QUANTITATIVE GEOMORPHOLOGY
OF THE
SAN DIMAS EXPERIMENTAL FOREST, CALIFORNIA

Technical Report No. 19

Project NR 389-042
Contract N6 onr 271-30: Nonr 266 (50)
Office of Naval Research

by

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Abstract

Methods of quantitative geomorphology, developed in regions of humid climate and moderate relief, were tested for applicability to mountainous terrain in five fifth-order watersheds in the San Dimas Experimental Forest, San Gabriel Mountains, southern California. Deep canyons, rocky cliffs, sharp-crested ridges and many waterfalls five to 50 feet high typify these watersheds. Their dense chaparral vegetation consists largely of chamise, sage, ceanothus, manzanita, and oak, which have been grouped in ten associations and areally mapped. Rainfall totals 20 to 40 inches, mostly from a few intense winter storms; summers are hot and dry. Stony residual soils are generally less than three feet deep. Bedrock of gneiss, schist, metadiorite, and granite, intermingled, is deeply weathered, friable to depths exceeding 50 feet in places, and fractured by many faults of small displacement. Over-steepened inner canyon walls, entrenched meanders, and knick-point waterfalls indicate recent rejuvenation.

During two summers' field work all channels and basin divides in the watersheds were drawn on 1/8000 topographic maps. Channel segment numbers and lengths, basin areas, diameters, perimeters, as well as relief, elongation, circularity, relief ratio, drainage density, and channel frequency, were measured from these maps. New or modified definitions were developed for channels, basin diameter, elongation, and relief ratio. Measurement precision was within sources of error arising from inaccuracies of the base maps and limitations of their scale. Field observation reliability was proven by a replication study in which another investigator using the same definitions and procedures independently remapped and analyzed two of the watersheds. Results, processed from punch cards with electronic computers, include the mean, standard deviation, maximum and minimum of each geomorphic property and its common logarithm for each watershed.

Measurement distribution normality was tested by Chi-square and Kolmogorov-Smirnof tests. Circularity distributions were normal; channel length, basin diameter, perimeter and relief, and drainage density distributions were log-normal. Polymodality of first-order area indicated that it may be useful in detecting multicycle erosional topography. Bartlett's test for homogeneity of variance showed that logarithms of first-order properties did not have homogeneous variance. Logarithms of higher order channel length, basin area and diameter, drainage density, and channel frequency were of homogeneous variance. These results cast some doubt on the assumption made in other studies that geomorphic properties measured in contiguous areas have homogeneous variances.

Differences between watershed logarithmic means of second-order and higher order channel length and first-order relative relief were found to be non-significant by analysis of variance. Significant differences were found between watershed logarithmic means of second- and third-order basin area and diameter, second-order drainage density, and second-order channel frequency. Laws of stream numbers, of channel lengths, and of basin areas were found to apply to the San Dimas watersheds. A law of basin diameters and a law of basin relief were postulated and applied. Elongation showed little variation with order. Drainage density and channel frequency were in inverse geometric relation to order.

Multiple correlations were computed between peak discharge and storm rainfall, cover density, antecedent rainfall, and nine geomorphic properties taken five at a time. It was concluded that the methods of quantitative geomorphology are applicable to mountain watersheds, that there are significant differences between the geomorphic properties of the San Dimas watersheds, and that these differences account for some of the differences in discharge from these watersheds.

Introduction

Quantitative research on morphology of stream-eroded landscapes entered its modern phase with the publication by R. E. Horton (1945) of a major paper in which he defined various measurable drainage basin properties observed during the years he successfully directed the Horton Hydrologic Research Laboratory. He found consistent relationships between the rank, or order, of stream channel segments and their numbers, lengths, drainage areas, and slopes. Since that time more than a score of other workers have modified, refined, and added to Horton's list of definable and measurable watershed properties. They have extended the slowly accumulating store of quantitative landform data to include many different geographic regions. They have applied methods of statistical analysis to these data to discover new relationships.

During the decade following publication of Horton's paper, most of the field work on quantitative geomorphology of fluvially-eroded landscapes was done in areas of moderate to low relief. Horton's work was done predominantly in Pennsylvania, New York and adjoining states, in a region of humid climate. Other areas studied in the humid eastern states include New England (Langbein, 1947), eastern Tennessee (Miller, 1953), northern New Jersey (Schumm, 1956), southern Indiana (Coates, 1958), southeastern Missouri (Ore and White, 1958) and several areas in the Appalachian Plateau (Morisawa, 1959). Work in the semi-arid and arid regions of the west-central and southwestern United States was done by Schumm (1956), Schumm and Hadley (1957), Melton (1957), and Smith (1958). Strahler (1950, 1952, 1958) carried out detailed field and map studies of the Verdugo Hills, southern California, the first application of Horton principles and slope analysis to a mountainous terrain in a Mediterranean-climate environment, but it remained for the writer to carry out a full-scale, comprehensive analysis of typical mountainous watersheds of southern California and to attempt to relate the observed morphologic properties to the hydrologic characteristics.

The erosional history of the selected area in the San Gabriel Mountains of southern California is complex. Variations in bedrock geology and vegetative cover present a wide range of conditions. It was felt that if methods developed for humid, hilly regions of the eastern United States should prove applicable in extremely precipitous mountainous terrain in an essentially semi-arid environment, the range of applicability and soundness of the Horton concepts on which the methods are established would be considerably enhanced. A critical analysis of the morphometric methods and assumptions of quantitative geomorphology, with an aim of improving the definitions and methods of analysis was a second objective.

Third, the use of digital electronic computors in statistical analysis was introduced for the first time to relate morphological, geological, vegetative, and hydrologic data.

The San Dimas Experimental Forest has been established by the United States Forest Service, in cooperation with the State of California, for research in mountain watersheds and watershed management. A wealth of meteorological, hydrological, ecological, pedological, botanical, and geological data has been collected for the area. Many forms of meteorological and hydrological data are being continuously recorded. The present investigation is intended to be, in addition to a broadening of the concepts and methodology of quantitative geomorphology, a contribution to the accumulated knowledge of these watersheds. The author hopes that the description of this area will encourage others to utilize the data available for further study.

Acknowledgments

Assistance of Professor A. N. Strahler, of Columbia University, who suggested the study area and supervised the investigation, is gratefully acknowledged. Charles Bell, William Cromie, Howard Boggs, Michael Rubel, and Diana Maxwell assisted with the field work. The author is grateful to James Trew, who performed the replication study described below, and to P. Carlyle Neely, who wrote the programs and operated the computer for much of the analysis of data. The author's greatest indebtedness and appreciation are to the office and field staffs of the San Dimas Research Center, and to its former director, Research Forester J. D. Sinclair. Their unfailingly friendly cooperation and the valuable data they had compiled helped make this investigation successful. The research reported here has been made possible through support and sponsorship by the United States Department of the Navy, Office of Naval Research, Geography Branch, through Project NR 389-042, under Contracts N6 ONR 271-30 and N-ONR-266(50) with Columbia University.

The San Dimas Experimental Forest

Physical Geography

LOCATION AND GENERAL TOPOGRAPHY

The San Dimas Experimental Forest, about 35 miles northeast of Los Angeles, occupies 17,000 acres on the southern slopes of the San Gabriel Mountains (Figure 1), within the Angeles National Forest of southern California. This experimental forest is considered to be a representative segment of the San Gabriels (Storey, 1948, p. 3) and is also representative of much of the chaparral covered mountain land in southern California. It contains two major drainage networks: San Dimas Canyon and Big Dalton Canyon (Figure 2). Each of these has a number of tributary watersheds. Five of the tributaries, Wolfskill, Fern and Upper East Fork in the San Dimas network, and Bell and Volfe in the Big Dalton network, were studied in this project. In addition, two groups of small watersheds, one in Bell Canyon and one in Fern Canyon, were studied in greater detail.

The San Gabriel Mountain range, oriented on an approximately east-west axis, is 70 miles long, 25 miles in maximum width, and occupies an area of 1400 square miles. The mountains are bounded by the Mojave desert and Santa Clara river on the north, by the Santa Ana and San Gabriel valleys on the south, the San Fernando valley on the west, and Cajon Canyon on the east. Summit altitudes increase from 5,000 feet at the western end to 10,059 feet (San Antonio Peak) near the eastern end. The range is a deeply-dissected, mature mountain mass, trenched by many steep-sided canyons. The only nearly level ground is in the narrow, debris-choked flood plains of the major rivers.

TOPOGRAPHY OF INDIVIDUAL WATERSHEDS

Wolfskill Canyon

Wolfskill Canyon, designated Watershed I in Experimental Forest studies and in this report, lies in the southeastern part of the San Dimas drainage system (Figure 2). It includes an area of 2.49 square miles,[1] with elevations from 1700 to 5200 feet and contains numerous steep-sided V-shaped canyons separated by narrow ridges. Wolfskill's long narrow form is unusual compared to the other more pear-shaped watersheds in the Forest. It is 3.3 miles long and less than one mile wide, oriented with its long axis trending east-northeasterly.

Another unusual feature of Wolfskill Canyon is the number and size of its waterfalls. Highest in the Experimental Forest are Wolfskill Falls, located on the main stream one-half mile upstream from the mouth of the canyon and rising more than 130 feet above a base elevation of 2050 feet. They have acted as a local baselevel for the stream above, and for a considerable distance upstream no other falls occur (Bean, 1946). The next large fall in the main stream is at 3650 feet elevation. At 4500 feet elevation is the uppermost of a short series of falls.

The main stream channel, narrow throughout its upper end, widens to 50 feet or more above Wolfskill Falls. Running water can often be found in the main stream during the dry season. The water disappears into the coarse channel-bottom deposits only to reappear further along the stream course. Along much of the length of the main stream the channel side walls are bare bedrock, extending upward tens of feet. In some places narrow alluvium floored meandering gorges with overhanging walls have been cut in the crystalline bedrock.

Tributary streams are characterized by very steep gradients and have many waterfalls, from 10 to 25 feet high, but some more than 80 feet high. Tributary channels are often choked with debris which has moved by creep, sheet wash, and slump from the steep adjacent slopes. The narrow channel bottoms are usually trenched through the debris into bedrock.

At the head of Wolfskill Canyon is a small area of about 30 acres whose gently rounded topography contrasts sharply with the rest of the canyon. The slopes in this area are more gentle, have sigmoidal profiles, and are covered with a deeper, apparently more stable soil. The valley transverse profiles are broadly up-concave rather than V-shaped. It is quite probable that this area is a small remnant of the gently rolling pre-Pleistocene erosion surface (see Erosional History). It has been protected from dissection by a group of resistant dacite dikes which cause the uppermost waterfalls in the main-

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[1] As measured from large scale maps in this study; see Measurement Precision below.

stream just below the upland remnant, and by its remoteness from regional base level at the head of an unusually long canyon.

Except on the upland remnant, the slopes of Wolfskill Canyon are equal to or steeper than the angle of repose of the coarse granular soil covering them. Small slumps and slides of dry debris are common. Bean (1946) states that the areas underlain by granodiorite, in the southwest part of the Canyon, have a tendency to develop into steeper slopes, on which there is more active sliding and soil movement, than those of the remainder of the Canyon underlain by gneiss.

Expressed in terms of the Davisian concept of landform evolution, the rejuvenated streams of Wolfskill Canyon are in the stage of youth. The landmass as a whole has reached very early maturity, with maximum relief and maximum extent of steep valley-wall slopes. If the upland remnant represents the oldest, or N erosion cycle, then the succeeding cycle, now in early maturity, may be designated the N + 1 cycle.

Fern Canyon

Fern Canyon, designated Watershed II, lies immediately north of Wolfskill Canyon in the San Dimas drainage system (Figure 2). It contains 2.20 square miles; elevations range from 2600 to 5500 feet. The watershed, of very roughly pear-shaped form is approximately 2.5 miles long and 1.1 miles wide. In common with the other San Dimas network watersheds, it consists of narrow, V-shaped canyons and sharp-crested mountain ridges.

A large, shallow closed depression known as Brown's Flat occupies approximately 40 acres at an elevation of 4250 feet on the southern side of this watershed. The depression is covered by a deep sandy loam soil which supports a pure stand of tall, widely-spaced Ponderosa pine and a continuous cover of wild grass. An area of about 150 acres on the south canyon wall drains into Brown's Flat, and hence does not contribute directly to the watershed's channel discharge during a storm. The underground drainage from Brown's Flat is into Fern Canyon. Several channels traversing the slope north of and below Brown's Flat noticeably increase in size, apparently because of groundwater inflow through the shattered and deeply weathered bedrock. The depression was formed by a major pre-historic slump movement on the southern boundary ridge of the watershed. A similar but much smaller slump block depression exists outside the Experimental Forest boundary on the east side of the ridge at the head of Fern Canyon.

The main stream and tributaries of Fern Canyon have steep gradients with many waterfalls 10 to 50 feet high. All of the channels are cut in bedrock, with a discontinuous veneer of bouldery alluvium covering the channel bottoms. With the exception of Brown's Flat the slopes are high-angle, unstable repose slopes. A slight steepening of the slopes, even that caused by walking on them, often causes local debris slides. Fern Canyon contains the highest point, elevation 5500 feet, in the San Dimas Experimental Forest, a rounded knob on the divide at the head of Fern Canyon.

Fern Canyon watershed has reached the Davisian stage of early maturity in the N + 1 cycle of landmass development although no upland remnant of the N cycle remains. The rejuvenated main stream is ungraded and youthful.

Fern small watersheds

Three small tributaries at the head of Fern Canyon have been mapped by Forest Service personnel at a large scale. These watersheds and an adjoining area on the same large-scale map are individually designated Watersheds II-1, -2, -3, and -4. They have been measured somewhat more intensively in the present investigation to establish relationships which could not readily be determined in the larger canyon watersheds. The Fern small watersheds and adjacent area are located in the northeast corner of Fern Canyon. They contain a total area of approximately 0.3 square miles with surface elevations from 4500 to 5400 feet. Directions of trunk drainage range from northwest to southwest. These sub-watersheds have the same steep-sided, V-shaped valleys and narrow, sharp-crested ridges as the other tributaries in Fern Canyon; all have slightly elongate, pear-shaped outlines.

Stream gradients in these small watersheds have been slightly modified by artificial structures. In 1938 a mountain wildfire burned into the head of Fern Canyon. To prevent excessive erosion of the stream channels and loss of the stream gaging stations and other instruments in floods which usually follow fires in these mountain watersheds, a large number of small check dams, one-half to three feet high, were built in the tributary channels. A few dams 6 to 16 feet high were built in the main channels. Sediment soon filled the channels above the dams, locally decreasing the channel gradients. The decrease in gradient reduced the capacity of the streams, permitting a gradual accumulation of debris along some of the channel banks. The accumulation of debris locally has caused a decrease in steepness of the lowest three to five feet of the valley side slopes. Hence the steepest segment of the valley side slope, which in southern California mountain watersheds is characteristically immediately above the channel bank, is often several feet above the channel bank in the Fern small watersheds.

The Fern small watersheds are in a mature stage of erosional development with maximum slope area and maximum relief. The channels within these watersheds would be described as in the late youth stage of stream development, with many streams locally approaching a graded condition.

Upper East Fork

The Upper East Fork of the San Dimas drainage, Watershed III, occupies the northeast corner of the Experimental Forest and lies immediately north of Watershed II. With narrow canyons and mountainous ridges it covers 2.18 square miles. Surface elevations range from 2600 feet to 5200 feet. The width of more than 1.5 miles, greatest of the watersheds studied, is large relative to its length of 2.6 miles.

The western, lowest third of Watershed III is constricted to a single large canyon. Two waterfalls, about 50 and 80 feet high, occur in this narrow canyon. Below the lower fall, near the outlet of the watershed, the main stream flows in a deep bedrock trench, plunging through a series of enormous coalesced potholes with smoothly polished, often overhanging walls 20 to 50 feet high.

Bell Canyon

Bell Canyon, Watershed VIII, in the western third of the San Dimas Experimental Forest, is at the northeastern head of the Big Dalton drainage system. It has an area of 1.36 square miles, with surface elevations ranging upward from 1880 feet; is about 2.3 miles long and 0.8 miles wide. Although the long axis of the basin is oriented north-northeast, near the southern end of the canyon, the main stream curves to the west, so as to leave the watershed approximately one-quarter mile north of the southern limit of the basin.

Although Bell Canyon has the deep, V-shaped side canyons, narrow sharp-crested ridged, and steep unstable slopes characteristic of the watersheds of the San Dimas system, its main stream more closely approaches a graded or equilibrium form. The high waterfalls and deeply entrenched bed rock gorges characteristic of the lower reaches of the main streams of Wolfskill, Fern, and Upper East Fork Canyons are absent in Bell Canyon. There are no falls on the lower two-thirds of the main channel, although near the mouth of the canyon the channel gradient steepens to more than five feet per hundred feet. Throughout the middle and most of the lower course of the main stream, the canyon bottom has been widened by lateral planation, leaving a discontinuous flood plain 10 to 30 feet wide, with a few stretches more than 50 feet wide. The valley floor is covered by a very thin veneer of alluvium, apparently less than five feet thick, which is scoured to bedrock in the present channel.

The remainder of the canyon is very similar to others in the San Dimas system; the tributaries have numerous falls 5 to 20 feet high in narrow, steep-gradient, bedrock channels.

Thus, according to the Davisian concept of stage, the landmass of the watershed has passed early maturity in the N + 1 cycle. Continued removal of mass will decrease relief and decrease the percentage of the total area which is steeply sloping. The main stream of the canyon has reached early maturity throughout much of its length.

