4. Comparison of the Actual Channel Length from Divide to Concavity Change with Those Predicted from Cumulative Tributary Density

All distances are in feet.

Stream	Length from divide to concavity change	Length predicted from tributaries	Difference (per cent of real distance)	Distance between bounding stations
Mustang 1	4200	4800	14.	2410
Mustang 2	4200	4300	2.4	970
Mustang 3	6000	6000	0.	2000
Whetstone 1	13500	12000	11.	4070
Whetstone 2	11000	8600	22.	4140
Whetstone 3	10000	10000	0.	2930
Sierrita 1	12000	14000	17.	5630
Sierrita 2	7500	4800	36.	3250
Sierrita 3	11000	8500	23.	6830

FIG. 16. RELATION OF CUMULATIVE TRIBUTARY DENSITY TO CHANNEL LENGTH AND CONCAVITY CHANGE

is above it. The drainage density also tends to be lower in the downstream segment. These features indicate that the low-concavity segment of the main channel will have longer reaches in which the only additions to discharge and sediment load will come from direct precipitation into the channel and overland flow. As a result, discharge and load will not increase greatly. Leopold, Wolman and Miller (1964, p. 244) indicate that $S \propto Q^{-.95}$ in a downstream direction in ephemeral channels, where S is channel gradient and Q is discharge. Thus when discharge remains constant, the channel will tend to maintain the same gradient.

The effect of basin shape on stream profiles is also reflected in the relation of drainage area and channel length. The change in this relation at the break in concavity has already been indicated. Table 5 shows that drainage area increases more rapidly in the high-concavity profile segments. If the relations between drainage area and discharge, and drainage area and sediment load remain constant, then both discharge and sediment load increase more rapidly in the high-concavity segments. Since precipitation has a constant relation with elevation, the upstream profile segment, with its higher slope, will experience a more rapid decrease in precipitation downstream than the lower profile segment. Thus the decrease in precipitation would tend to counteract the increase in area downstream and reduce the rate of increase of discharge. In addition, it would tend to decrease the difference in discharge relations between the two segments. However, the magnitude of the area increase predominates over the precipitation decrease to such an extent that the discharge should still increase more rapidly than sediment load as is the general case (Leopold and Maddock, 1953, p. 22). The channel

adjusts with a decreasing gradient, creating concavity. In the low-concavity reach, the increase of discharge is probably offset by infiltration into the channel bed, creating an increasing sediment concentration downstream. Stream gradient would have to decrease less rapidly in order to transport the material (Mackin, 1948). The more constant slope is reflected by the lower concavity.

The rate of change of particle size with channel length, q , is different above and below the concavity change in eight of the nine streams (Table 5). In each case q is more negative in the upstream segment than it is downstream. Thus roughness is decreasing more rapidly in the upstream segment, which according to Leopold and Miller (1956) and Hack (1957) should result in a higher concavity, as it does.

Table 5 shows the relations among concavity and rates of change of area and particle size. These data indicate that the variations of the concavities of the low-concavity segments are explained by drainage area and particle size. In general, the greater concavities are associated with more rapid changes of area or particle size. The high-concavity segments show less relation to particle size, but parallel more closely drainage-area increases and, as stated earlier, lithology.

The relation of width:depth ratio to length also tends to change at the break in concavity. Figures 5c, 8c and 11c show that the rate of change of width:depth ratio is highly variable, particularly in the low-concavity segments. A relation between width:depth ratio and concavity exists in the high-concavity segments, but not downstream. The general decrease downstream in the low-concavity segments probably reflects decreasing discharge.

Table 5. Comparison of Profile Concavity, Rate of Drainage Area Increase and Rate of Particle Size Decrease

Concavity is the exponent in the relation between channel length and stream gradient, $S = kL^m$. The rates of area and particle size changes are the corresponding exponents in the relations of those parameters with channel length, $A = jL^p$ and $D_{mm} = hL^q$.

Stream	High-concavity segment			Low-concavity segment		
	Concavity (m)	Rate of area change (p)	Rate of particle size change (q)	Concavity (m)	Rate of area change (p)	Rate of particle size change (q)
Mustang 1	-1.9	+1.8	-1.5	-.6	+1.2	-1.5
Mustang 2	-2.4	+2.4	-.8	-.4	+.7	-.4
Mustang 3	-1.0	+1.6	+.5	-.6	+1.4	-1.2
Whetstone 1	-1.2	+1.6	-2.1	-.6	+1.1	-2.0
Whetstone 2	-1.2	+1.9	-1.3	-.7	+.6	-.8
Whetstone 3	-1.2	+1.8	-.9	-.1	+.8	-.4
Sierrita 1	-1.1	+1.5	-.5	-.3	+.8	-.8
Sierrita 2	-1.0	+1.8	-1.3	-.8	+1.2	-.4
Sierrita 3	-1.0	+1.4	-1.3	-.2	+.9	-.5

Summary

Each of the streams studied flows between two imposed end points, the divide and the mouth. The profile which has developed to connect these points consists of two segments adjusted to different sets of conditions and connected at the point of concavity change. The location of the concavity change, which represents the downstream terminus of the high-concavity, or upstream, segment, is determined in each case by a change in the rate of increase of drainage area. Absolute channel gradient is determined by that part of the basin's total relief and length contained above and below the concavity change.

The concavity in each profile segment represents the adjustment of channel gradient to discharge, sediment load and roughness, which are functions of climate and lithology. They are represented primarily by drainage area and particle size, and to a lesser extent by width:depth ratio and perhaps precipitation. Roughness, or particle size, is controlled by the lithology and location of bedrock. It decreases more rapidly above the final bedrock outcrop in the channel than it does below it. Discharge and sediment load relate to drainage area, which tends to increase more rapidly in the upper profile segment. The greater rates of change of area and particle size in the upstream segment cause a greater concavity there. A greater change in concavity reflects large changes in area and size relations.

DEVELOPMENT OF EMPIRICAL EXPRESSIONS FOR THE PROFILES

If the proposed model is correct, a relation between gradient and drainage area, relief, particle size, width:depth ratio and precipitation should exist which represents a mathematical expression of the profile and will actually predict profiles elsewhere. The best fit equations were sought using a standard multiple regression approach (Snedecor, 1956). The statistical computations were done on a CDC 6400 computer using a program written by Charles K. Huszar of the University of Arizona Computer Center. The program is designed to minimize the sum of squares of deviations parallel to the axis of the dependent variable rather than perpendicular to the line of best fit. While the latter technique would have been more useful for this problem, no appropriate program was available, and the writer's computer experience did not warrant an attempt at developing one. The method used, however, is satisfactory as long as it is used consistently.

The relations which resulted from direct regression analysis of the raw data were unsatisfactory for two reasons. First, the relation between drainage area and the square of relief (Fig 13b) must be imposed on the data, for it will not necessarily result from the least squares analysis. Secondly, the streams sampled were too similar in precipitation values to allow development of a general relation containing that parameter. In other words, all nine streams sampled started roughly in the same high precipitation zone, flowed through

several zones of lower precipitation and ended in similar low precipitation zones. As a result, regression equations show only that for the streams sampled, steep gradients tend to occur in high precipitation zones. This is strictly a reflection of the geometry of the stream profile, where steeper gradients occur at higher elevations, and does not indicate precipitation's true effect. The nine sample streams must be compared later to streams in very different precipitation zones to determine this effect.

As a result of these findings, only four variables were used in the regression analyses, gradient, S, area:relief² ratio, A/R^2 , particle size, D_{mm} , and width:depth ratio, W/D . The equations, the correlation coefficients and their significance for each of the four data subdivisions follow:

Sedimentary concave:

$$S = \frac{(6.6 \times 10^{-5})R^{.80 \pm .34} D_{mm}^{.20 \pm .22} (W/D)^{.14 \pm .28}}{A^{.40 \pm .17}} \quad (1)$$

$$r = .800 \text{ (99\%)}, \quad F = 18.7 \text{ (99.5\%)}$$

Sedimentary straight:

$$S = \frac{(1.4 \times 10^{-3})R^{.38 \pm .14} D_{mm}^{.26 \pm .08}}{A^{.19 \pm .07}} \quad (2)$$

$$r = .795 \text{ (97.5\%)}, \quad F = 9.3 \text{ (99.5\%)}$$

Granitic concave:

$$S = \frac{(7.6 \times 10^{-6})R^{1.02 \pm .10} D_{mm}^{.28 \pm .10} (W/D)^{.22 \pm .14}}{A^{.51 \pm .05}} \quad (3)$$

$$r = .940 \text{ (99\%)}, \quad F = 46.0 \text{ (99.5\%)}$$

Granitic straight:

$$S = \frac{(1.6 \times 10^{-3})R^{.42 \pm .14} D_{mm}^{.062 \pm .056}}{A^{.21 \pm .07}} \quad (4)$$

$$r = .588 (99\%), \quad F = 5.76 (99\%)$$

Width:depth ratio was eliminated from the straight segments because it was statistically insignificant, probably due to the great variability in these segments. In general, the remaining variables exceed a significance level of 90%, indicating that there is only one chance in ten that a random variable could reduce the deviation of S as much as they do. The multiple correlation coefficients (r) indicate the channel gradient is closely related to these parameters. In addition, the F ratios (Snedecor, 1956 and Owen, 1962) show the significance level of all these equations exceeds 99%. The F ratio is the ratio of the mean square of the dependent variable, in this case S, to the mean square of the differences between real S and the S predicted by the regression. Thus a high ratio indicates the regression has a good fit.

Deviations of the gradients predicted by the equations from the real ones generally are the result of differences in concavity. Streams with higher than average concavity have steeper gradients upstream and gentler ones downstream than those predicted. Since concavity differences are related to lithology and basin shape, most of the deviations from the equations are functions of these two factors. Extremely large deviations result at stations where unusual features such as bedrock outcrops, active trenching, and unusual channel wall

properties like caliche cementing tend to produce unusual width:depth ratios or particle sizes. Vegetation seemed to have no consistent effect on the deviations. In addition, while drainage area generally increases with length, it does so in large increments at each major tributary. As a result, a station immediately below a tributary junction will have a drainage area which is unusually high for its location. A station just upstream would be unusually low. When these values are substituted in the general equation which assumes a uniform rate of increase, they produce additional deviations.

If precipitation effects gradient, a stream which flows through zones of lower precipitation than those in corresponding positions on another stream should tend to have a steeper profile. This effect would be apparent if the deviations showed the model predicted gradients too gentle for the lower precipitation stream and too steep for the higher one. No such relation to precipitation was found, however.

In addition to equations (1) to (4), a suite of functions relating each variable to the distance from the divide, L , was obtained for each subdivision (Table 6). The coefficient n in the equations $S = kL^n$ represents the average concavity for each profile segment. Note that in each case this average concavity is much lower than that which one would expect from the values in Table 5. The reason for this apparent inconsistency is the use of different methods to obtain the best fit equations. Recall that the computer minimizes the squares of deviations parallel to an axis. On the other hand, the best fit lines determined graphically by eye represent a minimization of squares of

deviations perpendicular to the best fit line. The difference between the two lines increases as sample size decreases or scatter increases.

In situations where a very small number of data points are available, such as in determining concavity for a profile segment with only four to eight points, the line fit by eye is probably just as valid a relation as that fit by computer. This method allows some interpretation of the scatter based on the relation of one profile segment to the other in a stream, the consideration of aberrant points related to unusual channel features and the realization that the relation of gradient to length becomes increasingly poor toward the divide as the error in measurement of both parameters increases. Data points can be weighted accordingly as the line is drawn, while the computer is unable to interpret information it has not received. Consequently, graphical values have been used on individual streams. When more sample points are available, as in the fourfold subdivision, the computer's results are more accurate and, in the case of multiple correlation, easier to obtain. Thus all equations relating only the four subdivisions are computer derived.