Bell small watersheds

The four Bell small watersheds are located at the upper, northern end of Bell Canyon, forming a radial, fan-shaped orientation, and including the entire headwaters of Bell Canyon. These watersheds are designated VIII-1 to VIII-4, from east to west. Watershed VIII-1 in the northeast corner of Bell Canyon, has an area of 0.12 square miles. Its elevation ranges from 2450 to 3475 feet, and its length is oriented southwesterly. Adjacent to it is the largest of these small watersheds, VIII-2, 0.16 square miles in extent, with elevations from 2480 to 3455 feet, oriented southerly. Watershed VIII-3 includes the highest point, 3536 feet, in Bell Canyon in its 0.10 square miles. Its lowest elevation is 2480 feet, and its principal drainage is southeasterly. Watershed VIII-4, the smallest of the Bell Canyon group, has an area of 0.06 square miles, elevations from 2400 to 3350 feet, and is oriented east-southeasterly.

All of the Bell small watersheds have steep-gradient channels in narrow, V-shaped canyons separated by precipitous, sharp-crested divides. Numerous waterfalls, up to 20 feet high, are characteristic of both main and tributary channels. The Bell small watersheds are in the stage of late youth and have youthful channels.

Volfe Canyon

Volfe Canyon, Watershed IX, is located immediately west of Bell Canyon, in the Big Dalton drainage system. It has an area of 1.18 square miles. The main stream joins that of Bell Canyon at an elevation of 1880 feet. The highest elevation in Volfe Canyon is 3500 feet. The watershed has a symmetric, pear-shaped outline; is approximately 1.9 miles long and 0.7 miles wide. The main stream flows southward.

The central section of Volfe Canyon contains several cone-like summits on the ends of lateral ridges which extend into and displace the channel.

The lateral ridges, which extend from the peripheral divide toward the center of the canyon, are generally narrow, sinuous, and sharp crested, as are most of the ridges in the Experimental Forest. Near their ends, the ridge crests rise a few tens to more than one hundred feet, often rising from a distinguishable saddle in the ridge. Beneath each terminal summit the base of the ridge usually broadens. The main stream usually swings around the conical base in a sweeping curve. These conical summits appear to be the result of canyon entrenchment around meander-cutoff remnants which were formed during an earlier erosion cycle.

The southern third of the main channel of Volfe Canyon has a continuous floodplain 50 to 150 feet wide. The floodplain terminates one or two hundred feet upstream from the mouth of the canyon, where the channel gradient steepens and the canyon becomes narrower. The floodplain is more maturely developed than that in Bell Canyon; it is covered by coarse, bouldery alluvium of undetermined thickness. The main channel, three to five feet deep, does not cut through the floodplain alluvium. Near the mouth of the canyon, the alluvial deposits are absent; the steepened boulder-choked channel is on bedrock.

Description of the Davisian stage of erosion of the watershed is made difficult by the steepened, inequilibrium section of the main stream at the mouth of the canyon. It is probable that continued erosion in the upper part of the canyon will decrease relief and, as the floodplain alluviation continues, increase the amount of area of low slope. However, the apparent rejuvenation at the mouth of the canyon may cause the floodplain to be trenched, increasing relief. Because the larger portion of the watershed is distant from the influence of the steepened channel, the watershed is considered to be early mature to mid-mature, with an early mature main stream channel.

CLIMATE

The San Dimas Experimental Forest has a subtropical Mediterranean climate (Köppen classification *Csa*) in common with most of southern California. The winters are mild and rainy; the summers are hot, dry, and sunny (Figure 3). The summer maximum daily temperatures often exceed 100 degrees Fahrenheit. The minimum daily winter temperatures at elevations above 4000 feet often drop below freezing; and some of the precipitation occurs as snow (Sinclair, 1954). Over the greater part of the Experimental Forest, however, most of the precipitation occurs as rain.

Most of the annual rainfall occurs during the winter from extra-tropical cyclones. Seventy eight per cent of the rainfall occurs between December and March while less than two per cent occurs between June and September. The rainfall varies within the Forest depending upon elevations and orientation with respect to prevailing storm paths.

In southern California, storms moving from the Pacific tend to travel towards the east and northeast. The moist air, forced to rise over the northwest-southeast trending ranges of the San Gabriel and San Bernardino Mountains, delivers much rainfall upon the south and west slopes. The result is a band of rainfall ranging from 20 to 40 inches annually on the southerly side of the San Gabriel-San Bernardino Ranges. An isohyetal map of the San Dimas Experimental Forest (Figure 4) shows the detail within a small part of this band of rainfall.

Rainfall was measured by a network of 310 standard vertical 8-inch raingages, a concentration of one gage to every 50 acres (Storey, 1939). Such large divergences in rain catch were observed that other sampling methods were tested, leading to the present installation of tilted gages inclined perpendicular to the contiguous slopes. Records from the tilted gages were used to correct the previous vertical-gage measurements (Hamilton, 1954).

The pattern of rainfall (Figure 4) is a result of topographic influences. Air currents passing up Big Dalton Canyon are cooled and yield increasing amounts of rain as they ascend. Reaching the lower parts of Bell, Volfe, and Monroe Canyons, the currents swing eastward and cross a low saddle in the Big Dalton-San Dimas divide. After passing into the San Dimas drainage, these currents encounter others traveling up San Dimas Canyon. The combined currents thence travel eastward, ascending the high ridge which bounds the east side of the Experimental Forest. Increased cooling there produces the heaviest rainfall on the Forest. Areas of comparatively low rainfall near the mouth of San Dimas Canyon and in the vicinity of Tanbark Flat are both on the lee side of high points on the Big Dalton-San Dimas divide (Storey, 1948, p. 10-12). A detailed study of the factors affecting precipitation within the Experimental Forest showed dependency upon elevation, local slope of the ground surface, aspect or orientation, topographic rise within five miles northeastward, and geographic position within the Forest (Burns, 1953).

The combination of cyclonic and orographic effects produces rainfall from several directions. The northerly storms usually produce small amounts of precipitation occurring generally at low intensity and at only slight inclinations from the vertical. Southerly storms are the great rain-producers of the area; and their precipitation is usually of much greater intensity than the northerly storms. The southerly storms are accompanied by higher winds than the northerly storms and their precipitation usually is inclined a considerable amount from the vertical (Hamilton, 1944, p. 517). Most of the precipitation occurs in a few of the winter storms. During a 14-year period, 23 per cent of the total precipitation fell in 3 per cent of the storms. High precipitation intensities are characteristic of the region: In 1926, at Opid's Camp in the Angeles National Forest, 0.65 inches of rain fell in 1 minute, a world record until 1955. In 1943, 26.13 inches of rain fell in a 24-hour period at Camp LeRoy, Angeles National Forest, establishing a new record for the United States (Hamilton, 1951, p. 3).

SOILS

Soils of the San Dimas Experimental Forest, typical of those of mountain watersheds in southern California, are of two kinds: (1) Narrow strips of immature alluvial soils form discontinuous borders to the main channels, but these soils occupy less than one per cent of the five watersheds described in this study. (2) The watershed slopes are occupied by a shallow, homogeneous residual soil.

The residual soil is a coarse-textured rock-filled sandy loam. Its depth varies from a few inches to more than 6 feet in a few instances. On the steep slopes shallower soils are typical and numerous bedrock outcrops occur. The average residual soil depth over the mountain watersheds within the Experimental Forest is less than three feet. No profile development or zonation, other than a downward gradational increase in apparent density and decrease in organic content, has occurred. The soil shows evidence of active downhill creep and dry-sliding. The greater depths of residuum usually occupy slopes of lower gradient which typically have fewer rock outcrops and exhibit less creep.

A detailed soil survey has been completed for Watershed Number X, Monroe Canyon, in the Big Dalton Drainage (Rowe and Coleman, 1951, p. 19-21). Monroe Canyon has lower elevations, (1700 to 3500 feet) than most of the other watersheds in the Forest. The higher watersheds have somewhat steeper slopes, hence a greater percentage of areas with very shallow soil and exposed bedrock. In Monroe Canyon 110 soil sample plots were excavated to bedrock. Depth to bedrock was measured, and samples from the pits were analyzed for texture, apparent density, field-capacity and wilting point. Statistical analyses of the results showed no significant relationship between these soil characteristics and the measurements used to characterize geology, vegetation, and topography. From this it was concluded that the variations in the characteristics were essentially random, and that the residuum was a single homogeneous soil type (Rowe and Coleman, 1951, p. 21). The characteristics as found in the soil study, and of 14 soil moisture plots, are summarized in Table I.

A local exception to the characteristic residuum which covers the slopes of the San Dimas Experimental Forest occurs on Watershed II, Fern Canyon. Here, in Brown's Flat, a shallow closed depression formed by an ancient land slip, deep organic zonal soil has developed on 40 acres, or three per cent of the total area of the watershed. The soil, a sandy clay loam, has been derived largely from sediment washed into the depression by adjacent ephemeral streams.

VEGETATION

The San Gabriel Mountains are covered by three different vegetation complexes: chaparral, woodland, and forest (Figure 5). Of these, chaparral, composed of many different shrubs and a few trees, is dominant on the San Dimas Experimental Forest. It grows at elevations of 1,000 to 6,000 feet above sea level, usually on loose soils and steep slopes that favor rapid runoff and high erosion rates when denuded of the protecting plant cover. It is characterized by evergreen shrubs, usually with thick, hard, flat leaves and rigid branching. The species and density of the vegetation vary in relation to age of the cover, aspect or orientation of the site, elevation, amount of rainfall and evaporation, and depths of the soil. During the long hot summers the chaparral dries and becomes very inflammable. Wildfires tend to perpetuate and extend the chaparral into areas originally occupied by other plant formations. At elevations usually above 5000 feet, where winter precipitation often occurs as snow, open forests of several coniferous species supplant the chaparral. The woodland complex generally grows between 3,000 and 6,000 feet elevation, intermingled with chaparral, on northerly-facing hillsides.

Ten vegetation types were identified by J. S. Horton (1941, 1944, 1951) in the San Dimas Experimental Forest. These are designated: sage and barren areas, chamise sage chaparral, chamise ceanothus chaparral, chamise manzanita chaparral, broad-leaf chaparral, oak chaparral, woodland sage, oak woodland, riparian woodland, and bigcone spruce. The percentage of each type covering each watershed is shown in Table II. Common and botanical names are listed in Table III.

Sage and barren areas are found on dry, steep, southerly slopes, and on other very steep slopes and rocky cliffs with gradients from 60 to 85 degrees. The vegetation consists of scattered individuals of white sage, buckwheat, and herbaceous semishrubs. Minor areas of graded road-surface which occur in several of the watersheds have been included in this vegetation type. Vegetation density varies from 20% to less than 5%. Areal extent of each vegetation type shown in Table II was determined by map planimetry, consequently the sloping surface areas are somewhat greater than indicated, especially for the sage-barren type which includes rocky cliffs. If chamise comprises more than 20% of the total vegetation the area is typed as one of the chamise associations. If there are individuals of either California live oak or canyon live oak the complex is called woodland sage.

The chamise chaparral is one of the most important chaparral associations of southern California. In the San Dimas Forest it occupies the hot, dry south-facing slopes and the ridgetops. The dominant species, chamise, is not a broad sclerophyll; its leaves are small and linear. Associated with the chamise are the xerophytic hoary-leaf ceanothus, white sage, black sage, bigberry manzanita, Eastwood manzanita, and other minor chaparral species (Horton, 1951, p. 12). The presence of chamise to an amount of more than 20% of the total vegetation distinguishes chamise chaparral. The chamise chaparral of Bell Canyon had an average cover density of 48% (i.e. 52% of the surface is not vegetated) in 1934 (Horton, 1941). The shrubs average about 5 feet high but range up to 15 feet high. A comparatively light litter layer accumulates under this association.

On the drier sites, intermediate between sage-barren type and the pure chamise, is a chamise sage chaparral association. The distinction between sage and chamise sage is sometimes difficult to make, but usually a break of slope or change of exposure will make it quite sharp. The percentage of sage varies from zero in the pure chamise to a theoretical maximum of 80% in the chamise sage. Below 2500 feet elevation white sage is characteristic, but black sage and buckwheat are the sage associates at higher elevations. Chamise sage chaparral has cover density somewhat less than the other chamise types, an average height close to 5 feet, and ranges up to 8-10 feet high. No attempt was made in the mapping to separate the pure chamise from chamise sage because, according to Horton (personal communication, 1959), pure stands of chamise are almost non-existent in the San Dimas Forest. Some sage is almost always present in the more xeric chamise type.

Two other chamise associations occur in the chaparral group. On sites slightly less arid than those of the chamise sage, hoaryleaf ceanothus occurs with the other chaparral shrubs. If chamise and ceanothus are each present to an extent of at least 20% the vegetation is called chamise ceanothus chaparral. In areas of its best development the ceanothus overtops the chamise. However, the ceanothus is relatively short-lived and is eventually supplanted by chamise. If bigberry or Eastwood manzanita occurs over 20% in this association, it is designated chamise manzanita chaparral. The average cover density of these two types is about 60%. The average height is about 7 feet for the chamise ceanothus; 5 to 12 feet for the chamise manzanita.

Near the heads of the watersheds stream gullies lose their definite channel characteristics and merge into amphitheatres leading to saddles on the divides. These amphitheatres are partially protected by ridges and thus are somewhat less arid than the exposed canyon slopes. At elevations above 4,000 feet the type may occupy a solid belt where slopes are moderate on upper portions of south facing ridges. The vegetation of these sites contains less than 20% chamise and may be dominated by manzanita, hoaryleaf, ceanothus, Christmasberry, or other broadleaved shrub species. At higher altitudes chaparral whitehorn is common and Christmasberry almost lacking. This type is designated broadleaf chaparral and is intermediate between the xeric chamise chaparral on south-facing slopes and the mesic oak chaparral on the cooler north-facing slopes. Broadleaf chaparral has a cover density of about 80% and an average height of 7 to 10 feet.

The north-facing slopes, with lower evaporation losses, support a more dense vegetation designated oak chaparral. At lower elevations the dominant species is California scrub oak. Above 4,000 feet the California scrub oak is usually replaced by interior live oak. At this altitude the oak chaparral sometimes occurs on south-facing slopes, where the oak is usually associated with chaparral whitethorn, bigberry manzanita, and Eastwood manzanita. An unusual feature of the north-facing association is the occasional occurrence of dense stands of Pacific poison oak. In these stands the poison oak grows as a shrub, reaching heights up to 6 feet, with trunk diameters of a few inches. Oak chaparral has a vegetation density of about 80%, and grows to an average height approximating that of broad leaf chaparral, with some individuals more than 20 feet high. Considerably more litter accumulates on the ground under this type than under the chamise type.

The oak woodland association occurs on the more humid of the north-facing slopes. Canyon live oak dominates this association. In drier portions interior live oak is abundant. California live oak becomes important where the soil or drainage conditions provide more moisture. The oak woodland covering much of watersheds I, II, and III is entirely of the canyon live oak type. Areas dominated by the more mesic California live oak have been included in riparian woodland. Most of these areas are in watersheds VII, VIII, and IX, hence the large percentages of riparian woodland shown in Table II for these watersheds. In general, older stands of oak woodland have very little understory because of dense shading. Oak woodland averages 15-18 feet in height with some stands more than 30 feet high. It produces an amount of ground litter comparable to that of oak chaparral.

Bigcone Douglas fir, locally called bigcone spruce, is found at altitudes between 2,500 and 6,000 feet. The bigcone spruce forest and its associated chaparral and woodland types constitute a tension zone between the chaparral of lower elevations and the coniferous forests which prevail in the more humid and cool higher elevations in southern Californian mountains. North-facing slopes in this tension zone are occupied by stands of bigcone spruce or canyon live oak woodland; south-facing slopes are often covered with oak chaparral.

A few artificial plantations and a small stand of ponderosa pine have been included in the spruce forest category in Table II. The small plantations of Coulter pine and knobcone pine are located in Watersheds V and VII, which are not included in the geomorphic study. The ponderosa pine covers less than 10 acres in a shallow land-slump depression, called Brown's Flat, in Watershed II, Fern Canyon. Surrounding and underlying the tall widely-spaced pines is an area of 40 acres of grassland. This is the only grassland in the Experimental Forest.

A complex of woodland associations, including riparian species, occurs in the canyon bottoms. Although these trees cover only a small part of the watersheds, their location near the stream channels and springs and their daily draft on the available moisture enable them to exert a direct influence on summer stream-flow. The major association is dominated by California live oak, which borders the main stream channels, but which may not require as much water as the other riparian species. These latter include California laurel, white alder, California sycamore, bigleaf maple, and several species of willows, all of which are found near seeps, springs, or in the main channels wherever there is a permanent supply of water. This type of vegetation has an herbaceous understory which is lacking in the chaparral types. Poison oak vines, using other vegetation for support, occur frequently.

J. S. Horton (1944) has determined general relations of vegetation cover density to cover age, cover type, and the geologic origin of the parent material of the soil. These relations permit the calculation of prevailing cover density at a given time after a watershed has been burned. The constants determined by Horton and the general equation used to calculate cover density from these constants are given in Table IV. Values of cover density for successive years were calculated and, with precipitation data and geomorphic characteristics, were correlated with annual flood discharge from the watersheds studied.

Geology

BEDROCK GEOLOGY

The San Gabriel Mountains are a complexly faulted horst, outlined and transected by three major fault zones and many minor faults. The San Andreas fault zone borders the north and east flanks of the mountains; an unnamed fault zone extends from the area north of San Fernando, through the Tujunga Creek drainage, to form the scarp along the south side. A third zone branches from the latter and extends eastward, controlling the east and west forks of the San Gabriel River. These principal faults are usually not sharply defined, but are composed of systems of roughly parallel fractures and brecciated zones 50 feet or more wide along which repeated movements have occurred. Branching faults are common. In addition to the major faults there are numerous well-defined small faults of only a few feet displacement. The San Gabriel fault block is composed of pre-Cretaceous schists, gneisses, and granitic rocks, surrounded on all sides by Tertiary and Quaternary alluvial deposits and interbedded volcanics. Thus it is largely similar to the other fault-block ranges of southern California. The intensive faulting and fracturing has greatly increased the permeability and groundwater storage capacity of the crystalline rocks, and aided the very deep weathering of the bedrock.