Each variable on the right sides of equations (1) to (4) can be replaced with an expression in terms of length (Table 6). Relief is constant for each stream, and when its value is substituted for R in an equation, an expression is produced for gradient in terms of channel length, predicted entirely by the longitudinal variations of the other parameters. For example, in the sedimentary concave subdivision,

Table 6. Regression Equations Relating Drainage Area, A, Particle Size, D_{mm} , Width:depth Ratio, W/D, and Gradient, S, to Channel Length, L

R is the correlation coefficient. The subscripts on its value indicate the significance. 2 = 99%, 1 = 95% and 0 is less than 95%. The number of samples in each subdivision is given by n.

Profile segment	Drainage area	Particle size	Width:depth ratio	Gradient
Sedimentary concave n = 13	$A = (9.5 \times 10^{-8})L^{2.03}$ R = .965 2	$D_{mm} = \frac{(1.15 \times 10^4)}{L^{.71}}$ R = .598 1	$W/D = 3.54L^{.14}$ R = .278 0	$S = 50L^{-.72}$ R = .804 2
Sedimentary straight n = 14	$A = (5.4 \times 10^{-6})L^{1.55}$ R = .925 2	$D_{mm} = \frac{(2.88 \times 10^4)}{L^{.81}}$ R = .786 2	$W/D = .90L^{.34}$ R = .645 2	$S = .25L^{-.23}$ R = .573 2
Granitic concave n = 22	$A = (1.4 \times 10^{-6})L^{1.69}$ R = .955 2	$D_{mm} = \frac{(7.40 \times 10^2)}{L^{.52}}$ R = .543 2	$W/D = .26L^{.56}$ R = .591 2	$S = 280L^{-.95}$ R = .935 2
Granitic straight n = 24	$A = (1.1 \times 10^{-5})L^{1.43}$ R = .910 2	$D_{mm} = \frac{(1.38 \times 10^2)}{L^{.42}}$ R = .571 2	$W/D = 1.57L^{.44}$ R = .334 0	$S = .19L^{-.19}$ R = .379 1

$$\log S = -1.78 - .40\log(A/R^2) + .20\log D_{mm} + .14\log(W/D).$$

Substituting from Table 5 produces:

$$\begin{aligned}\log S &= -1.78 + .80\log R - .40(-8.02 + 2.03\log L) \\ &\quad + .20(4.06 - .71\log L) + .14(.55 + .44\log L) \\ \log S &= -.08 + .80\log R - .93\log L \\ S &= -.83R^{.80}L^{-.93}\end{aligned}\tag{5}$$

For the remaining three subdivisions, the equations are:

$$\begin{aligned}\text{Sedimentary straight} \\ S &= -.29R^{.38}L^{-.50}\end{aligned}\tag{6}$$

$$\begin{aligned}\text{Granitic concave} \\ S &= -.11R^{1.02}L^{-.89}\end{aligned}\tag{7}$$

$$\begin{aligned}\text{Granitic straight} \\ S &= -.038R^{.42}L^{-.33}\end{aligned}\tag{8}$$

Despite differences in the variation of area:relief² ratio and particle size with length in the sedimentary and granitic concave segments, the exponents of length in equations (5) and (7) are similar. These exponents are the concavity of the predicted profiles. Thus the concave segments in general have similar shapes regardless of lithology, but the manner in which these concavities are attained differs. The exponent of length for sedimentary concave segments, $-.93$, gets $-.81$ from area, $-.14$ from particle size and $+.02$ from width:depth. These are $+87\%$, $+15\%$ and -2% respectively. In the granitic concave segments, the same three parameters contribute $-.86$, $-.15$ and $+.12$ to the exponent $-.89$, $+96\%$, $+17\%$ and -13% respectively.

The straight profile segments are not as similar, reflecting the consistent differences in concavity which sedimentary and granitic channels show downstream. In the sedimentary streams, length's exponent of $-.50$ is the sum of $-.29$ from area (58%) and $-.21$ from particle size (42%). On the other hand, particle size shows much less effect in the granitic streams where it contributes only $-.03$ (9%) to the exponent of $-.33$. The remaining $-.30$ (91%) is controlled by drainage area.

Table 7. Comparison of Real and Predicted Concavities

Profile segment	Predicted concavity	Average real concavity	Difference
Sedimentary concave	$-.93$	-1.0	-7%
Sedimentary straight	$-.50$	$-.56$	-11%
Granitic concave	$-.89$	-1.0	-11%
Granitic straight	$-.33$	$-.32$	$+3\%$

Table 7 compares the concavities predicted by longitudinal variations of parameters in equations (5) to (8) with average values for computer derived concavities of the individual washes in each subdivision. In each case the difference is within the limits of accuracy of the measurements, which would allow for a variation of 10 to 20%.

The equation for the profile, relating elevation and length, is simply the integral of the gradient-length expression. Again, using sedimentary concave as an example, the calculations are:

$$S = -.83R^{.80}L^{-.93} \quad (5)$$

$$dH/dL = -.83R^{.80}L^{-.93}$$

$$H = -.83R^{.80} \int L^{-.93} dL$$

$$H = -11.9R^{.80}L^{.07} + C \quad (9)$$

The equations for the remaining subdivisions are:

Sedimentary straight

$$H = -.58R^{.33}L^{.50} + C \quad (10)$$

Granitic concave

$$H = -R^{1.02}L^{.11} + C \quad (11)$$

Granitic straight

$$H = -.057R^{.42}L^{.67} + C \quad (12)$$

The integration constant can be determined for a given profile segment by substituting the values of H, L and R from one of the end points.