Bedrock of the San Dimas Experimental Forest, representative of much of the San Gabriel Mountains, includes both metamorphic and granitic rocks. The oldest rocks in the Experimental Forest comprise the San Gabriel Formation (or complex), thought by Miller (1934) to be of early pre-Cambrian age. In the western San Gabriel Mountains this complex has been divided into three mappable units, the Placerita metasediments, the Rubio diorite, and the Echo granite. Of the Placerita metasediments, little can be mapped as a separate unit because they have been so extensively intruded—first by diorite, then by granite—that only small remnants remain in the form of layers, lenses, and shreds. The numerous, small, widely scattered, mappable bodies of Rubio diorite are thought by Miller to be remnants of once larger masses, remaining after the wholesale attack of granite magma upon the Rubio diorite and earlier metasediments. During this attack both the metasediments and the diorite were extensively cut, locally injected lit-par-lit, and variably digested by the Echo granite, which is usually foliated, granulated and variably contaminated.

The next younger identifiable formation in the Experimental Forest is the Wilson diorite. It is a medium-grained, massive to very moderately foliated quartz diorite. It occurs as small irregular to sill-like bodies sharply cutting the rocks of the San Gabriel complex. It is probably of late Mesozoic age.

A few small scattered masses of buff-colored granodiorite which occur in the gneiss may be the same as the Lowe granodiorite identified by Miller in the western San Gabriel Mountains. Numerous aplite, granite, and pegmatite dikes, thought to be offshoots of the Lowe granodiorite, sharply cut all of the older formations in irregular branching networks. The granodiorite and associated dikes are younger than the Wilson diorite, but are also of late Mesozoic age.

Sharply cutting the pre-Tertiary formations are a suite of Tertiary dikes of quartz-latite porphyry, lamprophyre (or gabbro-diorite), and diabase. The latter two are sometimes laced with narrow stringers of quartz. The basic dikes are commonly fine-grained and more resistant to weathering and erosion than the gneisses and acidic intrusives they cut. These resistant dikes are rarely more than a few feet wide, and have little influence on larger topographic features, although they frequently cause small waterfalls where they are crossed by streams. An exception is the very resistant dacite dike, two feet wide, which controls the 100-foot high upper part of Wolfskill Falls near the mouth of Wolfskill Canyon.

For the present study it was necessary to categorize the rocks present. Miller (1934) had designated all of the rocks under the San Dimas Experimental Forest as belonging to the "San Gabriel Formation" which he described as "mainly Placerita metasediments or Rubio metadiorite injected by much Echo granite and often cut by later plutonics." Bean (1943, 1944, 1946), who mapped the area in greater detail, described it as one in which the various rocks do not occur in large, easily differentiable bodies, but as small intrusions which are intimately associated with other small bodies. He described the rocks as "gneisses and schists, which represent either highly metamorphosed sediments, or injected, somewhat metamorphosed, igneous rocks." The portions which were originally sedimentary and originally igneous are not known. Bean divided the rocks into four groups according to the dominant type of the group. He also mapped five different types of dikes. The classification used in this study (Table V) is based on Bean's division except that only two dike types, those which cover at least 30 per cent of the area of the smallest drainage basins in which they occur, have been retained.

EROSIONAL HISTORY

Prior to Miocene time the major east-west border faults were established. The mountains had begun to assume their east-west trend and had been repeatedly subjected to uplift and erosion (Nevadan and Laramide revolutions). Igneous activity along the border faults during the Miocene epoch produced volcanics along the flanks of the mountains and in the shallow seas which surrounded them. Continued uplift and strong erosion throughout Miocene and Pliocene time is evidenced by the fan and fluvial sediments now comprising shales, sandstones, and conglomerates overlying the Miocene volcanics. By the end of the Pliocene the landmass had been reduced to gently rolling hills and broad valleys. Remnants of this pre-Pleistocene erosion level are preserved on broad ridgetops in the western half of the San Gabriel Range. Pine Flats, Barley Flats, Pine Mountain, Josephine Peak, Mt. Lawler, Strawberry Peak, and Condor Peak in the southern third of the Tujunga quadrangle, and San Gabriel Peak, Mount Markham, Mount Lowe, and Mount Wilson in the northern part of the Pasadena quadrangle all rise to an altitude of between 5,350 and 6,152 feet (Miller, 1928, 1934). These summits, several of which are platform-like, bevel an irregular mixture of plutonic and steeply dipping metamorphic rocks.

The low-level, old age pre-Pleistocene surface was strongly uplifted during the Pleistocene Cascadian revolution. Tertiary sedimentary formations along the flanks of the mountains were folded and tilted nearly to the positions in which they are now found. The shallow seas surrounding the mountains withdrew to the west, leaving the present broad, flat lowlands. Uplift of the mountains progressed as a series of rapid elevations followed by still-stands and valley widening. At least four old erosion levels can be distinguished within the San Dimas forest. Each new uplift caused inner canyons to be incised into basin floors of the previous still-stand. Traces of older basins are preserved in the heads of the present canyons. Nickpoints progressed up the major channels. These uplifts are considered as a single event by Miller. The total uplift in the San Dimas area was at least 2000 to 2500 feet and may have exceeded 4500 feet. The sediments produced during this period built great alluvial fans along the flanks of the mountains.

Another marked uplift or rejuvenation of the southern block of the San Gabriel mountains occurred in the Late Pleistocene (Wisconsin?). This caused V-shaped, over-steepened canyons 400-450 feet deep to form in the somewhat wider older canyon floors. Erosion during this stage removed much of the very large alluvial fans which had been built during the earlier Pleistocene stages. New alluvial fans were built with surfaces at lower elevations than the remnants of the older, uptilted, early Pleistocene fans. By late Pleistocene major streams in the San Dimas area had reached early maturity and had begun to meander in the canyon bottoms. Less than 25,000 years ago the most recent uplift caused the meandering streams to entrench their channels. The entrenched meanders are about 200-250 feet below the floors of the older early-mature floodplains of the canyon stage. The impassable meandering gorge at the mouth of the North Fork (Watershed V) of the San Dimas River, the very deep gorges of lower Fern Canyon and Upper East Fork, and Wolfskill Falls, 130 feet high, are all results of this latest uplift.

Morphometric Properties

GENERAL STATEMENT

One of the principal objectives of this investigation was to determine which of the many measurable geomorphic properties would most effectively describe the rugged, chaparral-covered mountain watersheds in southern California. To accomplish this purpose twelve basic properties, and seven additional properties derived by combination of the basic properties, were studied. These basic and derived properties are discussed below and summarized, with their units of measurement, in Table VI. All of the properties studied, except slope and gradient, were measured on large-scale, field-corrected topographic maps.

BASIC PROPERTIES

Channel Location

The location of every channel in the drainage net of each watershed was determined by field inspection and plotted, in the field, on a topographic map. Aerial stereophotographs were used to help obtain the correct planimetric location of the channels and tributary basin divides. Difficulties encountered and criteria established for the recognition of channels are discussed below (see Replication of Field Observations). Four criteria were found to be adequate. Accuracy of drainage network mapping was verified by the replication study. In mountainous terrain in a climate having a prolonged dry season stream channels are not always readily identifiable. Most reliable and most frequently used is the criterion that stream eroded depressions usually have well-defined, nearly vertical banks. In many cases debris or litter carried by running water was draped over branches and roots of vegetation protruding over and into the channel. In other cases debris was oriented in sub-parallel flow-lines along the sides of the channel. Direct evidence of water erosion and deposition, similar to that caused by extreme sheet erosion of slopes, was usually found within the channel boundaries.

Channel Order and Numbers of Streams

Ordering is a means of designating the sequence or succession, in terms of the joining of tributaries, of channels within a drainage network. A system of channel ordering was first proposed in Germany by Gravelius (1914, p. 5) and was used in the United States by Horton (1932, 1945) and other hydrologists (Wisler and Brater, 1947). Gravelius' method as modified by Strahler (1952, p. 1120) was used in this study to eliminate ambiguity and subjective decision. Strahler's method designates the smallest fingertip tributaries as first-order channel segments. Confluence of two channel segments of the same order forms a channel segment of the next higher order. (Figure 6). Because numbers are used to designate the different orders, and there must be, by definition, a successively increasing sequence, stream ordering is an ordinal level of measurement (Siegel, 1956, p. 24ff.). Order is an enumerational property, achieved by counting. In this study the order, u, of each channel and the number, N_u, of channels of each order were determined within each watershed (Figure 7).

Channel Length, Basin Area, and Basin Perimeter

One or more of the three basic size properties of channel length, basin area, and basin perimeter, have been used by hydrologists and geomorphologists investigating watersheds. Gravelius (1914) related mainstream length to watershed area. Horton (1932, 1945) expressed length, area, and perimeter in terms of order. V. C. Miller (1953) measured length, area, and perimeter although he expressed perimeter as the area of a circle; Schumm (1956) used length and area; Melton (1957) used length, area, and perimeter.

In the present study, the entire network of drainage channels within a watershed was first drawn on a map and the order of each channel determined. The curvilinear map length, L_u, of each channel segment of each order was measured along the channel, from its head at the junction of the two channels segments of the next lower order (or at the upper end, if first-order) to its junction with a channel of the same or higher order. Area, A_u, of the planimetric projection of the basin drained by each channel segment was measured from the map. For each second-order and higher order channel, basin area includes the basins of all the lower order channels tributary to the higher order channel. Perimeter, P_u, was measured on the map along the topographic drainage divide, starting and ending at the lower end of a channel of a given order, and including all tributary basins.

Basin Diameter

To express the length of a basin, and for use in describing the orientation and shape of the basin, a straight line here termed basin diameter, L_d, was drawn approximately parallel to the main stream of the basin. This property is essentially the same as basin length defined by Schumm (1956, p. 612) as "the longest dimension of the basin parallel to the principal drainage line." Schumm does not clarify whether "longest dimension" is to have more or less emphasis than "parallel to principal drainage" when the two are in conflict. As it is recognized that subjective judgment is required to locate a straight line "approximately parallel" to a sinuous line, and because scientific procedure requires the repeatability of a measurement, free as far as possible from subjective error, a detailed definition of diameter is required. Fortunately, in almost all cases encountered in practice the location of the diameter is much more obvious and simple than the following definition implies. Basin diameter, L_d, is here defined as the length of the horizontal projection of the straight line extending from the mouth of the basin to its headwater divide, with the following criteria applied according to the procedure described below.

Criteria. The diameter must be a straight line and

1) be essentially parallel to the longest drainage line,
2) divide the main channel into segments such that the sums of segment lengths on opposite sides of the diameter are approximately equal,
3) be parallel to the line which separates opposite-facing valley slopes,
4) bisect the basin area,
5) be the longest diameter.

Application. The first criterion listed below is to have the greatest weight and the last the least weight. If the channel is essentially:

straight and longer than one-half of diameter, use criteria 1, 2, and 3
straight and shorter than one-half of diameter, use criteria 1, 3, and 4
curved and longer than one-half of diameter, use criteria 5, 3, and 2
curved and shorter than one-half of diameter, use criteria 3, 4, and 5

Although this definition seems very cumbersome, its use can be learned with very short practice and serves as a guide to reduce subjective decision. Elaborate application is necessary in relatively few instances (Figure 8).

Maximum Flow Length

The length of a drainage basin is sometimes measured along a curved line instead of a straight line. An obvious line to follow is the channel, extended to the basin divide. Horton (1945, p. 279) mentions such a measure of extended stream length measured along a stream and extended to the watershed line. Elsewhere Horton (1945, p. 291) says "the distance along the course of a stream from its mouth extended to the watershed line is called mesh length." Horton gave no numerical values for this property, and he may not have measured it. Recently Maner (1958, p. 672) used a similar property, which he called "length", defined as "maximum watershed length . . . measured approximately parallel to mainstream drainage from dam-site to watershed divide." Although Maner measures a curvilinear length (1958, personal communication) it is not clear to what extent his "approximately parallel" line approaches the maximum meander length of the channel.

Broscoe (1959, p. 6, Fig. 2) extended stream profiles to a headward reference point defined as the upper end of the longest flow path, orthogonal to the contours, leading to the channel head. This length he designated L_g a special case of Horton's length measure, overland flow.

Maximum flow length, L_f, in this study is defined as the curvilinear length of a drainage basin measured from the basin mouth along the longest channel and its extension perpendicular to the countour lines above the channel head to the basin divide, and measured on the projection to a horizontal surface. It is the sum of Broscoe's L_g, and the channel length, L_u, for a basin of order, u. Flow lengths were measured of all basins in the Fern and Bell small watersheds. The path, or trajectory, itself is referred to below as the longest flow path.

Relief

The elevation of the mouth of each basin (the lower end of each channel) was determined from the contours of topographic maps. For use in computing the relief of the basin, the elevation of the upper end of the diameter was determined for all basins. The upper elevation of the longest flow path and the maximum elevation were also determined in all basins in which flow length was measured.

Many geomorphic and hydrologic studies since Gravelius (1914) have used a measure of maximum basin relief. In the San Dimas Experimental Forest many low-order basins occupy a side-hill position on the flanks of long ridges (Figure 8) and are so disposed that the highest point is often not at the point on the divide farthest from the basin mouth. In other basins the highest points are residual local summits or monadnocks which rise sharply above the adjacent divides or, in a few cases, are on subsidiary ridges in the interior of the basins. To eliminate the spurious effects induced by use of such unusual summits basin relief, H_d, in this study was measured as elevation difference between the basin mouth and upper end of the diameter. This definition generally leads to a value less than the maximum relief. The upper end of the diameter and of the longest flow path frequently fall on a saddle or low point on the divide between two opposed basins. To ascertain the relations among the three similar properties, basin-length relief, H_d, maximum relief H_{max}, and relief of the longest flow path, H_f, all were computed for those basins for which flow lengths were measured.

Basin Azimuth

Basin diameter can serve also as an axis for determining the azimuth in which the drainage is directed. In mountainous watersheds of southern California, orientation of a basin affects both the precipitation it receives with respect to the prevailingly southwesterly approach of storms, and its water loss by evapotranspiration. These factors in turn affect the vegetative cover and the rates of erosion in the basin. Basin azimuth, α, is defined as the number of degrees of arc in a horizontal angle measured from the direction of geographic north clockwise to the mouth direction of the basin diameter.

Maximum valley-wall slope

Maximum slope, θ_{max}, of the valley-walls leading down to stream channels was sampled in each of the watersheds. The slope was measured in the field, using a Brunton compass and Abney hand level. Several profiles extending from channel to ridgetop and many valley-side measurements showed that valley walls in the San Dimas Forest have a nearly constant slope from the bottom to within a short distance from the top. Where not uniform the maximum value occurs near the foot of the slope. Although an effort was made at each measurement to determine the slope over a distance of 100 feet to minimize the effect of minor surface irregularities, very dense chaparral vegetation often prevented visibility between two points separated more than 20 feet, even when intense light beams were used. Average length of the slope measurements is 48.5 feet.

No attempt was made to randomize the sampling formally. Only those slopes which lead directly to a channel bank are included in each sample. Valley walls which are separated from the channel by a flood plain, those which contain rock cliffs, and short, oversteepened basal slopes caused by channel scour are omitted. Otherwise an effort was made to distribute the measurements uniformly throughout each watershed, within the limitations imposed by the impenetrability of the chaparral. Most of the measurements are located near a trail or road. At each observation station where slopes were measured, the maximum valley-wall slope on both sides of a straight stretch of channel and the corresponding channel gradient were measured. The channel segment over which the gradient was measured occasionally included waterfalls a few feet high.

DERIVED PROPERTIES

Basin Shape, Circularity, Elongation

Several different combinations of basic linear and areal properties have been used to describe the planimetric shape of a drainage basin. Miller (1953, p. 8) defined basin circularity, R_c, as the ratio of basin area to area of a circle having the same perimeter. This is similar to the Cox coefficient of roundness of a plane section of sand grains (Cox, 1927, p. 180). Melton (1957, p. 5) used a ratio of channel length to basin perimeter as a shape index. Both this and Miller's circularity ratio fail to discriminate between departures from perfect circularity due to irregularities in gross outline and those due to crenulations in the perimeter.

Schumm (1956, p. 612) used an elongation ratio, R_e, defined as the ratio between diameter of a circle with the same area as the basin and maximum length of basin parallel to the principal drainage line. Although Schumm stated that the elongation ratio is the same as the Wadell sphericity ratio used in petrology the latter explicitly requires use of the maximum diameter of a plane figure, whereas in many natural drainage basins any straight line dimension approximately parallel to the principal drainage line is shorter than the maximum diameter of the basin.

Basin elongation ratio, R_e, is here re-defined as the ratio of the diameter of a circle having the same area as the basin to the diameter of the basin. This, except for the definition of diameter, is the same as Schumm's elongation ratio. Elongation ratio was computed for every basin of each order. In order to test the usefulness and applicability of a perimeter-based shape index, basin circularity, R_c, as defined by Miller was computed for many basins of several orders.

Relief Ratio, Relative Relief

Ratios of basin relief to some other length dimension have been found to be closely correlated with other geomorphic properties and with sediment discharge. Schumm (1954, p. 2) defined relief ratio, R_h, as the ratio between total relief of a basin and longest dimension of the basin parallel to the principal drainage line. Melton (1957, p. 5) defined relative relief, R_{hp}, as the ratio of basin relief to length of perimeter. This measure also is sensitive to irregular crenulations in the perimeter as noted above in discussion of basin shape. Using curvilinear basin length, Maner (1958, p. 672) computed a relief-length essentially analogous to Schumm's relief ratio.