TEST OF THE PROFILE EQUATIONS

Two streams from both the Catalina and Tucson Mountains were chosen for testing the model (Fig. 17). Both channels in the Catalinas drain regions of Catalina Gneiss, a coarse-grained rock resembling granite in composition and some weathering properties. The Tucson Mountain washes flow through areas of varied lithology, including rhyolite, sandstone, mudstone and limestone, the same lithologies found in the four original sedimentary-volcanic streams. The units in Tucson 3 are relatively soft and, unlike the sediments in the Mustangs and Whetstones, weather to sand size fragments. The Tucson 2 basin, on the other hand, is crossed by several rhyolitic dikes, which have caused some local metamorphism. This factor, together with a tougher sandstone unit, creates more resistant bed material. Map and field data for these four streams are listed in Appendix II.

Profiles were constructed for each stream using equations (9) to (12). The position of the change in concavity was defined on the basis of the cumulative tributary density discussed earlier. The point where the density began its final decrease downstream was used, and is shown on Figures 18 and 19 as the "predicted break". In three of the four cases this location method was very accurate, while in the fourth, Catalina 1, the inaccuracy apparently did not effect the results.

The calculations involved will be demonstrated on Catalina 2. The cumulative tributary density indicated that the concavity break

FIG. 17. LOCATION MAP FOR STREAMS AND STATIONS IN CATALINA AND TUCSON MOUNTAINS.

occurs 11500 feet, L, from the divide at an elevation of 2960 feet, H. Since the divide is 6000 feet high, the upper profile segment has a relief of 3040 feet, R.

$$H = -R^{1.02}L^{.11} + C \quad (11)$$

$$H = -3610L^{.11} + C$$

At the concavity break,

$$2960 = -3610(11500)^{.11} + C$$

$$2960 = -10150 + C$$

$$C = 13110$$

Thus for the concave segment,

$$H = -3610L^{.11} + 13110$$

Substitution of a number of arbitrary channel lengths between 0 and 11500 feet and calculation of the corresponding elevations will give sufficient data to plot the profile. The computed profiles have not been used between 0 and 1000 feet length, however, since gradient, dH/dL , approaches infinity or vertical as L approaches zero. This is not the case in the natural channels, as a consistent concavity is not maintained this close to the divide. It was also necessary to define both computed profile segments as passing through the concavity break in order to insure a continuous profile.

For the straight segment of Catalina 2, relief is 660 feet, and the channel length and elevation at the concavity break are 11500 and 2960 feet respectively.

$$H = -.057R^{.42}L^{.67} + C \quad (12)$$

Substituting for R, L and H produces:

$$2960 = -465 + C$$

$$C = 3425$$

Thus:

$$H = -.88L^{.67} + 3425$$

Again, substitution of arbitrary lengths and computation of elevations produces the points for the profile plotted in figure 18. The remaining predicted profiles were obtained in the same manner.

Figures 18 and 19 show close similarities between the computed and actual profiles. The maximum vertical and horizontal separations in each segment are also shown. These distances are actually cumulative errors, but they never exceed 15% in the concave segments, well within the error from measurements alone. The errors tend to be larger in the straight segments, going up to 20%, which is probably beyond simple measurement error.

In each case, however, the deviation from the model can be explained on the basis of the lithology, bed material or basin shape. Catalina 1, which shows the poorest fit in the concave segment, is in gneiss below numerous steep cliffs. Large bed material is maintained far downstream, and the rate of particle size decrease is thus low. As a result, concavity is lower than expected in the model. In the straight segments, the predicted profile is gentler and less concave than the real one in Catalina 1. Field investigations confirmed that the particle size decreases more rapidly in the straight segment than is usual for granitic streams, due to the maintenance of large bed material far downstream in the concave segment of Catalina 1. The

FIG. 18. COMPARISON OF REAL AND PREDICTED PROFILES
IN CATALINA MOUNTAINS

FIG. 19. COMPARISON BETWEEN REAL AND PREDICTED PROFILES
IN THE TUCSON MOUNTAINS

computed profile for Catalina 2 shows little deviation from the actual profile, because the stream shows a rate of particle size decrease similar to the granitic streams in the Whetstones and Sierritas.

Tucson 3 also shows a close relation between real and predicted profiles in the concave segment, due to a rate of particle size decrease similar to the other sedimentary streams. Most of the deviation between the Tucson 2 real and predicted profiles results from the stream's flowing along the flank of a hill between 2950 and 2600. This situation creates an unusually low rate of area increase which results in the low concavity in that part of the segment. Both Tucson Mountain streams are less concave than the predicted profiles in their downstream segments due to a low rate of particle size decrease compared to the other sedimentary streams.

The Tucson streams flow at elevations almost totally below all stations on the original nine streams. Thus if precipitation is a factor, it should have some effect on the profiles of these streams. A lower precipitation should result in a smaller discharge for a given drainage area, which in turn would require a steeper gradient to transport material. However, exactly the opposite is the case. On both profiles, the gradient predicted from the model is steeper than the real gradient.

Apparently precipitation has no effect on the profiles, or if it has an effect, it is so minor that the study was not precise enough to detect it. It could in fact be overshadowed by the other factors affecting gradient. It is also possible that the total summer

precipitation does not relate to hydraulic factors such as discharge.

A more important parameter might be average storm intensity, which could in fact be relatively constant throughout the study area. Insufficient data were available to evaluate this possibility. However, if this were the case, storm discharges per unit area would be the same at all elevations. The only effect of the greater total precipitation at higher elevations then would be to tend to increase rates of weathering.

The test has thus shown that equations (9) through (12) derived from the longitudinal variations of drainage area, particle size and width:depth ratio can be used to predict profiles when relief, lithology and tributary distribution are known. Furthermore, it has verified the proposed model of these ephemeral stream profiles as two segments adjusted to different sets of conditions. Deviations of the predicted profiles from the real ones can be explained by unusual longitudinal changes of the particle size. Precipitation, as measured by the index relating it to elevation shows no discernible effect.

CONCLUSIONS

The longitudinal profiles of ephemeral streams draining from the mountains to the alluvial valleys in southeastern Arizona are adjusted to four major independent variables, relief, local base level, lithology and climate. Relief and local base level, the mouth of the stream, determine the vertical drop a channel must undergo and the distance in which it must do it. In essence, this imposes the maximum channel slope on the system. The path the channel follows to connect the divide and the mouth, the profile, is adjusted to the lithology and climate, which determine the discharge, sediment load and roughness. These hydraulic features have been approximated in the dry stage by drainage area, bed material size and width:depth ratio.

Profile adjustment takes the form of two segments of different concavity connected at the point of concavity change. The location of this point is determined by a change in the rate of increase of drainage area with channel length, which is reflected by a change in the number of tributaries entering per unit distance and drainage density. The different concavities reflect the existence of two different sets of hydraulic relations in each channel. A more rapid increase of drainage area and decrease of particle size together with a general increase of width:depth ratio produce a higher concavity in the upstream segment than downstream where the rates of change of area and particle size are smaller and width:depth ratio is very inconsistent or decreases. In

each case, drainage area, which represents discharge and sediment load, is the dominant control.

Equations were developed relating gradient to drainage area, relief, particle size and width:depth ratio in each of the four subdivisions:

Sedimentary concave

$$S = \frac{(6.6 \times 10^{-5}) R^{.80 \pm .34} D_{mm}^{.20 \pm .22} (W/D)^{.14 \pm .28}}{A^{.40 \pm .17}} \quad (1)$$

Sedimentary straight

$$S = \frac{(1.4 \times 10^{-3}) R^{.38 \pm .14} D_{mm}^{.26 \pm .08}}{A^{.19 \pm .07}} \quad (2)$$

Granitic straight

$$S = \frac{(7.6 \times 10^{-6}) R^{1.02 \pm .10} D_{mm}^{.28 \pm .10} (W/D)^{.22 \pm .14}}{A^{.51 \pm .05}} \quad (3)$$

Granitic straight

$$S = \frac{(1.6 \times 10^{-3}) R^{.42 \pm .14} D_{mm}^{.062 \pm .056}}{A^{.21 \pm .07}} \quad (4)$$

Each parameter, except relief, was then replaced by an equation relating it to channel length in a particular subdivision. An expression for gradient in terms of length and relief resulted. It was used to predict profiles in mountain ranges other than those from which the original data was collected by substitution of the known relief and arbitrary channel lengths. Variation between the real and predicted profiles was generally within the limits of accuracy imposed by the

error of measurements. Most of the variation was explained by lithologic, or particle size, differences, while the variation of precipitation among the ranges showed no apparent effect. There may not be enough variation in precipitation to allow detection of an effect, or rainfall intensities may be similar throughout the elevation range studied. Sufficient data for a decision were not available.

Thus the profiles in the ephemeral channels studied are adjusted to discharge, sediment load and roughness as is the case in perennial streams and in the ephemeral streams studied by Leopold and Miller (1956). The change in concavity which occurs is primarily a function of a change in the rates of discharge increase and roughness decrease.

REFERENCES

- Babcock, H. M., and Cushing, E. M., 1942, Recharge to groundwater from floods in a typical desert wash, Pinal County, Arizona: Am. Geophys. Union Trans., v. 23, p. 49-56.
- Battan, Louis J., and Green, Christine R., Data on summer precipitation in the Santa Catalina Mountains, Pima County, Arizona, (unpublished).
- Brush, Lucion M., Jr., 1961, Drainage basins, channels and flow characteristics of selected streams in central Pennsylvania: U. S. Geol. Survey Prof. Paper 282-F, p. 145-181.
- Folk, Robert L., 1965, Petrology of Sedimentary Rocks: Hemphill's, Austin, Texas, 159 p.
- Green, Christine R., and Martin, S. Clark, 1967, An evaluation of precipitation, vegetation and related factors on the Santa Rita Experimental Range: University of Arizona Institute of Atmospheric Physics Technical Reports on Meteorology and Climatology of Arid Regions, no. 17, p. 1-82.
- _____, and Sellers, William D. (editors), 1964, Arizona Climate: University of Arizona Press, Tucson, 503 p.
- Hack, John T., 1957, Studies of longitudinal stream profiles in Virginia and Maryland: U. S. Geol. Survey Prof. Paper 294-B, 97 p.
- Huszar, Charles K., A generalized stepwise multiple regression analysis: University of Arizona Computer Center, Tucson (ditto edition for limited distribution).
- Keppel, Robert V., and Renard, K. G., 1962, Transmission losses in ephemeral stream beds: Journal of Proceedings of Amer. Soc. of Civil Engineers, v. 88, no. HY3, p. 59-68.
- Leopold, Luna B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U. S. Geol. Survey Prof. Paper 252, 57 p.
- _____, and Miller, John P., 1956, Ephemeral streams - hydraulic factors and their relation to the drainage net: U. S. Geol. Survey Prof. Paper 282-A, p. 1-37.

- _____, Wolman, M. Gordon, and Miller, John P., 1964, Fluvial Processes in Geomorphology: W. H. Freeman and Co., San Francisco, 522 p.
- Lootens, Douglas J., 1965, Structure and petrography of the east side of the Sierrita Mountains, Pima County, Arizona: unpublished doctoral thesis, University of Arizona, 224 p.
- Mackin, J. Hoover, 1948, Concept of the graded river: Geol. Soc. America Bull., v. 59, p. 463-512.
- Miller, John P., 1958, High mountain streams; the effects of geology on channel characteristics and bed material: New Mexico State Bureau of Mines and Mineral Resources, Memoir 4, 51 p.
- Owen, Donald B., 1962, Handbook of Statistical Tables: Addison-Wesley Publishing Co., Inc., Reading, Massachusetts, 580 p.
- Renard, Kenneth G., and Keppel, Robert V., 1966, Hydrographs of ephemeral streams in the southwest: Journal of Proceedings of Amer. Soc. of Civil Engineers, v. 92, no. HY2, p. 33-52.
- Schumm, Stanley A., 1963, Sinuosity of alluvial rivers on the Great Plains: Geol. Soc. America Bull., v. 74, p. 1089-1100.
- _____, 1968, River adjustment to altered hydrologic regimen - Murrumbidgee River and paleochannels, Australia: U. S. Geol. Survey Prof. Paper 598, p. 1-65.
- Snedecor, George W., 1956, Statistical Methods: Iowa State College Press, Ames, Iowa, 534 p.
- Shulits, Samuel, 1941, Rational equation of river-bed profile: Am. Geophys. Union Trans., v. 22, p. 622-631.
- Wolman, M. Gordon, 1954, A method of sampling coarse river-bed material: Am. Geophys. Union Trans., v. 35, no. 6, p. 951-956.
- _____, 1955, The natural channel of Brandywine Creek, Pennsylvania: U. S. Geol. Survey Prof. Paper 271, 56 p.
- Woodford, A. O., 1951, Stream gradients and Monterey Sea Valley: Geol. Soc. America Bull., v. 62, p. 799-852