The relief ratio, R_h, is here defined as the ratio of basin-diameter relief, H_d, to basin length, L_d, in the same units. This ratio could equally well be called the gradient of the basin diameter. This property is closely related to Reliefenergie studied by European geomorphologists (Neuenschwander, 1944, p. 74ff.) and still widely used (Ichikawa, 1958, p. 16). Relief ratio was computed for all basins. Relative relief, R_{hp}, as defined by Melton (1957, p. 5) was computed for those basins the perimeters of which were measured.

Bifurcation Ratio

The ranking of tributary channels and basins within a watershed is accomplished by ordering as described above. An indicator of the frequency of channel segment branching within the watershed is the ratio of number of channels of one order to number of channels of the next higher order, designated the bifurcation ratio, R_b, by Horton (1945, p. 286). Thus $R_b = N_u/N_{u+1}$ where N_u is number of stream segments of order u. He noted that when the numbers of channels, N_u, are plotted against order, u, on semi-log graph paper (or the logarithms of numbers of channels against order on linear graph paper) the points on the scatter diagram appear to lie close to a straight line (Figures 7 and 10). Because order number involves only an ordinal level of measurement, the degree of correlation between number of streams and order number must be tested by nonparametric measures such as Spearman or Kendall rank-correlation (Siegel, 1956, 202 ff.). Bifurcation ratio, R_b, has been defined as the antilog of the slope of a straight line fitted by inspection equally to all points of a scatter diagram of the logarithms of numbers of channels of each order plotted against order number (Maxwell, 1955, p. 520). This definition avoids the statistical inferences of linear regressions which are not mathematically justifiable with ordinal measurements. However, in the discussion of analysis of measurements below, values of bifurcation ratios were obtained from lines fitted by the least-squares method. This method, which has been used in several other studies of bifurcation ratio, was used as a choice of convention. The reason for fitting equally to all points, instead of requiring the line to pass through the point of the highest order, is illustrated in Figure 7. In a watershed which is apparently fourth order, the number of channels of fourth order, and conversely the order of the watershed, can vary if one or two first-order channels are added or omitted. Hence the highest-order point should not be considered more reliable or more exact than any other point when fitting the bifurcation ratio line to the points in the scatter diagram. It is interesting to note the apparent up-concavity of the trend of the points in Figure 7. This trend has been noted in other watersheds (Schumm, 1956, p. 603).

Drainage Density, Channel Frequency

Drainage density, D, or total length of channels per unit drainage area, is a widely used geomorphic index of scale of topographic texture. In this study both length and area were measured from maps. A similar index, introduced by Melton (1957, p. 4), the density of first order channels, D_1, is the total length of first order channels in a basin of second or larger order, divided by the basin area. Melton found D_1 useful in determining the relations among planimetric properties of basins.

Probably the earliest use of a quantitative geomorphic property was by Belgrande in his study of the Seine (Horton, 1932). Belgrande determined the ratio of the area of a watershed to the number of streams within it. The reciprocal of Belgrande's ratio was used by Horton (1932) and called stream density, and later (Horton, 1945) stream frequency. Following Horton, channel frequency, F, is defined here as the total number of channels within a basin divided by the basin area. A corollary index, the frequency of first order channels, F_1, is used as defined by Melton (1957, p. 4): the number of first order channels in a larger order basin, divided by the area of the basin. This index can be used with D_1 to determine whether an increase in drainage density is due to headward growth of channels or to an increase in the number of first order channels.

Measurement and Computation Precision

MAP ACCURACY

Base maps used in this study are special large-scale maps prepared by the staff of the San Dimas Research Center. They were modified from photographic diapositive enlargements of U. S. Geological Survey topographic maps of the area. These topographic maps, published in 1940, are of the $7\frac{1}{2}$-minute series with a scale of 1/24,000 and contour interval of 25 feet, and were surveyed during 1925 and 1933 by plane-table rather than photogrammetric methods*. The $7\frac{1}{2}$-minute maps show

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*A photogrammetrically surveyed $7\frac{1}{2}$-minute map of part of the Experimental Forest became available after the study started.

considerable detail, although many minor errors and a few major ones exist. A close study of the maps and observation of the terrain during field mapping of the drainage network convinced the author that much of the topographic mapping was done from the ridge crests without descending into tributary canyons. Most of the substantial topographic errors are in cul-de-sac tributary canyons in the central areas of the watersheds. Usually these tributary canyons cannot be clearly seen from the boundary ridges. Some of the errors agree closely with misleading views obtained from nearby ridgetops. One of these gross errors is shown, with the corrected drainage net, in Figure 9. In addition, there were numerous small errors of the head of a first- or second-order channel incorrectly joined with the lower reaches of another separate channel, of channels shown where ridges exist, and of ridges shown where channels occur. Such errors, corrected, can be seen in the drainage net maps, Appendix III, prepared by the author for this study. The fact that a plane-table survey was completed, with generally good fidelity, in such densely brush-covered precipitous terrain is a great tribute to the skill of the topographers.

The San Dimas Research Center photographically enlarged the 7½-minute U. S. G. S. maps to a scale of approximately 1/8,000. Both the negatives and diapositives were made on plastic base material of high dimensional stability to reduce errors arising from differential swelling during photographic processing. Modifications and revisions were made directly on the diapositives. Most of the modifications consisted of redrawing areas of very steep topography where the contour lines were so closely spaced and heavily drawn as to make the map almost illegible. The redrawn contours followed the original, often incorrect, ones. The revisions consisted of redrawing some contours on watershed divides, and redrawing trails and roads, when surveys by the Research Center revealed errors in the maps.

For the present geomorphic investigation, ozalid-type dry process contact prints were made from the revised, film-base large scale maps. The scales of these ozalid base maps were carefully determined by comparison with new copies of the corresponding U. S. G. S. maps. Repeated measurements were made parallel and perpendicular to the grain of the paper of the ozalid maps, to determine the extent of differential shrinkage. The average error (difference between E-W and N-S scales) was one-half of one percent, and the greatest difference was 1.32% (on Wolfskill map an unusually long and narrow sheet). Because the mean of the N-S and E-W scales was used to determine each map scale, length properties scaled from the maps may have an error, due to map scale, of plus or minus 0.25% (0.66% for Wolfskill Canyon).

Special maps of the Fern and Bell small watersheds areas had been made by the Forest Service. These were made at a scale of 1/2400 by plane-table methods. Because they were made by specialists for hydrological and ecological studies, they depict the ground surface very accurately. Lengths scaled from these maps are believed to have errors due to map inaccuracy of less than five feet.

INSTRUMENT PRECISION

Channel lengths were measured from the maps using a dial-type map measurer, Dietzgen Number 1719B, graduated to 1/32-inch, and a straight flat scale graduated to 0.02-inch. Readings on the map measurer could be estimated accurately to 1/64-inch and were recorded to the nearest 0.01-inch. The readings from the flat scale were estimated and recorded to 0.01 inch. It was found that many of the nearly straight first-order channels and some of the second-order channels could be measured more quickly and as accurately with the straight scale as with the map measurer. Repeated measurements on widely separated dates by various operators showed most of the readings to be reproducible within plus or minus 0.01-inch and all except the Fern Canyon and fifth-order readings to be within plus or minus 0.02-inch. The Fern Canyon readings were reproducible within 0.03-inches. The much longer, more meandering fifth-order length measurements were reproducible within plus or minus 0.1 inch. Because the map scale is approximately 1/8000, the full scale channel length measurement errors are less than plus or minus 0.0025 miles for all but Fern Canyon, 0.0038 miles for Fern Canyon, and 0.0125 miles for all fifth-order channels. In the field mapping of the drainage network there was often some doubt about the exact location of the heads of first-order channels. Some of the channels may have been drawn as much as 50 feet longer or shorter than their true length, and a few may have errors up to 100 feet. Most are believed to be correct within plus or minus 20 feet. Thus the accuracy of first-order channel lengths is limited by field mapping errors rather than map measurement errors.

Basin diameters were all measured with a flat scale graduated in 0.02 inches. Because the diameters are straight lines with well-defined termini, they could be measured more precisely. The maximum measurement error is approximately 0.013 inches at map scale, or plus or minus 0.0015 miles at full scale, for all diameters.

Basin perimeters were measured with a less precise map measurer, Dietzgen Number 1718, graduated to 0.5 inches and read to 0.1 inches. Most of the perimeter measurements used in the quantitative analysis were measured on the detailed

1/2400-scale small watersheds maps. The measurements are repeatable within plus or minus 0.2 inches at map scale, or 0.008 miles in the small watersheds and 0.025 miles for the measurements on the canyon maps.

Basin areas were measured using a compensating polar planimeter, Post Number 1600D. Various degrees of precision were used for the different watersheds; consequently the measurement errors vary between watersheds. Repeated readings were made, tracing each area clockwise and counterclockwise with the planimeter pole both to the left and to the right of the tracing point. This procedure compensated for any small errors of adjustment of the instrument. The mean of the repeated readings was recorded. One-half of the maximum range of the sets of readings was the basis for estimating the precision of the measurements. In Fern and Volfe Canyons the measurement errors were within plus or minus 0.05 square centimeters, or 0.00012 square miles at ground scale. In upper East Fork Canyon the discrepancies were less than 0.1 square centimeters, which represents 0.00024 square miles on the ground. The half-maximum-range value for Wolfskill and Bell Canyons were 0.02 square inches, or 0.0025 square miles full scale. The small watersheds in Fern and Bell Canyons were also measured to a precision of plus or minus 0.02 square inches, but at the much larger map scale this represented an error of only 0.00003 square miles on the ground. The above precision applies to the first-, second-, and third-order areas. Most of the fourth-order and all of the fifth-order areas had to be arbitrarily subdivided for measurement. This led to a loss of precision. The loss was greatest for the fifth-order areas measurements which were repeatable to plus or minus 0.2 square inches, or 0.025 square miles. Previously published measurements (Sinclair, 1953) obtained by planimetering the fifth-order watersheds as shown on small scale USGS maps, differ from those of this study by a maximum of 0.10 square miles and an average of 0.04 square miles.

Azimuths of the basin diameters were measured with the calibrated head of a drafting machine, Bruning Model 2701. The instrument is graduated in minutes of arc, but was read only to one-half degree and the readings recorded to one degree. The readings were reproducible to one-half degree.

Valley-wall slope and direction, and channel gradient and direction were measured in the field. At each location, slope and gradient measurements were made independently by the observers at opposite ends of the line of measurement. If the measurements did not agree they were immediately redone. The instruments, a Keuffel and Esser Brunton-type pocket transit and focusing Abney hand level, graduated respectively to one minute and one degree, were read to one-half degree. The downhill direction of the gradient was usually measured by only one of the observers. The other would check the quadrant of the measurement by subjective orientation. No analysis was made of the field measurement errors, but it is believed that the slope and gradient readings were reproducible within plus or minus one-half degree, and the direction measurements reproducible within plus or minus two degrees.

DATA PROCESSING EQUIPMENT AND ACCURACY

Most of the computations necessary for the analysis of measurements were carried out on modern mass data processing equipment. Individual measurements of geomorphic properties were transcribed into digital punch cards by key punch machines. The correctness of the punching was verified by a duplicate but separate punching which was automatically compared with the first punching. These verified cards were further checked by reading a listing of the data from the cards comparatively with the original data. It is possible that in the approximately 36,000 four-digit numbers thus recorded a few incorrectly recorded digits may have escaped detection. The relatively small second-order and higher order sets of data, in which a single incorrect value would have had a greater influence on derived results, were checked with proportionally greater care. Later, when the data were sequenced for normality tests, extreme values were examined for gross errors and none was found. Thus it is believed that undetected errors, if any, in the transcribing of data to punch cards exist only in mid-range values of low order properties and do not affect the results within the accuracy reported.

All of the properties which had been measured from maps were converted to standard units of miles or square miles by multiplying by appropriate map scale factors in an electro-mechanical computer, an IBM 602A. New data cards, with the data in a floating-point format suitable for electronic computers, were prepared by machine from the standardized cards. Using an IBM 650 electronic computer, the means, standard deviations, and extremes for each order of each property were computed. All of the sets of data which were sufficiently large were sequenced and grouped by the 650 for Chi-square tests. Values of Chi-square were computed from grouped data with a desk calculator. Homogeneity of variance and analysis of variance computations were similarly completed with a desk calculator using statistics computed on the 650.

The calculations on the electromechanical 602A were in fixed-point numbers, hence contained no errors due to machine rounding-off. Because the map scale constants were rounded to six digits the results were as accurate as the original unstandardized values. In the floating-point format used in the 650, round-off errors of one in the tenth digit could occur. In summations of the larger samples this error theoretically could exceed one in the sixth digit although the probability of this was less than one percent. The maximum probable error due to machine rounding was less than one in the seventh digit. Both the 602A and the 650 have extra circuits built in to check against possible machine error. In the 650 each digit of each number is checked several times during each operation as the number is moved about within the machine. There was no evidence of machine malfunctioning in the data output.

Data for the multiple regressions were punched into coded paper tapes and processed on an LGP-30 electronic computer. The programs used computed correlation coefficients, partial correlation coefficients, variance of coefficients, analysis of variance, and t-tests for significance. Computations were performed in floating point with nine-digit accuracy. Because of possible cumulative round-off error, and because of low accuracy—only three or four digits—in some of the input data, the computed statistics are accurate to only five or six digits.

The use of punch cards, paper tapes, and mass data processing techniques and equipment in this study was the first application of these techniques in quantitative geomorphology. Melton (1957) used edge-punched cards, which were manually processed, to file and sort his data conveniently. Computer processing of topographic coordinates was widely used prior to this study for photogrammetric and cartographic purposes but had not been applied to geomorphic analysis. More recently several other investigators have used mass data processing in projects related to landform analysis and evaluation (Wood, 1959; Bryson and Dutton, 1960; Dacey, 1960). Evaluation of geomorphic properties often requires the analysis of a large number of measurements. It is expected that the present rapid evolution of data processing techniques and equipment will accelerate progress in quantitative geomorphology.

Analysis of Measurements

SAMPLING

Statistical description is used to express quantitatively and succinctly various characteristics of a group of observations. Statistical description often relies heavily upon charts and diagrams. Statistical analysis, on the other hand, is used to infer conclusions about a large group of observations, the population, from a smaller group of actual observations, the sample. The methods of parametric statistical analysis are largely based on the condition that a sample must be obtained in such a way that each observation in the population has an equal and independent chance of being included in the sample, i.e., a random sample.

In the present study all of the basins within each watershed were measured. The objective was to find characteristic values for each geomorphic property within similar watersheds. The bases of similarity were unknown but presumably were determinable, whether related to watershed shape and orientation, rock type, climatic condition, or some combination of these and other conditions. Analysis of the observations will indicate some of the geomorphic properties which may be useful for defining distinctive populations of watersheds.

Assuming that the effort to measure all values of a given property in each watershed was successful, the sets of measurements could be viewed either as populations or as samples. Each set is the population of all measurements for a specified watershed. Population parameters could be obtained and directly compared, without estimation from sample parameters. Such a viewpoint would limit comparisons to the five watershed populations and might prohibit estimation of the parameters of larger populations.

Alternatively, each set of measurements could be viewed as a sample. This viewpoint assumes that there exist other chaparral-covered watersheds in southern California which are not significantly different from those studied. Each set of measurements could be considered as a sample from the population consisting of the same geomorphic property in all basins of the same order in watersheds similar to that in which the set or sample was measured. The San Dimas and Big Dalton Watersheds had been carefully selected as representative of San Gabriel Mountain watersheds and of mountain chaparral watersheds in general. The bases on which any one of the studied watersheds are similar to or different from others was not known at the beginning of the study, hence any bias in selecting the samples is indeterminable. Throughout the following analysis of measurements the assumption is made that each set of measurements is a random unbiased sample.

Results of the analytical procedures may be considered as descriptive statistics. For example, the normality tests may be considered as describing the particular sets of measurements without inference to any populations. Certain modifications of degrees of freedom would have to be made in such cases but the direction of this modification is such that a deviation found significant when considered as a sample deviation would also be significant when considered as a complete set. Similarly F-values in the analysis of variance tests may be considered simply as descriptive ratios between two variances, without carrying the test to the final step of statistical inference. Complete mathematical rigor in the statistical inference depends upon future verification of the unbiased nature of the sample.

MEANS, STANDARD DEVIATIONS, AND EXTREMES

The mean, standard deviation, maximum and minimum of each property measured was computed for each order in each large watershed. The same values were computed also for the two sets of small watersheds. Means, pooled standard deviations, maximum maxima, and minimum minima were computed for the combined total of all basins of each order measured. The results of these computations are listed in Appendix I.

The values listed in the columns headed "Log" are the antilogarithms of the means of the logarithms of the measurements. The antilogarithms were tabulated to permit direct comparison with the arithmetic means of the measurements. The variances of most of the logarithmic measurements were used in analysis of variance tests summarized in Table IX. No figures were tabulated in the Log columns for standard deviation because it is thought that the antilogarithms would be meaningless and the logarithmic values could not be compared with the corresponding arithmetic values. The antilogarithms of the extremes of the logarithms are the same as the arithmetic extremes so were not tabulated.

Standard deviation was computed using the quantity N-1, rather than N, as a divisor. This was done to follow the tacit assumption that each group of basins, of a single order in a given watershed, represented a sample from a population composed of the same order basins from all watersheds which were not significantly different from the given watershed. The bases of similarity which were undefined were assumed to be definable. The sample standard deviation so defined was then considered to be a best estimate of the standard deviation of the population.

NORMAL DISTRIBUTIONS ASSUMED IN OTHER STUDIES

Several of the methods used in geomorphic statistical analysis require that the measurements in a sample have a normal distribution. Particularly, inferences from t-tests, F-tests, and analysis of variance are valid only when the samples used are normally distributed. Sample and population distributions of various geomorphic properties are themselves, aside from statistical considerations, subjects of geomorphic interest.