APPENDIX I

PRECIPITATION DATA USED TO DERIVE THE PRECIPITATION INDEX.

Station Name	Mean Daily Summer Rainfall (inches)	Elevation (feet)	Station Name	Mean Daily Summer Rainfall (inches)	Elevation (feet)
Santa Rita Experimental Range (Green and Martin, 1967)					
Box	.10	3920	18	.09	4260
Brown Ranch	.13	4520	130	.10	3800
Cholla Station	.09	3300	131	.10	3480
Desert	.08	3080	140	.11	3480
Desert Grass	.12	3880	149	.09	3540
Desert Rim	.09	3400	152	.10	4020
Eriopoda	.10	3740	155	.08	3240
Florida Station	.14	4300	161	.08	3190
Forest Station	.12	4160	163	.08	3160
Gravelly River	.09	3040	164	.09	3120
Huefano	.10	3880	166	.10	3960
Hughes Station	.08	3120	169	.11	4100
Muhlenbergia	.09	3440	173	.09	3690
Northeast	.09	3280	184	.10	3720
Northwest	.08	2960	185	.09	3490
Parker Station	.12	4320	187	.08	3300
Road	.10	3640	188	.10	3040
Robinson	.13	4200	191	.09	3450
Rodent	.10	3560	192	.09	3600
Ruelas Ranch	.11	4560	205	.10	3720
Southwest	.10	3360	229	.14	4200
Water Retention	.09	3660			
Water Spring	.10	3720			
Whitehouse	.12	3880			

Station Name	Mean Daily Summer Rainfall (inches)	Elevation (feet)	Station Name	Mean Daily Summer Rainfall (inches)	Elevation (feet)
Catalina Mountain Experiment (Battan and Green, unpublished)					
1	.07	4200	16	.18	9150
2	.09	4500	17	.18	9000
3	.11	5000	18	.16	7920
4	.10	4450	19	.17	8400
5	.16	5800	20	.14	5980
6	.16	7050	21	.10	4960
7	.12	4680	22	.07	3400
8	.12	4820	23	.18	8400
9	.11	3840	24	.15	6800
10	.11	3950	25	.09	2720
11	.07	3740	27	.09	2920
12	.09	3650	28	.09	2700
13	.09	3350	29	.08	2740
14	.07	3025			
15	.08	2960			

Community Rain Gages (Green and Sellers, 1965)					
Apache Powder Co.	.10	3690	Benson	.09	3575
Canelo	.14	4985	Benson	.09	3640
Fairbank	.10	3867	Elgin	.13	4900
Fort Huachuca	.12	4664	Elgin	.10	4780
Patagonia	.14	4044	Elgin	.13	4730
Tombstone	.13	4540			

APPENDIX II

FIELD AND MAP DATA FOR THE MUSTANGS, WHETSTONES AND SIERRITAS

The abbreviations used to head the columns are:

Elev. - elevation of station in feet
Area - drainage area in square miles
 A/R^2 - drainage area:relief² ratio x 10⁶
L - channel length from the divide in feet
S - channel gradient in feet/feet
W - channel width in feet
D - channel depth in feet
W/D - channel width:depth ratio
 D_{mm} - mean bed particle size in millimeters
 D_{84} - 84th percentile of bed material in millimeters

Elev.	Area	A/R^2	L	S	W	D	W/D	D_{mm}	D_{84}	P
Mustang 1										
5600	.004	-----	680	.58	-----	-----	-----	-----	-----	---
5500	.010	-----	890	.49	-----	-----	-----	-----	-----	---
5400	.016	-----	1080	.43	-----	-----	-----	-----	-----	---
5300	.024	.024	1390	.27	15.	.9	17.	138.	1024.	1.5
5200	.033	-----	1830	.20	-----	-----	-----	-----	-----	---
5100	.086	.082	2580	.092	12.5	2.6	4.9	40.	147.	1.4
5000	.137	.130	3770	.062	18.	1.5	12.	37.	85.	1.4
4900	.363	2.59	6180	.033	22.5	1.4	17.	20.	43.	1.4
4800	.417	-----	9180	.038	-----	-----	-----	-----	-----	---
4700	.633	4.52	12960	.020	26.	1.2	23.	17.	60.	1.4
4625	1.30	9.29	16270	.020	13.	.7	19.	5.0	13.	1.3
Mustang 2										
5800	.004	-----	680	.645	-----	-----	-----	-----	-----	---
5700	.010	-----	840	.53	-----	-----	-----	-----	-----	---
5500	.013	-----	1240	.49	-----	-----	-----	-----	-----	---
5400	.017	.015	1450	.36	6.0	.63	9.5	97.	355.	1.5
5300	.033	-----	1750	.27	-----	-----	-----	-----	-----	---
5200	.064	.055	2310	.12	6.0	.47	13.	53.	166.	1.4
5100	.167	.144	3470	.059	19.5	1.5	13.	60.	256	1.4
5050	.405	5.34	4440	.037	19.0	1.4	15.	30.	111.	1.4