Miller (1953, p. 10) used analysis of variance to compare means of samples of four different geomorphic properties. He noted (p. 14) that "when frequency distribution (of basin area) was studied by means of class intervals on an arithmetic scale that there is invariably extreme skewness to the right, and that by converting the areas into logs a more nearly symmetrical, normal distribution was obtained." However, he gave no evidence of tests for the normality of any of his sample distributions. Schumm (1956, p. 607) stated, "Frequency distribution histograms of the stream lengths and basin areas show marked right skewness, which appears to be fully corrected by plotting log values on the abscissa." No tests other than graphic plotting were made to check the distributions. Melton (1957, p. 23) discussed the question of normality of distributions of geomorphic properties, but did not perform normality tests because the size of samples taken in any category was insufficient to allow detection of moderate departures from normality. He used analysis of variance extensively, but tested means of samples, which tend to be normally distributed even when the populations have moderate departures from normality. Coates (1958, p. 13) sampled a number of geomorphic properties. He grouped the data into classes, computed means, standard deviations, and variances, and showed distribution characteristics in tables or histograms. Apparently no analysis of normality other than tabulation and plotting of histograms was done.

NORMALITY TESTS USED IN PRESENT STUDY

The number of individual measurements of each property was sufficiently large for the lower order basins to permit rigorous testing of sample normality. Variates in each of the large samples were grouped into twenty equal intervals. The grouped data were tested for goodness of fit to a normal distribution having the same mean and standard deviation as the sample, using a Chi-square test. The sample groups were combined where necessary to meet two restrictions: that for each group the expected or normal frequency was not less than one, and that not more than twenty percent of the expected frequencies were less than five (Dixon and Massey, 1957, p. 22). Chi-square was computed for each sample,and the probability for each Chi-square value was obtained from Chi-square-degrees-of-freedom tables. Degrees-of-freedom were taken as three less than the sample size. The probabilities are tabulated as percentages in Appendix II and are summarized in Table VII. Each percentage value tabulated is the probability of obtaining as large or larger a Chi-square as was observed, under the null hypotheses that the sample was a random sample drawn from a normal population.

For those sets of measurements which were not sufficiently large to satisfy the restrictions of the Chi-square test a Kolmogorov-Smirnov test for goodness of fit (Massay, 1951; Birnbaum, 1952) was used. This test is based on the maximum difference between the cumulative sample distribution and a cumulative normal distribution.. The distribution of the maximum difference is known for completely specified normal distributions. However, as Massey (1951, p. 73) points out:

> The distribution (of d, the maximum difference) is not known when certain parameters of the population have been estimated from the sample. It may be expected that the effect of adjusting the population mean and standard deviation to those of the sample, either by calculation or by visually fitting a straight line on normal probability paper, will be to reduce the (actual) critical level of $\underline{d}$. If the (theoretical critical value of d) is exceeded in these circumstances, we may safely conclude that the discrepancy is significant, i.e., that the distribution is not normal.

Therefore, the percentages tabulated in Appendix II should be considered as maximum probabilities of obtaining as large, or larger, a difference between each sample distribution and a normal distribution having the same mean and standard deviation as the sample. The exact probabilities are smaller. For a given sample size the probability is an indication of the maximum deviation; it can be used as a qualitative index of goodness of fit, the larger probability indicating generally a lesser deviation.

RESULTS OF NORMALITY TESTS

Length

Using a one-percent level of significance the lengths of first- and second-order channel segments were found to be significantly non-normally distributed, with the exception of the measurements from Bell small watershed No. 3. No reason was apparent either from the maps or in the field for this variation. It seems plausible that if the lengths population is non-normal, an occasional sample might deviate sufficiently from its population distribution to yield a distribution that was not significantly different from a normal distribution.

Distributions of the log lengths were found to be not significantly different from normal at the one-percent level. However, it was noted that if a ten-percent level of significance had been used, none of the first-order and only three of the second-order log distributions from the large watersheds would be considered normal. The larger alpha, ten percent, reduces the chances of making a type two or beta error, of accepting as normal a non-normal distribution.

For samples taken from the small watersheds the log transformation generally reduced the disparity between the sample and normal distribution, as indicated by either Chi-square or K-S difference, but the results were not conclusive regarding the non-normality of the arithmetic distribution. The samples for third- and fourth-order segment lengths were too small for Chi-square tests. The K-S test did not indicate that either the arithmetic or logarithmic distribution was non-normal, nor did it clearly indicate that the log distribution more closely approximated the normal.

Lower order distributions appeared, upon subjective inspection, generally to be monomodal with a strong right skewness, which apparently caused the non-normality and which was apparently eliminated by log transformation.

Area

Departure from normality of the area distributions for larger samples was highly significant, with probabilities much less than one-tenth percent. For the first-order basins in the large watersheds the distribution of logarithms of the areas was also significantly different from normal, except for Volfe Canyon, which was significantly non-normal at the five-percent level.

In the Fern small watersheds the log area distributions seem to approach normality more closely than the arithmetic distributions, as shown by the K-S differences. For Fern No. 4, which was large enough for Chi-square testing, the arithmetic distribution was significantly non-normal, the log distribution not. All of the Fern small watersheds are in the upper part of Fern Canyon (Figures 2 and 4), above 4,500 feet elevation.

The Bell small watersheds, which, except for Bell No. 4, are larger than the Fern small watersheds, show no consistent relationship. In the two larger of the Bell small watersheds neither the arithmetic nor logarithmic distributions were normal.

Upon subjective inspection most of the sample distributions, both arithmetic and logarithmic, appeared polymodal, with some right skew in the arithmetic distributions. The Fern small watershed samples appeared essentially monomodal, with a strong right skewness in the arithmetic distributions. The multi-level, or multi-cycle nature of the large watersheds has been described above in the discussion of erosional history. From analysis of the measurements it appears that first-order basin area, or some other factor which affects area (such as infiltration capacity), is sensitive to either elevation above base levels or to duration or stage of erosional development or to both. It further appears that the Fern small watersheds are within a single geomorphic stage, that the effects of the earlier rejuvenations have reached the headwater basins and the effects of the latest rejuvenations have not yet reached the 4500-foot level in Fern Canyon.

The discovery of this quantitative evidence for the sensitivity of first-order basins to the effects of interruptions of the geomorphic cycle, and its implications regarding the up-valley migration of knick-points, may become a powerful tool of quantitative geomorphology if confirmed by additional studies. Locally it could provide a quantitative basis for relating the tilted, dissected alluvial fans surrounding southern Californian mountain ranges to multiple erosion levels within the mountain watersheds. On a much broader level it could contribute to the basic understanding of the evolution of fluvial topography.

Diameter

Distributions of first-order diameters of the large watersheds were significantly non-normal. The non-normality of second-order diameters was not significant at the one-percent level, except for Fern Canyon, but was significant at the ten-percent level for Wolfskill, Fern, and Upper East Fork canyons. Non-normality of the first- and second-order log diameter distributions was not significant at the one-percent level. Those for the first order, except for Fern Canyon, were significant at the ten-percent level. For higher orders and for the Small Watersheds, tests did not show any distributions to be non-normal. Consistently, except for Bell No. 3, the approximation to normality was closer for log diameters than for diameters as shown by higher probabilities.

Perimeter

As noted previously, perimeter was not measured in all basins or in all watersheds. For the samples obtained, arithmetic distributions in the large watersheds were non-normal, whereas the log distributions were not non-normal. For the small watersheds, neither the arithmetic nor logarithmic distributions were non-normal, even for those samples large enough for Chi-square testing. The arithmetic samples showed a moderate right skewness. Since the larger of the small watershed samples barely met the restrictions for the Chi-square test, it is felt that a larger sample might have shown non-normality of the arithmetic distribution. For all of the small watershed samples the log distribution more closely approached the normal distribution.

Elevation

The samples of elevation were not expected to have either normal or log normal distributions. If a watershed had an elongate elliptical shape with a greater number of individual basins concentrated near some central elevation and a few at high and low elevations, the sample distribution might approximate a normal distribution. Such a watershed would not usually occur in nature. Of the measured samples, none of the first-order distributions was normal; two of the second-order distributions were not significantly different from normal.

Relief

All of the first-order distributions of relief were found to be significantly different from normal at the one-percent level. Of the second-order relief distributions, one was significantly non-normal at the one-percent level, another at the five-percent level. The remaining three second-order distributions were not significantly different from normal. Four of the five logarithmic transformations of the non-normal first-order distributions were normal. All of the second-order logarithmic distributions were normal at both the one- and ten-percent levels. The first-order logarithmic distributions showed some moderate polymodality, even though most of them were not significantly different from normal. This, in connection with the polymodality of the area distributions, led to the tentative hypothesis that first-order basins are sensitive to stage of development of their watersheds, and that there are two or more stages of development present in most or all the five watersheds studied.

Relief ratio

Three of the first-order relief ratio distributions were non-normal at the one-percent level; all were non-normal at the ten-percent level. Logarithmic transformations of the two which were arithmetic normal were non-normal. Logarithmic transformations of the three which were arithmetic non-normal were normal at the one-percent level but only one was normal at the ten-percent level. Three of the second-order arithmetic distributions are non-normal at the one percent level; all are non-normal at the five-percent level. All of the second-order logarithmic distributions were not different from normal at the one-percent level, although one was significantly different at the five-percent level. Because relief ratio is a quotient of relief, and first-order relief was non-normal, it was not unexpected that first-order relief ratio was non-normal. Although the results did not provide quantitative proof of the general distribution of relief ratio, there is qualitative evidence that the distributions of single homogeneous populations of this property are logarithmically normal.

Relative relief

This property was computed only for three watersheds in which perimeter was measured. The arithmetic distribution of one sample was significantly non-normal. The logarithmic distributions were normal at the one-percent level, but two were non-normal at ten percent. The departure from normality was greater for two of the three arithmetic distributions than it was for their corresponding logarithmic distributions.

Elongation

Four of the five samples of first-order elongation ratios had distributions significantly different from normal. Logarithmic transformations of those four samples yielded three distributions not significantly different from normal at the one-percent level; one which was. A logarithmic transformation of the arithmetic distribution which was normal had less departure from normality than the arithmetic distribution. Of the five second-order samples, three were arithmetically non-normal; logarithmic transformation normalized one of them. Logarithms of the two samples which were arithmetically normal had less departure from normality, as measured by Chi-square. Thus it appeared, in a qualitative sense, that logarithmic distributions of elongation ratio tend to depart less from normality than arithmetic distributions of this property, when sampled from homogeneous populations. The non-normality of the area distributions apparently was not compensated by dividing by diameter in the computation of elongation.

Circularity

Three sample distributions of circularity ratio were tested. None departed significantly from normal. The logarithmic transformations of these distributions showed greater departures from normality, one being significantly non-normal at the one-percent level; another was non-normal at the five-percent level. It was notable that for arithmetic values of the two properties, elongation tended to be non-normal and circularity normal, but for logarithmic values the opposite relation seemed to hold. However, the comparison is only suggestive because two of the samples of elongation ratio included basins which were not in the circularity samples.

Drainage density

None of the arithmetic distributions of first-order drainage density was normal. The distributions of logarithms of first-order drainage density were not significantly different from normal at the one-percent level, but one, Wolfskill, was non-normal at the five-percent level. The second-order arithmetic distributions were not significantly different from normal at the one-percent level but two departed from normality at the five-percent level of significance. The second-order logarithmic distributions were also not significantly different from normal at the one-percent level, but one distribution was different at the five-percent level. The probability of the observed departures from normality was consistently higher, except for Wolfskill Canyon, for the logarithmic distributions, than for the arithmetic distributions. From this it was concluded that the distribution of the logarithm of drainage density is not significantly different from normal.

Channel frequency

Five first-order and five second-order channel frequency distributions were tested by Chi-square tests. All departed significantly from normality even at the stringent one-tenth percent level. Logarithmic transformations of the first-order distributions were significantly non-normal at the one tenth-percent level, except for Volfe Canyon. The distribution for this canyon, Watershed IX, was not significantly different from normal at the one-percent level, but was different at the five-percent level. Of the logarithmic transformations of the second-order circularity distributions, only that for Upper East Fork, Watershed III, was significantly different from normal. Thus within watersheds, first-order channel frequency in the Experimental Forest is neither normally nor log-normally distributed. Second-order channel frequency may be log-normally distributed.

HOMOGENEITY OF VARIANCE

Statistical Inferences

Statistical inference drawn from analysis of the variance of sample means depends upon an assumption that the samples were drawn from normally distributed populations having equal variances. The assumption that variances are equal or homogeneous is, fortunately, amenable to testing. Bartlett's test (Dixon and Massey, 1957, p. 179) for homogeneity of variances, used in this study, uses an approximation of the F-ratio to test for significant differences among the variances. Pooled variance and other terms needed for Bartlett's test were computed on a desk calculator from sample standard deviations derived by an IBM 650 digital computer. Except for circularity, which had been found to have an arithmetic normal distribution, only the sets of logarithms were tested for homogeneity of variances. The arithmetic data were excluded from consideration for analysis of variance by their non-normality. The results of the homogeneity tests are summarized in Table VIII and are discussed below.

Length, Basin Area, and Diameter

Significant differences were found among the variances of the five sets of logarithms of first-order stream lengths. Variance of first-order stream lengths in Fern Canyon was significantly greater than average for the watersheds studied; that in Volfe Canyon was less than average. No significant differences were found among the variances of the second-, third-, or fourth-order sets, considering each order separately. The observed differences among second-order lengths were small. Observed differences among the third- and fourth-order sets were large, factors of 2.5 and 10 respectively, between extremes. The small number of values from each watershed made these relatively large differences non-significant.

Results of homogeneity tests of the variances of logarithms of basin area were similar to those for length. Significant differences were found among the first-order statistics but not among those for the higher orders. Among the first-order variances the observed value for Volfe Canyon was lowest, that for Fern Canyon a little higher than average, and that for Upper East Fork was highest. The observed differences among the second-order variances was small, and among the third- and fourth-order area logarithms was of less magnitude than among third- and fourth-order length logarithms.

Homogeneity of variance among the sets of logarithms of basin diameter followed the same pattern as for channel length and basin area. Variances of first-order sets were significantly different; those for higher orders were not. The variance of the Volfe Canyon measurements was again least among the first-order variances; that of Upper East Fork was the greatest. Differences among the second-order variances were very small; range of variances for logarithms of the third-order diameters was comparable to that for third-order length logarithms. Variances of fourth-order diameter logarithms had a very large range, the largest variance being four hundred times greater than the least. This was due entirely to an unusually small value for Fern Canyon which had only two fourth-order basins, of nearly the same diameter.

From the foregoing it appears that in the three basic properties of channel length, basin area, and diameter, first-order basins are sensitive to differences or changes in erosional history. Within the San Dimas Experimental Forest, second-order values of these properties give a much better basis for comparing watersheds. The number of measurements of third- and fourth-order properties was not large enough to determine whether apparent differences in variance were significant. Volfe Canyon, Watershed IX, had consistently less variation among first-order properties, which may indicate that interruptions in erosional history, which increased first-order variation in other watersheds, had less effect in Volfe Canyon. The writer considers it more probable that erosional changes which have only partially affected other watersheds have progressed closer to completion in Volfe Canyon.

Relief, Relief Ratio, and Relative Relief

None of these measures of relief had homogeneous variances among sets of the same order, except for the very small sets of fourth-order logarithms. Among the sets of logarithms of relief, except for fourth-order values, the variances of Watersheds II and III, Fern and Upper East Canyons, were consistently greater than those of the other watersheds. Among the fourth-order log relief sets, the variance of Fern Canyon was based on only two measurements, of nearly alike values, hence was very small. The fourth-order variance for Upper East Fork was greater than for the other three sets of relief logarithms. The significant differences among variances of the relief ratio logarithm sets are not so consistently arranged. Excluding the unusual Fern Canyon fourth-order value, the Volfe Canyon variances are smaller, order by order, than those of other watersheds. The variances of Fern Canyon are larger than average and for the second- and third-order sets are largest. The largest variance of the first-order sets was that for Bell Canyon. Relative relief was calculated for only three watersheds, II, III, and VIII, in which perimeters were measured. The differences among the variances of these three sets were not significant at the two percent level but were at the five percent level. Fern Canyon had the largest variance.

The results of homogeneity of variance tests indicate that, at least in the San Dimas Experimental Forest, differences between means of measures of relief cannot properly be compared on a watershed basis by analysis of variance. This restriction probably applies to most of the watersheds in the San Gabriel Mountains. Whether it pertains to other areas with less complex erosional history is not known. However, future investigations using measures of relief should include tests of homogeneity of variance if analysis of variance is to be used. The results of tests of relief properties support the conclusion that geomorphic variation, presumably related to erosional conditions, is least in Volfe Canyon and greatest in Fern and Upper East Fork Canyons.

Perimeter, Elongation, and Circularity

Drainage basin perimeters were measured only for first-order basins in Watersheds II, III, and VIII. Inhomogeneity among the variances of the perimeter logarithms was not significant at the five-percent level, but was significant at ten percent. Upper East Fork had the greatest variance and Bell Canyon the least. Inhomogeneities among variances of the first-, second-, and third-order sets of elongation logarithms were significant at the one-percent level. No regular ranking was apparent from order to order: among first-order ratios, Watershed VIII had a larger than average variance; among second-order sets, the variance of the set for Watershed I was much larger than average; Watersheds I and VIII had variances much less than average of the third-order group. The three sets of circularity measurements and their logarithms had variances that were significantly non-homogeneous. Bartlett's test was applied to the arithmetic values of this property in addition to the logarithmic values, because the distribution of untransformed values had been found to be not different from normal. The variances for the Fern Canyon sets were larger than those of the other two watersheds tested.

Drainage Density and Channel Frequency

Tests of homogeneity of variances of these two closely related properties produced unexpected results. Differences among third-order variances were significant even though those among second- and fourth-order variances were not. The first-order variances of both drainage density logarithms and channel frequency logarithms were, as expected, significantly non-homogeneous. Differences among variances of first- and second-order drainage density logarithms were small, although the differences among the first-order variances was found to be significant at the one-percent level. The significant inhomogeneity of third-order logarithms of drainage density and channel frequency was due in both cases to unusually small variance of the Volfe Canyon values. In all instances, all orders of both properties, whether homogeneous or not, the Volfe Canyon sets of logarithms had the least variance.

ANALYSIS OF VARIANCE

Statistical Inferences

Analysis of variance yields an estimate of the probability that means of populations from which samples have been obtained are equal. A very small probability is taken as basis for the inference that the population means are unequal. Population means are estimated from sample means. As discussed above, assumptions basic to analysis of variance include normality of the sample and population distributions and homogeneity of population variances. These assumptions have often not been tested in previous geomorphic investigations. Although moderate departures from homogeneity of variance do not greatly affect analysis of variance results, the effect of large departures is not known.

Analysis of the variance of the means of logarithms of each order of each geomorphic property were computed, using a desk calculator, from means and variances computed by an IBM 650 digital computer. Inferences from the results are considered to be valid only for those sets of measurements which have homogeneous variances and no significant departure from normality. To facilitate comparison with results of other studies analysis of variance was computed for sets of data which were not normal and of homogeneous variances. The results of these latter analyses should be considered as descriptive statistics and not used as a basis for inference. For convenience in tabulation these descriptive statistics have been listed in Table IX as "percent probabilities". These "probabilities" are not valid inferences and are intended only as expressions of a descriptive ratio of variances. For analytical purposes the non-underlined figures in Table IX should be converted to F-ratio values by using the appropriate degrees of freedom (k-1, and N-k, where k is the number of watersheds and N the total number of observations). Such F-ratios should then be considered as descriptive statistics of the between-means to the pooled variance ratios. Results of valid analyses of variance also are summarized in Table IX and discussed below.

Channel Length, Basin Area, and Diameter

Analyses of the variance of second-, third-, and fourth-order channel length logarithm means showed no significant differences between means. The means of logarithms of first-order lengths had an F-value of 32, which would indicate highly significant differences between means if the measurement sets had homogeneous variances. Logarithms of second-order basin areas had highly significant differences between watershed means. Differences between means of third-order area logarithms were significant at the ten-percent level but not at five percent. Differences between fourth-order watershed means of basin area logarithms were not significant. The polymodal first-order sets of basin area logarithms had a variance ratio of 60. Results for diameter logarithms were similar to those for basin area logarithms. Significant differences were found among second- and third-order means. No significant differences were found among the means of the small fourth-order sets of measurements. The first-order sets, which had large inhomogeneity of variances, had a between-means to pooled variances ratio of 42. These results indicate that, except for first-order channels, there is little difference in average channel lengths among the watersheds studied. Conversely there are significant differences between second-order means and between third-order means of both basin area and basin diameter.

Relief, Relief Ratio, and Relative Relief

Only the small sets of fourth-order properties and the incomplete sets of perimeter logarithms and relative relief logarithms had been found to meet the prerequisites for analysis of variance. The fourth-order sets probably met conditions only because the small number of values in each set provided scant basis for discrimination of non-homogeneities of variances. The two incomplete first-order sets provided only three watershed means and variances, instead of five. Analysis of variance showed that differences between means of fourth-order relief ratio logarithms were significant at the five-percent level but not at two percent. Differences between log relief fourth-order means were significant at ten percent but not at five percent. No significance was found to differences between the three first-order log relative relief means. Other orders of the several relief properties had between-means to pooled variance ratios ranging from approximately 6 to 36.

Perimeter, Elongation and Circularity

Differences between the three watershed means of first-order perimeter logarithms were found to be significant at three percent but not at two percent. Only the fourth-order sets of elongation logarithms met the requisites of normality and homogeneity of variances; means of these sets had no significant differences. The ratios of between-means to pooled variances for the second- and third-order logarithms of elongation were quite small. This indicates that differences between the watershed means may be non-significant. Large differences between the variances make accurate evaluation of the analysis of variance results impossible. The sets of first-order circularity and of logarithms of circularity had variances which were non-homogeneous, consequently their means could not validly be compared by analysis of variance. The variances ratios for these sets were moderately large. The inconclusive results of tests of these three measures of drainage basin size and shape suggest that there may be no important differences between watersheds for second-order and higher order values of these properties but that there probably are differences between first-order watershed averages.

Drainage Density and Channel Frequency

The sets of logarithms of second-order drainage density, and of second-order channel frequency were normally distributed and of homogeneous variances. The differences between the means of these sets were highly significant. Variance ratios of means of the third-order drainage density logarithms and channel frequency logarithms indicate significant differences between means of these properties, if the moderate (significant at one-half percent) departures from homogeneity of variances do not invalidate the analyses of variance for these properties. Fourth-order drainage density logarithms had valid significant differences between watershed means. The between-means to pooled variance ratio of fourth-order channel frequency logarithm means indicated significant differences between watershed means, although the measurement sets did not have homogeneous variance. Logarithms of first-order drainage and channel frequency sets, which had non-homogeneous variances, had between to pooled variance ratios of, respectively, 70 and 64. The results of analysis of variance of log drainage density and log channel frequency means indicate that these properties provide a significant basis for distinguishing differences and similarities between watersheds.

DRAINAGE COMPOSITION

R. E. Horton (1945) formulated from observed relationships a group of laws of drainage composition relating numbers of streams, stream lengths, stream slopes, and basin areas respectively to order number, by geometric series. The geometric ratios of these series were called respectively the bifurcation ratio, length ratio, slope ratio, and area ratio. The law of basin areas had been implied by Horton but was first explicitly stated by Schumm (1956, p. 606). Schumm also established a new law of drainage composition which related basin areas and channel lengths as a linear function whose slope was designated the constant of channel maintenance. Because these laws were postulated to be geometric series, graphs of the relationships on semi-logarithmic coordinates appear as sets of points lying on straight lines, with slopes which are the geometric ratios. For convenience these ratios are referred to below as watershed ratios to distinguish them from other ratios. Each of the watershed ratios has a single value for each watershed. The relationship of eight geomorphic properties to basin order was investigated in the present study. Figures 10 through 17 are graphs of the laws of drainage composition based on these eight properties. Logarithms, base 10, of the watershed ratios are given in each case, because these are the regression coefficients of the regressions of the logarithms of each property on order.

The law of stream numbers, as stated by Horton, seems to apply well to the San Dimas watersheds (Figure 10). The logarithms of bifurcation ratios were all similar, the greatest being 0.70, for Fern Canyon, and the least 0.62 for Upper East Fork. The San Dimas channel length-order data do not seem to fit a geometric series closely (Figure 11). In the five watersheds studied, the fifth-order channel segment is shorter than would be expected if a semilog linear relation based on the first four orders were extended to the fifth order. In other words, the functions appear to be concave up when plotted on semilogarithmic coordinates. Strahler (1953) found similar relations for several other watersheds. Much of this apparent departure from linearity may be due to Strahler's revision of Horton's method of stream ordering. Horton considered the length of a fifth-order stream to extend from the mouth of a fifth-order watershed to the head-water extremity of its furthest fingertip tributary. Strahler's revision, which eliminated subjective choices about the trunk stream, considers the fifth-order segment to extend only from a junction with a fifth-order (or higher order) segment up to the highest confluence of two fourth-order segments. Such fifth-order segments would, on the average, be shorter than fifth-order streams as defined by Horton. Broscoe (1959, p. 5) gave a similar explanation for this apparent non-linearity. When more data are available, for sixth-order or higher order watersheds, it will be possible to ascertain which method of ordering yields results most closely fitting Horton's law and, conversely, what function best fits channel lengths as defined by Strahler.

Mean basin area measurements seem to follow closely the law of basin areas as stated by Schumm (1956, p. 606). The logarithms of watershed area ratios were all between 0.71 and 0.72 except that for Fern Canyon which was 0.78 (Figure 12). A plot of mean basin diameters on a logarithmic scale versus channel order is very closely fitted by a straight line (Figure 13). From this observation another law of drainage basin composition can be formulated: the mean diameter of basins of each order within a higher order watershed tend closely to approximate a direct geometric series in which the first term is the mean diameter of the first-order basins and the ratio is the diameter ratio.

Logarithmic plots of mean drainage basin relief (or, more exactly, diameter relief) against order also fall close to straight lines (Figure 14). Hence, a law of basin relief, which describes this relation, is postulated: the mean relief of basins of each order in a watershed tend closely to follow a direct geometric series in which the first term is the mean relief of the first-order basins and the ratio is the watershed relief ratio. Obviously this law will be valid only for watersheds of low to intermediate order; the maximum regional relief quickly becomes a limiting factor as order increases. It is unfortunate that the phrase "relief ratio" thus has two meanings. The use of "relative relief" for the relief of the diameter would improve terminology if that term had not already been used by Melton for the ratio of relief to perimeter. The logarithm of watershed relief ratio found in this study ranged from 0.21 for Volfe Canyon to 0.26 for Fern Canyon. It is notable that Fern Canyon had the largest watershed ratios for stream numbers, channel lengths, basin areas and relief. The significance of this fact has not yet been determined.

The derived geomorphic properties of elongation, drainage density, and channel frequency showed much less variation with basin order (Figures 15, 16, and 17). The largest value of the slope of mean elongation plotted logarithmically against order was 0.015. In general, the mean elongation of first-order basins was less than that of higher order basins. This may indicate that first-order basins start as insequent gullies unaffected by processes which control the shape of better integrated higher order basins, or it may indicate that a recent rejuvenation affected the shape of many first-order basins but has not yet affected the higher order basins. It is probable that in regions characterized by dendritic drainage patterns, elongation is independent of order.

The semi-logarithmic graph of drainage density against order showed that this property decreases with increase in order (Figure 16). The points scatter widely about a straight line, but all watersheds show the same inverse relationship. No consistency in the departures from linearity was apparent. The largest value of decrease in log drainage density per unit increase in order was 0.025, for Fern Canyon; the least was 0.019, for Volfe Canyon. Semilogarithmic plots of channel frequency against order showed a relationship similar to that of drainage density (Figure 17). Departures of the plotted points from straight lines were less than those of the drainage density—order plots. The logarithm of channel frequency ratio was largest for Fern Canyon (-0.079); least for Wolfskill Canyon, (-0.063). The larger channel frequencies in the Big Dalton drainage, Watersheds VIII and IX, compared with corresponding orders in the San Dimas drainage, Watersheds I, II, and III, are apparent on the graphs. A similar but less conspicuous segregation can be seen on the drainage density-order graphs. This tendency of channel frequency-order plots to segregate into groups suggests that channel frequency may be a useful property for distinction between watersheds which are in the same physiographic province but which have subtle geomorphic and hydrologic differences.

Replication of Field Observations

PLAN OF FIELD TESTS

Quantitative geomorphic analysis tacitly assumes objectivity, or at least freedom from significant subjective bias, in the collection of field measurements. Little, if any, evidence has been presented to substantiate this assumption. Reproducibility of an observation, measurement, or result is a fundamental criterion of validity in physical science. Although this test of reproducibility is often precluded by practical considerations in the geological sciences, it should be applied where possible.

To test the reproducibility of the field mapping and measurements of the present study, independent duplicate studies of two fifth-order watersheds were made. After the author had mapped the channel network and drainage divides and measured maximum valley-wall slopes in Wolfskill and Bell Canyons, Mr. James Trew of Brown University independently mapped and measured the same properties. Mr. Trew's work was done for part of his dissertation for the Master of Science degree (Trew, 1956) under the direction of Professor Richard Chorley, Brown University Department of Geology.

CHANNEL NETWORK

Geomorphic properties are usually compared according to the order of the channel or drainage basin with which the properties are associated. Determination of the order of a channel is dependent upon the correct identification of its tributary channels. This, in turn, depends upon the field observer's ability to recognize a stream channel. Simple criteria for defining a stream channel were found to be elusive. In chaparral-vegetated mountainous terrain, in a climate which has a prolonged dry season, stream channels are often indistinct. Mechanical erosion by rolling and sliding of rock debris produces linear depressions, called debris chutes, which resemble but are not stream channels. Leaves fallen from wilting chaparral during the dry season often conceal small channels bridged by dense vegetation. Formal definition of the properties to be studied was required for uniformity in the field mapping and for reproducibility in the replication study.

In the San Dimas area four criteria were found to be sufficient to distinguish a stream channel: the presence of stream banks, the presence of suspended and oriented debris, the presence of wash marks, and continuity with a larger channel. It was observed in the field that inclined linear depressions which frequently carried running water, developed well-defined nearly vertical banks. Those eroded by loose debris did not. This criterion was the most reliable and most frequently used. Debris or forest litter carried by running water was often draped over branches and roots of vegetation protruding over and into the channel. In some instances debris was oriented in sub-parallel flow-lines along the sides of the channel. Wash marks, small rill marks, terracettes, and dams of fractional-inch size, similar to those produced by sheet erosion, were often found within the channel boundaries. The last criterion, continuity with a larger channel, was not applicable to the few first-order channels which drained into Brown's Flat in Fern Canyon. This caused no difficulty because the other criteria were applicable. Usually at least two of the four criteria were recognized in each channel mapped.

Inaccuracy of the large-scale base maps used was another practical problem affecting the replication study. An enlarged portion of the map of Upper East Fork Canyon (Figure 9) shows some of the map inaccuracies encountered in the field work. Figure 9b shows first-order stream channels found where the contour lines of the map indicate a ridge. Above the center of the area another channel crosses a ridge indicated on the original map.

With the exception of two half-days during which the identification of channels was field-verified with Maxwell, Trew mapped the drainage network of Bell and Wolfskill Canyons independently and without reference to Maxwell's maps of the same watersheds. Difficulty in recognizing the more obscure channels, inaccuracy of the base maps, and the physical impossibility of checking every square foot of the rugged mountain watersheds led to discrepancies between the two drainage networks as mapped by the two investigators. Subjective errors in identification of first-order channels led to two kinds of differences. One channel may join another in either of two ways, here arbitrarily called A-type and B-type junctions. The confluence of a channel with another of the same order forms an A-type junction and a higher order channel results. If one channel joins another of a higher order, forming a B-type junction, the order of the higher order channel is not affected. The dotted lines in Figure 6 show the effect of a channel mapped by only one investigator. On the left an A-type junction has increased the number of second-order and higher order segments. The addition of the first-order segment generally decreases the average length of first- and second-order segments and the average area of first- and second-order basins by adding a new, smaller basin and by substituting only a part of the original basin.

Results of the drainage network mapping and channel enumeration are listed in Table X. The table shows the number of segments of each order mapped by each investigator, with differences listed as percentages of the channels mapped by Maxwell. The fact that some of the differences are positive and some negative can best be understood in terms of the types of tributary junctions. A detailed comparison of the Bell Canyon maps revealed that Trew found three A-type first-order junctions more than did Maxwell, while the latter found twenty three more B-type first-order junctions than did Trew. Two of the A-type first-order junctions caused the positive second- and third-order differences.

There are at least three reasons why the differences are greater in the Wolfskill Canyon data. Although Wolfskill Canyon is almost twice as large as Bell Canyon, Trew spent most of his field time in Bell. Trew refers to this (Trew, 1956, p. 90-91) as ". . .the predominance of time spent in the field being in Bell Canyon, where existing conditions allowed more exacting work to be done... In contrast, much less field time was spent in Wolfskill Canyon and the area was much less accessible." Accessibility in upper Bell Canyon is by moderately well-maintained contour trails at 300-foot vertical intervals; a paved road diagonally transects the lower half of the canyon. These trails and road intersect many of the Canyon's tributaries. By contrast the contour trails in Wolfskill Canyon are vertically separated by 1000 feet and are partially abandoned; the road in the lower fifth of the Canyon follows the canyon bottom and provides poor access to tributaries. In addition to differences of accessibility and of duration of study, there is a difference in topography. Wolfskill Canyon is more precipitous, with greater local relief and many narrow, well-concealed small tributary canyons not visible from the bordering ridges.

Thus it appears that in the area studied trained observers working independently may be able to enumerate the first-order channels with a reproducibility of approximately five percent except when the topography is more rugged than usual for the San Gabriel Mountains and when access to the area, both in space and in time is limited; then a reproducibility of approximately ten percent may be expected. The errors of reproducibility in enumeration of higher order channels depends upon the type of junction of incorrectly mapped (omitted) first-order channels. The mean bifurcation ratios for the original and replicate channel enumerations is also shown in Table X. These results seem to indicate that the bifurcation ratio is only slightly affected by differences in channel enumeration.

MEAN CHANNEL LENGTHS AND BASIN AREAS

After Trew completed his field mapping, and before any comparisons with Maxwell's data, Trew made measurements of his channel lengths and basin areas. For these measurements he used definitions and procedures as described above under the discussion of geomorphic properties and measurement precision. Trew's replication measurements did not include first-order basin areas.

The results of the replication measurements are shown in Tables XI and XII, which list mean values of stream length and basin areas respectively. To facilitate a roughly quantitative evaluation of the significance of the difference between corresponding means, the estimated standard errors of Maxwell's means are also listed. It can be seen that, except for first-order means, the differences between means of the same order are less than one estimated standard error. A somewhat improved estimate of the significance of the difference between means is possible for second- and third-order basin areas in Table XII. Trew calculated estimated standard deviations for these properties. From these the estimated standard errors of differences of means were calculated (Table XII). Standard errors listed for the fourth-order basin areas are based only on the standard deviation of Maxwell's samples.