Elev.	Area	A/R ²	L	S	W	D	W/D	D _{mm}	D ₃₄	P
5000	.547	7.24	6160	.033	27.5	1.7	18.	20.	43.	1.4
4900	.665	8.80	8660	.030	11.5	.57	21.	25.	64.	1.4
4860	.681	-----	10160	.027	-----	-----	-----	-----	-----	---

Mustang 3

5800	.008	-----	750	.34	-----	-----	-----	-----	-----	---
5700	.020	.018	1125	.23	10.5	1.25	8.6	20.	218.	1.5
5600	.057	-----	1625	.21	-----	-----	-----	-----	-----	---
5500	.069	-----	2250	.13	-----	-----	-----	-----	-----	---
5400	.086	.078	3000	.15	12.5	1.1	13.	25.	355.	1.5
5300	.113	-----	3660	.16	-----	-----	-----	-----	-----	---
5200	.129	-----	4370	.13	-----	-----	-----	-----	-----	---
5100	.167	.151	5245	.080	13.0	.85	16.	37.	159.	1.5
5000	.540	-----	7245	.032	-----	-----	-----	-----	-----	---
4900	1.67	13.6	10459	.028	19.5	1.2	16.	23.	97.	1.4
4800	1.89	15.4	14935	.020	23.5	.93	32.	13.	37.	1.4
4700	2.10	17.1	19685	.019	18.5	1.3	15.	11.	30.	1.4

Whetstone 1

7200	.01	-----	490	.55	-----	-----	-----	-----	-----	---
6800	.04	-----	1060	.35	-----	-----	-----	-----	-----	---
6600	.08	-----	1710	.25	-----	-----	-----	-----	-----	---
6400	.14	-----	2680	.21	-----	-----	-----	-----	-----	---
6200	.19	-----	3650	.20	-----	-----	-----	-----	-----	---
6000	.57	.092	4620	.25	16.0	2.11	8.0	53.	338.	1.7
5800	.63	-----	5350	.29	-----	-----	-----	-----	-----	---
5600	.86	.138	6000	.15	16.5	1.64	10.	8.0	69.	1.7
5400	1.05	.168	7790	.10	23.0	1.65	14.	11.	40.	1.6
5200	1.81	.289	9990	.062	23.0	1.10	16.	19.	74.	1.6
5000	3.19	1.68	14060	.042	26.0	1.04	26.	20.	49.	1.6
4780	4.07	2.17	20470	.034	28.5	1.00	29.	21.	69.	1.5
4600	5.27	2.78	26080	.031	31.0	.7	45.	6.0	26.	1.5
4480	5.59	2.96	30310	.019	20.5	.9	23.	7.5	48.	1.5
4300	10.29	5.45	37540	.021	34.0	1.05	32.	4.0	43.	1.4

Whetstone 2

5500	.04	.017	1710	.26	7.5	.40	19.	15.	147.	1.6
5100	.24	.100	4150	.11	10.5	.60	18.	15.	209.	1.5
5000	.30	.126	5075	.11	20.5	.71	30.	4.5	11.	1.5
4800	.71	.296	8005	.043	31.5	.47	65.	5.0	11.	1.4

Elev.	Area	A/R ²	L	S	W	D	W/D	D _{mm}	D ₃₄	P
4600	1.41	1.11	12145	.045	37.5	.43	88.	4.0	6.0	1.4
4400	1.78	1.41	17675	.035	88.0	.55	160.	3.5	5.5	1.4
4200	1.96	1.55	23685	.026	51.5	.32	160.	2.0	4.0	1.4
4000	2.88	2.27	32135	.022	42.5	.38	115.	1.5	3.5	1.3
Tributary 1										
5700	.02	.008	1220	.41	4.5	.25	18.	19.	256.	1.6
5400	.03	.013	2030	.33	7.0	.52	17.	35.	218.	1.5
5200	.07	-----	2690	.21	-----	-----	-----	-----	-----	---
Tributary 2										
4600	.23	.998	7650	.042	20.0	.45	45.	3.5	5.0	1.3
Whetstone 3										
5800	.01	-----	1220	.45	-----	-----	-----	-----	-----	---
5600	.03	-----	1790	.27	-----	-----	-----	-----	-----	---
5400	.07	.033	2850	.12	14.5	.9	16.	5.0	64.	1.5
5200	.09	-----	3900	.11	-----	-----	-----	-----	-----	---
5000	.19	.090	5690	.067	15.0	.85	18.	3.0	16.	1.5
4800	.69	-----	9760	.036	-----	-----	-----	-----	-----	---
4720	1.22	.622	12690	.037	76.0	.8	95.	1.5	3.0	1.4
4600	1.31	-----	16100	.028	-----	-----	-----	-----	-----	---
4400	1.78	.907	24230	.028	41.0	.49	88.	1.0	2.5	1.4
4200	2.26	1.15	31060	.028	60.0	.29	210.	1.0	2.5	1.3
4000	2.48	1.26	37070	.034	95.5	.14	700.	1.0	2.0	1.3
3800	5.68	2.90	42620	.035	93.0	.14	655.	1.0	1.5	1.3
Sierrita 1										
5250	.04	.026	1470	.22	8.0	.63	13.	23.	74.	1.5
5000	.15	.096	2610	.23	13.0	.61	22.	9.5	37.	1.4
4750	.36	.230	4320	.079	20.0	.46	46.	8.0	44.	1.4
4525	.65	.416	8960	.044	9.5	.73	17.	12.	69.	1.4
4440	1.07	.685	9770	.045	19.5	.68	30.	12.	69.	1.4
44MT	.71	.454	9770	.045	12.0	.66	18.	24.	89.	1.4
4250	1.88	.578	15300	.032	42.0	.23	185.	2.0	3.5	1.3
4000	2.55	.789	23750	.033	37.5	.51	74.	3.5	6.5	1.3
3750	3.37	-----	34150	.024	-----	-----	-----	-----	-----	---
3425	4.75	1.47	48950	.023	36.0	1.08	34.	1.0	3.0	1.2
Tributary 1										
4440	.36	.230	7150	.064	10.0	.68	15.	15.	316.	1.4