Some understanding of the causes of the differences between means was obtained from a comparison of the field maps. On both the Bell and Wolfskill maps, Maxwell extended quite a few first-order channels slightly further headward than did Trew for the same channels. In several instances Maxwell mapped minor bends in channels which Trew mapped as straight. These two factors account for the larger first-order mean length found by Maxwell for Bell Canyon. In Wolfskill Canyon almost all of the first-order channels which Trew omitted were small. This bias overweighed the opposite effect of the previous two factors. One of the A-type first-order streams which Trew mapped in Bell Canyon formed a smaller-than-average second-order channel, which also made an A-type junction producing a smaller-than-average third-order basin. The smaller third-order mean length reported by Maxwell for Bell Canyon was apparently caused by two of the pairs of second-order channels mapped by him which joined just a short distance above a fourth-order channel. This formed an unusually short third-order segment. The differences between means of the same order in Wolfskill Canyon were due almost entirely to omission of short channels by Trew. The greater sinuousity of channels mapped by Maxwell may account for the difference in fourth-order channel length means.

From the results tabulated it was concluded that mean channel length and mean basin area for second-order and higher order basins have been objectively measured, within the natural variability of the property, in this region of rugged topography and dense vegetation. First-order channels, intrinsically more difficult to recognize, have not been so accurately measured. Factors which have influenced the objectivity of the mapping and measurements have been identified.

Correlation of Geomorphic Properties and Flood Discharge

SOURCES OF HYDROLOGIC DATA

The present sharp-crested ridges and deep, precipitous canyons of the San Gabriel Mountains are the result of repeated uplift of the range during vigorous down-cutting by streams. Sheet erosion during rainstorms, and soil creep, slump, and slides deposit debris in the stream channels. Most of this sediment is removed from the mountains during infrequent large floods, whose erosive effectiveness is generally related to the magnitude of their momentary peak discharges. Peak discharge in turn is related to storm and watershed properties. Quantitative estimation of the relationship between flood peak discharge, storm characteristics, and watershed properties is possible with the statistical technique of multiple correlation.

Channel flow from the watersheds studied in this investigation is continuously measured by recording gages on specially designed flumes. From these measurements the annual maximum momentary discharge for each year and each watershed was tabulated, a total of 113 annual peak discharges from 1935 to 1957 inclusive. Records for Watersheds II and III were interrupted for one year during World War II. Storm characteristics of 460 floods, including all annual flood producing storms, are published for the San Dimas Forest (Reimann and Hamilton, 1959). These data, together with the log-normally distributed geomorphic properties which had homogeneous variances, were grouped in multiple correlations. Eighteen variables, including discharge, the dependent variable, were tested. These variables and their definitions are listed in Table XIII.

A logarithmic linear form was used for the estimating equation. Logarithms of annual peak discharge were assumed to have a normal distribution, although it is recognized that, because they are extreme values, annual peak discharges can be shown theoretically to have a Gumbel-type extreme-value distribution, which departs significantly from log-normality for long records. Several studies by the United States Army Corps of Engineers and United States Geological Survey have shown that for records of a few decades duration the log-normal is a useful approximation of flood discharge distribution.

STORM CHARACTERISTICS AND WATERSHED CONDITIONS

The momentary peak discharge produced from a watershed by a given storm is a result of accumulated depth of rain that falls, the intensity (depth per unit time) of the precipitation, and the wetness of the watershed preceding the storm. The maximum rainfall during a sixty-minute period and during a twenty-four hour period were used as measures of both total storm rainfall and its intensity. Wetness of the watershed was estimated by the depth of rain which fell in the seven-day and twenty-one day periods prior to the beginning date of the storm. The flood-reducing effect of vegetative cover was computed according to methods used by Anderson (1949, p. 570):

> An estimation of average cover density on the watershed at the time of the storm was assumed to represent a single-valued quantitative expression of cover effectiveness (Anderson and Trobitz, 1949). The assumption is reasonable, for practically all of the beneficial effects of cover tend to increase with increase in cover density: the protection of the soil from beating rain, the production of leaf litter which further protects the soil and retards surface runoff and erosion, and the secondary effects on soil structure and permeability. The cover density for the actual watershed condition for each storm was obtained by applying the density-age relations for various cover types on various geologic types as developed by J. S. Horton of the California Forest and Range Experiment Station.

These density-age relations are given in

Table IV. The percentage area of each watershed covered by each vegetation type, shown in Table II, was multiplied by the appropriate density-age factor for each year of flood record. These percentages were added, for each watershed, to give an average cover density for each year. In Watersheds I, II, and III, which had been damaged by wildfires in recent years, the amount of damage to each vegetation type was estimated from fire maps. The area of undamaged cover was reduced accordingly.

To test for independence of the storm and watershed condition variables simple correlations between each of the variables were computed. As expected, a highly significant correlation was found between maximum sixty-minute rainfall and maximum twenty-four-hour rainfall. Anderson (1949, p. 571) had found a similar result. Seven-day antecedent precipitation was found to be highly correlated with twenty-one-day precipitation. This was to be expected inasmuch as each seven-day period was a one-third estimate of the corresponding twenty-one day period. Simple correlation coefficients between each of the four precipitation variables and discharge were found to be highly significant. Unexpectedly, the simple correlation coefficient between cover density and discharge was small and not significant. It is thought that the effect of watershed area probably masked the effect of cover density. Significant positive simple correlation was found between maximum twenty-four hour storm rainfall and both seven- and twenty-one day antecedent precipitation. Maximum sixty-minute storm rainfall was significantly and positively correlated with twenty-one day, but not with the seven-day antecedent precipitation. Because no a priori reason is known to exist for storms following dry periods to be less intense than storms following wet periods, the positive correlation between antecedent precipitation and storm intensity is assumed to be indicative of some other factor, such as long-term climate cycles, rather than of cause and effect relationship.

Five multiple correlations between annual peak discharge, cover density, and the precipitation variables were computed to determine which combination best estimated discharge as the dependent variable. The first two related only storm intensity and cover density to discharge. For sixty-minute precipitation, P_{60}, and cover density, C_d, the multiple correlation coefficient was 0.556; for twenty-four hour precipitation, P_{24}, and C_d it was 0.786. Thus when only these variables are considered, P_{24} seems to explain more of the variation in peak discharge, Q. When watershed wetness, as measured by rainfall prior to the flood-producing storm, was considered, more of the variation was accounted for. The multiple correlation coefficient for P_7, seven-day prior rainfall, and P_{24} and C_d versus Q was 0.795. The multiple correlation coefficient for P_{21}, the twenty-one day prior rainfall, P_{24}, and C_d versus Q was 0.807. Thus these three variables alone appear to account for nearly 65 percent of the variation in discharge. To check whether the inclusion of prior rainfall would affect the relative quality of P_{60} as a predictor, P_{60}, P_{21}, and C_d were correlated with Q. The multiple correlation coefficient for this was only 0.677. An unexpected result appeared in these correlations in the coefficients of estimation, or regression, of cover density. In all the above correlations except that of P_{24}, P_7, and C_d versus Q, the estimating coefficients of cover density were positive. This would indicate that the magnitude of flood peak discharge increases as the vegetative cover on a watershed increases. Because theory and observation both refute this inference it is quite evident that the correlations are incomplete, that significant pertinent variables have been omitted.

GEOMORPHIC PROPERTIES

The influence of geomorphic properties on flood peak discharge is more complex and less well known than that of storm characteristics. The effect of only one property, watershed area, has been well-established by measurements. In general, for small to moderate size watersheds, as watershed area increases, flood peak discharge increases. Anderson (1949, p. 575) investigated the combined effect of bifurcation ratio, slope ratio, and length ratio, and found it to be not significantly related to peak discharge. Potter (1953) found that a geomorphic property involving the length and gradient of a watershed's principal waterway was significantly related to peak discharge per unit area. The property investigated was

> . . .designated as the T-factor and may be defined as the length of the principal water way divided by the square root of the channel slope. Since velocity varies as the square root of slope, the T-factor is indicative of time of channel flow. Considered with area and peak rate of runoff in a multiple correlation it is also indicative of time of concentration, channel storage, and watershed shape. (Potter, 1953, p. 69).

In the present study a characteristic value of each geomorphic property was available for each of the five watersheds studied. When combined with the 113 records of peak discharge these characteristic values permitted unique solutions of estimating equations having not more than five geomorphic variables.

The computation of multiple-variable estimating equations was simplified by establishing a new dependent variable which expressed the variation in peak discharge after allowance for the variation explained by storm characteristics and watershed condition. Each value of the new dependent variable was formed by subtracting from the original dependent variable its corresponding value of log Q calculated by the best four-variable estimating equation. This gave 113 values of unexplained discharge. It was recognized that this procedure would yield inexact values of the estimating coefficients and multiple correlation coefficients because the estimating coefficients used in the four-variable equation were almost certain to be different from those in a nine-variable equation. However, it was believed and later demonstrated that the second-order partial correlation coefficients, which had been relatively large in the four-variable equations, indicated that the four-variable equation gave a useful approximation of the portion of the dependent variable which would be estimated by the corresponding three terms of an eight-variable equation.

The first geomorphic variable added to the correlation was area of the fifth-order watersheds. As was expected, fifth-order area was significantly correlated with peak discharge. The correlation of area with discharge often, unfortunately, conceals other significant effects. This was well expressed by Anderson (1957, p. 922) who states:

> . . .'area' can well be called the devil's own variable. Almost every watershed characteristic is correlated with area. So every characteristic that is left out as a separate variable is in part hidden in 'area'. Big watersheds are not like little watersheds and the differences may be disguised in the term area. Therefore, it is dangerous to ascribe physical significances to the regression coefficients of the area variable.

An effort was made to find other geomorphic variables which might separately express the effects combined in area. When fifth-order diameter was substituted for area in simple logarithmic linear correlation with unexplained discharge, the correlation coefficient was 0.441, which compared favorably with 0.388 for log area versus log unexplained discharge. When second-order basin area was added the correlation coefficient was increased from 0.388 to 0.427. When diameters were used instead of areas, the multiple correlation coefficient rose from 0.427 to 0.448.

A series of simple and multiple logarithmic linear correlations was computed to find which combination of variables gave the best prediction, as measured by the multiple correlation coefficient. The variables and corresponding correlation coefficients of these equations are tabulated in Appendix IV. The geomorphic variables considered were fifth-order area and diameter, means of second-order area, diameter, relief, drainage density, channel frequency, and relief ratio, and watershed bifurcation, length, diameter, and area ratios. Fifth-order diameter and area had the two highest simple correlations with unexplained discharge, as indicated in the preceding paragraph. Length ratio yielded the third highest simple correlation. Second-order channel frequency and diameter, in that order, were next highest. The remainder, with the exception of bifurcation ratio and area ratio, yielded approximately similar correlation coefficients. Correlation with bifurcation and area ratios was very low.

Next, multiple logarithmic correlations of pairs of geomorphic variables and unexplained discharge were computed. Fifth-order area was first used as one of the independent variables, successively with each of the other variables except fifth-order diameter. Then fifth-order diameter was substituted for area and paired successively with the same other independent variables, in correlation with unexplained discharge. All of the multiple correlations using fifth-order diameter had larger multiple correlation coefficients than those involving fifth-order area. Fifth-order area and diameter were not included in the same correlation because they were highly correlated with each other.

Using the results of the three-variable correlations, a number of four-variable correlations were computed. Fifth-order area or diameter was included as one of the independent variables in all of these correlations. It was found that when correlated with the bifurcation, length, area, and diameter ratios and with mean second-order relief ratio, the combination of fifth-order diameter and second-order area gave better estimates of unexplained discharge than did the combination of fifth-order diameter and second-order diameter. The opposite, i.e. that second-order diameter gave better estimates than second-order area, when used with fifth-order diameter, was found when the third independent variable was second-order relief, drainage density, or channel frequency. Second-order channel frequency was found to be highly correlated with second-order area, diameter, and drainage density, hence it could not be used as an independent variable with any of these three. The largest multiple correlation coefficients among the four-variable correlations were for those which included fifth-order diameter and second-order drainage density as two of the three independent variables.

To confirm the apparent relative effectiveness of the variables, two series of five-variable and two series of six-variable multiple correlations were computed. In the first series of five-variable correlations, fifth- and second-order diameters, second-order drainage density, and successively six other geomorphic properties were used. In the second five-variable series, fifth- and second-order areas were substituted for diameters. Very little difference was found among the multiple correlation coefficients of these two series, although those for the series using areas were generally slightly larger. For the two six-variable series, second-order relief ratio and drainage density were paired with fifth- and second-order diameters or, alternatively, areas, and successively five other properties. When the multiple correlation coefficients of these equations were rounded to three significant digits they were alike except for the equation of diameters with diameter ratio, which was very slightly larger.

These results indicate that, for the sample of peak discharges and geomorphic properties that was studied, fifth- and second-order areas or diameters, together with second-order drainage density and relief ratio, provide a good estimate of the variability in peak discharge which can be explained by geomorphic variation between watersheds. Several other geomorphic variables improve the estimating equation slightly, and about equally. Several of these may be related to another, unidentified, geomorphic property which would improve the estimating equation more than any of these taken singly.

COMBINED EQUATIONS

The results of the correlation of storm characteristics and watershed condition with peak discharge, and the correlation of geomorphic properties with unexplained discharge determined the selection of variables for correlations which would combine both. Five nine-variable multiple correlation equations were computed. The equations were of the form:

$$\log Q = k + b_1 \log P_{24} + b_2 \log Cd + b_3 \log P_{21} + b_4 \log A_5 + \log A_2 + b_6 \log D_2 + b_7 \log R_2 + b_8 \log Ra$$

Numerical values of the estimating coefficients, their standard deviations and the partial correlation coefficients for each term are listed in Table XIV. The largest coefficient of multiple correlation obtained was 0.8965. This was for the equation using fifth- and second-order areas and the area ratio, with P_{24}, Cd, P_{21}, D_2, and R_2, to estimate Q. The equation using fifth- and second-order area and mean second-order relief with the same other variables had the smallest multiple coefficient, 0.8888. The coefficient of multiple determination for the best correlation was 0.8037, indicating that more than 80 percent of the variation in peak discharge can be explained by this combination of rainfall, cover density, and geomorphic variables. It is quite probable that more of the variation will be explained when better measures of storm conditions are available. All precipitation values used were measured at the main San Dimas Experimental Forest rain gage located at Tanbark Flat. Thorough investigation has indicated that this gage samples local rainfall accurately. Precipitation data measured within each watershed would probably correlate more closely with watershed peak discharge.

The estimating, or regression, coefficients listed in Table XIV show the effect of change in one variable when the others are held constant. A very large range was found for estimating coefficients of the geomorphic variables from equation to equation. For the two equations which had the largest multiple correlation coefficients, the estimating coefficients of the geomorphic variables were approximately ten times greater than the corresponding coefficients in the other three equations. The standard deviations of the geomorphic variables also were larger by factors of three to six in the first two equations. In these two equations all of the estimating coefficients were significant, being one to three standard deviations different from zero. In the remaining three equations, only fifth-order area or diameter was consistently different from zero.

The partial correlation coefficients, also listed in Table XIV, indicate relative influence of the several variables. Storm intensity has the largest partial correlation coefficient, 0.77. Cover density is second only to storm intensity; antecedent precipitation accounts for less of the variation in peak discharge than does cover density. In the equation having the largest multiple correlation, the geomorphic variables have approximately equal partial correlation coefficients. Evaluating the significance of the partial coefficients is difficult because of complications in the degrees of freedom. For the first three variables, P_{24}, Cd, and P_{21}, 113 different groups of data were available. For the geomorphic variables there were five groups of approximately 22 identical values each, correlated with 113 different values of peak discharge. If, in using a t-test to evaluate the significance of the partial coefficients, the sample size is taken as 113, the coefficients are all significant. If five is used for sample size N, the t-value cannot be calculated, because the degrees of freedom, N-m (where m is the number of variables) is negative.

Without drawing a probability inference, an indication of the influence of the geomorphic variables can be seen in the increase in multiple correlation coefficient from 0.807 for the best four-variable equation to 0.897 for the best nine-variable equation. Pertinency of the five geomorphic variables is indicated by the increase in partial correlation coefficients of the first three variables. After having much experience using multiple correlation to investigate watershed discharge and sediment production, H. W. Anderson (1957, p. 123) has criticized routine dropping of "non-significant" variables:

> Frequently, in the past, variables have been dropped "because they were non-significant". The arbitrary choice, say the five-percent level, for this decision is statistical nonsense. Why we should choose to drop a measure which is unbiased, small, but differing from zero, and substitute the biased value of zero is not clear.
>
> The statisticians do not suggest that we make any such arbitrary decision at the five-percent level; they tell us we must decide on the basis of the risks we are willing to take of (1) retaining a variable whose apparent effects are really due to chance and (2) dropping a variable with real effects. The 'real effect' of a variable which is worthwhile retaining in analyses relating sediment yield (or peak discharge) to watershed variables is one which would affect the results, most importantly affect the partial effects of the other variables. The added possibility that the several small effects may add up to an important effect makes dropping of individual variables risky.

Regarding the interpretation of partial-correlation coefficient-significance tests, Croxton and Cowden (1955, p. 735) state that these do not tell us that we should necessarily exclude a non-significant variable from our analysis, since it may contribute some useful information even though its significance has not been demonstrated. The author believes that inclusion of the above geomorphic variables contributes useful information in at least two ways. Directly, their inclusion improves the estimation of flood peak discharge by making allowance for basic differences between watersheds. Indirectly, an estimation of the relative influence of different aspects of the landscape on flood peaks is provided, indicating which properties might be most fruitful for further investigation, and giving a clue to cause and effect relationships between streams and the equilibrium forms they produce.