Elev.	Area	A/R ²	L	S	W	D	W/D	D _{mm}	D ₈₄	P
Sierrita 2										
5500	.02	.017	970	.34	4.5	.39	12.	21.	97.	1.5
5250	.11	.091	2270	.13	7.5	.44	20.	21.	85.	1.5
4925	.56	.207	4710	.081	22.5	.22	110.	4.5	10.	1.4
4750	.82	-----	7960	.068	-----	-----	-----	-----	-----	---
4500	.85	.213	11370	.060	34.0	.23	155.	3.0	5.0	1.4
4250	1.22	.305	16570	.042	39.0	.28	140.	3.5	7.5	1.3
4000	2.16	.540	23560	.028	128.5	.34	420.	2.0	4.5	1.3
3825	3.02	.755	31060	.020	56.0	.66	87.	2.5	4.5	1.2
3750	3.39	-----	35610	.021	-----	-----	-----	-----	-----	---
Sierrita 3										
5250	.02	-----	890	.20	-----	-----	-----	-----	-----	---
5000	.05	.038	2190	.23	7.0	.42	23.	12.	49.	1.4
4750	.20	.151	3820	.10	10.0	.47	23.	16.	91.	1.4
4500	.62	.469	8380	.062	17.5	.37	50.	4.5	20.	1.4
4250	1.45	.473	15210	.027	73.0	.22	400.	4.0	6.0	1.3
4000	1.76	.575	23820	.030	29.5	.18	165.	3.0	4.5	1.3
3750	2.75	.898	32760	.025	23.5	.24	100.	2.5	5.2	1.2
3500	3.56	1.16	43320	.022	27.0	.24	98.	2.5	4.5	1.2
Sierrita 5										
3550	.19	2.51	6800	.024	20.5	.26	85.	3.0	5.0	1.1
Sierrita 6										
3500	.34	2.78	8800	.019	19.0	.27	76.	1.5	3.0	1.1
3400	.59	4.82	13300	.021	33.0	.32	110.	2.0	4.5	1.1
Sierrita 7										
3325	.63	3.94	16000	.023	21.5	.41	56.	1.5	3.0	1.1
Catalina 1										
6800	-----	-----	1230	.29	-----	-----	-----	-----	-----	---
6400	-----	-----	2870	.26	-----	-----	-----	-----	-----	---
5600	-----	-----	4810	.33	-----	-----	-----	-----	-----	---
4800	-----	-----	7790	.26	-----	-----	-----	-----	-----	---

Elev.	Area	A/R ²	L	S	W	D	W/D	D _{mm}	D ₈₄	P
4000	-----	-----	11170	.18	-----	-----	-----	-----	-----	---
3600	1.25	.076	13310	.14	19.	.81	24.	64.	660.	1.5
3200	-----	-----	17210	.082	-----	-----	-----	-----	-----	---
3100	1.61	.098	18645	.070	18.	.80	21.	24.	190.	1.4
2800	-----	-----	23600	.056	-----	-----	-----	-----	-----	---
2720	-----	-----	26250	.018	-----	-----	-----	-----	-----	---
2640	-----	-----	30200	.017	-----	-----	-----	-----	-----	---
2560	-----	-----	35800	.017	-----	-----	-----	-----	-----	---

Catalina 2

4400	-----	-----	3080	.40	-----	-----	-----	-----	-----	---
4000	-----	-----	4200	.27	-----	-----	-----	-----	-----	---
3600	-----	-----	6480	.14	-----	-----	-----	-----	-----	---
3200	-----	-----	9840	.11	-----	-----	-----	-----	-----	---
3000	-----	-----	11360	.11	-----	-----	-----	-----	-----	---
2800	-----	-----	15280	.029	-----	-----	-----	-----	-----	---
2760	1.66	3.98	16920	.030	23.0	.59	40.	5.5	28.	1.1
2600	-----	-----	23120	.021	-----	-----	-----	-----	-----	---
2560	1.91	5.22	25740	.021	29.0	.91	34.	5.5	46.	1.0

Tucson 2

3250	-----	-----	2080	.16	-----	-----	-----	-----	-----	---
3000	-----	-----	3120	.13	-----	-----	-----	-----	-----	---
2900	-----	-----	4680	.096	-----	-----	-----	-----	-----	---
2800	-----	-----	6240	.043	-----	-----	-----	-----	-----	---
2700	-----	-----	9360	.031	-----	-----	-----	-----	-----	---
2675	1.66	9.20	10580	.031	29.0	.84	25.	8.5	23.	.9
2650	-----	-----	10920	.027	-----	-----	-----	-----	-----	---
2600	-----	-----	12500	.019	-----	-----	-----	-----	-----	---
2550	-----	-----	16650	.018	-----	-----	-----	-----	-----	---
2525	2.52	14.0	18750	.017	29.0	.79	38.	9.5	16.	.9
2500	-----	-----	19580	.018	-----	-----	-----	-----	-----	---

Elev.	Area	A/R^2	L	S	W	D	W/D	D_{mm}	D_{84}	P
Tucson 3										
3500	-----	-----	800	.48	-----	-----	-----	-----	-----	---
3250	.02	.015	1025	.27	6.0	.40	15.	46.	316.	1.0
3000	-----	-----	2600	.13	-----	-----	-----	-----	-----	---
2950	.18	.136	3080	.077	14.5	.59	25.	30.	91.	1.0
2900	-----	-----	4160	.063	-----	-----	-----	-----	-----	---
2800	-----	-----	5200	.043	-----	-----	-----	-----	-----	---
2700	-----	-----	8310	.031	-----	-----	-----	-----	-----	---
2650	-----	-----	9890	.024	-----	-----	-----	-----	-----	---
2600	-----	-----	12500	.021	-----	-----	-----	-----	-----	---
2550	-----	-----	14580	.014	-----	-----	-----	5.0	10.5	---
2500	-----	-----	18200	.012	-----	-----	-----	-----	-----	---