Conclusions

APPLICABILITY OF METHODS

The results described above indicate that methods of quantitative geomorphic analysis can be meaningfully applied to mountain watersheds of precipitous slopes and high relief, despite greater difficulties of conducting field operations in mountainous terrain than in areas of more moderate slopes and lower relief. Probably the greatest difficulty encountered in applying the quantitative methods was in identification of stream channels. This was overcome by defining stream channels in terms of recognition criteria which had logical bases in theory, which were readily visible, and which excluded channel-like depressions not formed primarily by concentrated stream flow. That the definition and recognition criteria were adequate was verified by a replication study, in which another investigator, working independently but using the same definition and criteria, obtained consistent results.

Generalizations, such as the laws of stream numbers and of basin areas, were found to be valid for chaparral covered mountain watersheds. Characteristic values of the many geomorphic properties investigated were consistent with those found elsewhere, and were consistent with subjective descriptions of the investigated area. Thus it was concluded that concepts which were developed in the humid, hilly eastern United States are sufficiently general to be applicable to mountainous areas in a Mediterranean climate.

ANALYSIS OF METHODS

Analysis of the methods of quantitative geomorphology, during application of these methods to mountain watersheds, revealed that a few of the definitions of geomorphic properties contain ambiguities. Resolution of difficulty with the identification of channels has been mentioned above. Some of the methods used in previous studies for measusing drainage basin shape failed to discriminate between gross differences in shape and minor crenulations in basin perimeter. To overcome this difficulty a shape index based on basin diameter was proposed and applied. Partly to facilitate definition of the shape index, but primarily to provide a more adequate definition of a basic property, basin diameter was explicitly defined. A somewhat lengthy definition was needed to accomodate all anticipated conditions. Fortunately, the definition was generally easy to apply. After review of the several methods used to express the relative relief of drainage basins, one based on the diameter was used. Because quantitative geomorphology is a very recently established branch of science, it is to be expected that many significant basic properties have not as yet been identified and defined. New definitions used in this study are tentatively presented with the expectation that they may be improved by future work.

Methods of geomorphic analysis often include comparison of means by statistical analysis of variance. Inference from analysis of variance is valid only when the populations compared are normally distributed and have equal variances. In some previous studies of watershed morphology the normality of sample distributions was tested. Tests for homogeneity of variance of geomorphic data had not been made prior to the present study. The results of normality tests in this study indicated that first-order drainage basin areas are sensitive to interruptions in their erosional development. Consequently, measurements of first-order basin area are likely to be polymodal and non-normal when grouped on a watershed basis. The non-normality found in first-order basin areas in the San Dimas Experimental Forest may indicate a very useful means of objectively determining the area affected by a younger erosion cycle encroaching upon forms developed to a later stage by an earlier cycle of erosion. Homogeneity of variance tests revealed that groups of the same order and property from adjacent watersheds had significant differences between variances. It is not known whether this condition is characteristic only of San Dimas watersheds, or of mountain watersheds, or whether it is often true of watersheds in general. Future studies which use analysis of variance should include tests for normality of distributions and homogeneity of variance.

CORRELATIONS WITH FLOOD DISCHARGE

Storm rainfall, watershed cover, antecedent precipitation, watershed area, mean second-order basin area, mean second-order drainage density, mean second-order relief ratio, and watershed area ratio were correlated with 113 measurements of annual peak discharge. The multiple correlation coefficient was 0.8965. Several other multiple correlations indicated that fifth-order and second-order diameters, mean second-order relief, and watershed diameter ratio were also useful in estimating peak discharge. Partial correlation coefficients indicated that storm rainfall, watershed cover, and antecedent precipitation accounted for more of the variation in discharge of fifth-order watersheds than did any of the geomorphic variables. It was concluded that there are significant quantitative differences in geomorphology between the watersheds of the San Dimas Experimental Forest, and that these differences account for otherwise unexplained differences in flood peak discharge from these watersheds.

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Tables

Table I MONROE CANYON SOIL CHARACTERISTICS

Characteristic		Average for Soil Survey	Average for soil-moisture plots
Soil Depth	feet	3	4
Slope	percent	-	78
Rock Content[1]	do	-	11
Sand	do	81	81
Silt	do	16	15
Clay	do	3	4
Field-capacity storage[2]	inches	7.5	8.2
Wilting-point storage[3]	do	3.4	3.2
Available water	do	4.1	5.0

Footnotes: 1- Percent of volume occupied by solid rocks more than 1 inch in diameter.
2- Determined by field-moisture sampling of freshly drained soil (mean for 2 years).
3- Based on 15-atmosphere moisture percentage.

From Rowe and Colman, 1951

Table II San Dimas Vegetation Distribution
Percentage of Watershed Area Covered by Vegetation Type

Watershed:	Sage and: Barren :	Chamise: Sage :	Chamise : Ceanothus:	Chamise : Manzanita:	Broad Leaved: Chaparral :	Oak Chaparral:	Woodland: Sage :	Oak Woodland:	Riparian: Woodland:	Spruce: Forest:
I	9.0	6.2	5.1	12.9	3.4	25.7	1.4	19.0	3.2	14.1
II	6.5	0.1	0.4	12.4	3.3	17.6	-	42.1	2.4	15.2
III	6.1	3.9	3.1	18.7	2.3	24.9	0.5	22.3	4.3	13.9
IVA	16.4	4.0	14.3	14.9	1.4	26.2	3.5	9.8	5.2	4.3
V	8.9	6.2	35.6	7.7	5.7	21.6	0.3	0.2	8.2	1.2
VIA	19.7	6.0	31.2	1.3	1.5	19.1	8.7	1.4	9.9	1.2
VII	10.4	6.2	33.6	0.7	0.7	25.1	7.9	0.8	10.5	4.3
VIII	11.8	4.3	40.7	1.0	2.9	24.1	1.4	-	11.9	2.0
IX	11.8	1.6	43.3	2.1	3.5	23.3	1.5	-	12.8	0.1
X	11.9	12.4	34.5	-	3.1	24.6	5.2	-	7.7	0.6
Map Designation	1	2	3	4	5	6	7	8	9	0

From the files of the San Dimas Experimental Forest

TABLE III

COMMON AND BOTANICAL NAMES OF SOME SPECIES OF THE SAN DIMAS EXPERIMENTAL FOREST

Alder, white	Alnus rhombifolia
Berry, Christmas	Photinia arbotifdlia
Budswheat, California	Erigonum Fasciculatum
Ceanothus, deerbrush	Ceanothus integerrimus
Ceanothus, hairy	C. oliganthus
Ceanothus, hoaryleaf	C. crassifolius
Chamise	Adenostoma fasciculatum
Laurel, California	Umbellularia californica
Manzanita, bigberry	Arctostaphylos glandulosa
Manzanita, Eastwood	Arctostaphylos glandulosa
Maple, bigleaf	Acer marophyllum
Mountain-mahogany, birchleaf	Cercocarpus betuloides
Oak, California live	Quercus agrifolia
Oak, California scrub	Q. dumosa
Oak, canyon live (Golden Oak)	Q. chrysolepis
Oak, interior live	Q. wislizeni
Pine, Coulter	Pinus coulteri
Pine, knobcone	P. attenuata
Pine, ponderosa	P. ponderosa
Poison oak, Pacific	Toxicodendron diversilobum (Rhus diversiloba)
Sage, black	Salvia mellifera
Sage, white	S. apiana
Spruce, bigcone	Pseudotsuga macrosarpa
Sumac, laurel	Rhus laurina
Sumac, lemonade	R. integrifolia
Sugarbush	R. ovata
Sycamore, California	Platanus racemosa
Whitethorn, chaparral	Ceanothus leucodermis
Willows	Salix spp.

Table IV Constants for Approximating Density of Cover Types for Southern California Watersheds for Burned Areas "t" Years After a Fire[1]

Cover Type	Geology	Cmin	Cmax	K
Oak Chaparral	Metamorphic	0	90	0.156
	Igneous	0	80	0.139
	Sedimentary	0	65	0.152
Oak Woodland (Quercus Chrysolepis)	All	0	90	0.263
Chamise-manzanita and Chaparral	Metamorphic	0	80	0.123
	Igneous	0	75	0.123
	Sedimentary	0	65	0.112
High Elevation Chaparral	Metamorphic	0	80	0.138
	Sedimentary & Igneous	0	70	0.143
Oak Woodland (Quercus Agrifolia)	All	30	40	0.105
Desert Chamise and Chaparral	Metamorphic	0	65	0.100
	Igneous	0	60	0.094
	Sedimentary	0	30	0.080
Pure Chamise and Chamise Sage	Metamorphic	0	60	0.110
	Sedimentary & Igneous	0	50	0.058
Timberland Chaparral	All	0	50	0.054
Coastal Sage	All	0	40	0.153
Desert Sage	All	0	30	0.100
Semibarren	Metamorphic	0	20	0.093
	Sedimentary & Igneous	0	20	0.053

Footnote 1: $C_t = C_{min} + C_{max} (1-e^{-kt})$, Where C_t = Cover density t years after a fire.

From Anderson and Trobitz, 1949.

Table V

GEOLOGIC MAPPING UNITS

1. Granodiorite, buff-colored, may be same as Lowe granodiorite, and metadiorite; mostly in southwest Wolfskill Canyon.

2. Quartz diorite, includes some fine-grained (quartz) diorite or metadiorite, Wilson quartz diorite, diorite gneiss and schist; interfingering augen gneiss, leucocratic gneiss and other gneiss, varying amounts of granite, granodiorite and associated dikes.

3. Augen gneiss predominant; some other gneiss, (quartz) diorite and metadiorite, granite, granodiorite and associated dikes.

4. Banded gneiss predominant; considerable (quartz) diorite and metadiorite; some augen gneiss, granite, granodiorite and associated dikes.

5. Dacite dikes and quartz diorite.

6. Dacite dikes and augen gneiss.

7. Dacite dikes and banded gneiss.

8. Pegmatite dikes.

Table VI

GEOMORPHIC PROPERTIES

Symbol	Name	Units	Dimensions
u	Order	Enumerative	Dimensionless
N_u	Number of channel segments of order u	Enumerative	Dimensionless
L_u	Length of channel segment of order u	Miles	L
A_u	Area of drainage basin of order u	Sq.miles	L^2
P_u	Perimeter of basin of order u	Miles	L
L_d	Basin diameter	Miles	L
L_f	Flow length along channel,to divide	Miles	L
H_d	Basin relief, measured on diameter	Feet	L
H_f	Basin relief, measured on maximum flow path	Feet	L
H_{max}	Maximum basin relief	Feet	L
α	Basin azimuth (downstream direction of diameter)	Degrees	Dimensionless
θ_{max}	Maximum valley-side slope	Degrees	Dimensionless
γ	Channel gradient	Degrees	Dimensionless
R_c	Basin circularity	----	Dimensionless
R_e	Basin elongation ratio	----	Dimensionless
R_h	Relief ratio	----	Dimensionless
R_{hp}	Relative relief	----	Dimensionless
R_b	Bifurcation ratio	----	Dimensionless
D	Drainage density	Mi.per sq.mi.	L^{-1}
F	Channel frequency (stream frequency)	No.per sq.mil	L^{-2}

TABLE VII

Summary of Normality Tests[1]

PROPERTY	CONCLUSION
Channel length	All log-normal
Area	First order polymodal; higher orders log-normal
Diameter	All log-normal; higher orders may be arith-normal
Perimeter	Three measured were log-normal
Elevation	Not arith-normal; not log-normal
Relief	Log-normal
Relief ratio	Inconclusive; not arith-normal; may be log-normal
Relative relief	Inconclusive; not arith-normal; may be log-normal
Elongation	Inconclusive; probably log-normal
Circularity	Normal
Drainage density	Log-normal
Channel frequency	May be log-normal

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[1] See Appendix II for tabulation of tests.

TABLE VIII

Summary of Homogeneity of Variance Tests

Order	1st	2nd	3rd	4th
Property	Percent probability of homogeneity			
Log length	-.05	65-75	25-35	25-50
Log basin area	.05-0.1	50-60	60-70	75-90
Log diameter	--.05	95-98	25-35	25-50
Log perimeter	5-10			
Log relief	-.05	-.05	.05-0.1	25-50
Log relief ratio	--.05	-.05	-.05	50-75
Log relative relief	2.5-5			
Log elongation	--.05	--.05	0.5-1.0	50-75
Circularity	--.05			
Log circularity	--.05			
Log drainage density	0.5-1.0	10-25	0.1-0.5	25-50
Log channel frequency	-.05	10-25	0.1-0.5	1-2.5

-.05 should be read as "less than five hundredths percent";--.05 should be read as "much less than five hundredths percent".

TABLE IX

Summary of Analysis of Variance

Order	1st	2nd	3rd	4th
Property	Percent Probability of Equal Means			
Log length	--.05	35-45[1]	40-50	25-50
Log basin area	--.05	-.05	5-10	10-25
Log diameter	--.05	-.05	1-2.5	10-25
Log perimeter	2-3[1]			
Log relief	--.05	--.05	-.05	5-10
Log relief ratio	--.05	--.05	.05-0.1	2.5-5
Log relative relief	30-40			
Log elongation	-.05	90-95	10-20	99-99.5
Circularity	0.5-1.0			
Log circularity	0.1-0.5			
Log drainage density	--.05	--.05	1-2.5	0.5-1
Log channel frequency	--.05	--.05	0.1-0.5	0.5-1

-.05 should be read as "less than five hundredths percent";--.05 should be read as "much less than five hundredths percent".

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1. Probability inference is valid only for underlined values; see text.

TABLE X

Comparison of Numbers of Stream Segments

Bell Canyon

Order	Maxwell	Trew	% Diff.
N_1	386	366	-5.2
N_2	89	90	1.1
N_3	24	25	4.2
N_4	4	4	0
N_5	1	1	
$\bar{R}_b$	4.51	4.48	-0.4

Wolfskill Canyon

Order	Maxwell	Trew	% Diff.
N_1	409	366	-10.5
N_2	96	83	-13.5
N_3	21	17	-19.0
N_4	5	5	0
N_5	1	1	
$\bar{R}_b$	4.51	4.42	-2.0

TABLE XI

Comparison of Mean Lengths of Stream Segments

Bell Canyon				Wolfskill Canyon			
Order	Maxwell	Trew	$s_{\bar{x}}$	Order	Maxwell	Trew	$s_{\bar{x}}$
$\bar{L}_1$	0.0493	0.044	0.0017	$\bar{L}_1$	0.0713	0.081	0.0021
$\bar{L}_2$	0.0839	0.082	0.0063	$\bar{L}_2$	0.1096	0.118	0.0096
$\bar{L}_3$	0.1405	0.147	0.0179	$\bar{L}_3$	0.1910	0.220	0.0291
$\bar{L}_4$	0.3142	0.328	0.0618	$\bar{L}_4$	0.2930	0.274	0.0915
L_5	2.011	2.000		L_5	2.839	2.710	

(lengths in miles)

TABLE XII

Comparison of Mean Basin Areas

Bell Canyon				Wolfskill Canyon			
Order	Maxwell	Trew	$s_{\bar{x}-\bar{y}}$	Order	Maxwell	Trew	$s_{\bar{x}-\bar{y}}$
$\bar{A}_2$	0.00867	0.0086	0.00095	$\bar{A}_2$	0.0156	0.018	0.0020
$\bar{A}_3$	0.0387	0.033	0.0061	$\bar{A}_3$	0.0610	0.070	0.0176
$\bar{A}_4$	0.0854	0.086		$\bar{A}_4$	0.2242	0.236	
A_5	1.357	1.370		A_5	2.4915	2.470	

(areas in square miles)

TABLE XIII

VARIABLES USED IN MULTIPLE CORRELATIONS

Symbol	Definition	Units
Q	Maximum yearly peak discharge	cfs.
P_{60}	Maximum 60-minute precipitation during storm	inches
P_{24}	Maximum 24-hour precipitation during storm	inches
P_7	7-day precipitation prior to date of storm	inches
P_{21}	21-day precipitation prior to date of storm	inches
C_d	Cover density on the watershed	percent
a_5	Fifth order watershed area	sq. miles
d_5	Fifth order watershed diameter	miles
a_2	Mean second order basin area	sq. miles x 10^4
d_2	Mean second order basin diameter	miles x 10^3
h_2	Mean second order relief	feet
D_2	Mean second order drainage density	miles^{-1}
C_2	Mean second order channel frequency	miles^{-1}
R_2	Mean second order relief ratio	x 10^3
R_b	Watershed bifurcation ratio	---
R_l	Watershed length ratio	---
R_a	Watershed area ratio	---
R_d	Watershed diameter ratio	---

TABLE XIV

COEFFICIENTS FOR MULTIPLE CORRELATIONS WITH PEAK DISCHARGE

x_i	b_i	s_b	r_{yx}	b_i	s_b	r_{yx}	b_i	s_b	r_{yx}
k	-238.3	0.039		-5.092	0.039		-4.351	0.039	
P_{24}	1.976	0.161	0.768	2.000	0.164	0.767	2.000	0.164	0.767
C_d	-10.09	1.810	0.480	-8.627	1.693	0.447	-8.579	1.690	0.446
P_{21}	0.281	0.069	0.372	0.282	0.070	0.367	0.282	0.070	0.367
d_5	79.43	34.37	0.221	9.922	5.174	0.185	7.060	1.417	0.439
d_2	153.2	73.86	0.199	11.55	25.02	0.045	8.801	29.04	0.030
D_2	157.5	76.92	0.197	8.983	24.13	0.036	-4.537	2.548	0.172
R_2	-68.97	33.42	0.198	-6.693	14.59	0.045	12.55	29.81	0.041
R_d	320.3	152.3	0.202						
R_a				20.61	37.55	0.054			
h_2							11.29	29.86	0.037
Multiple r		0.8935			0.8891			0.8889	

Estimating equation is of the form:

$$\log Q = k + b_1 \log P_{24} + b_2 \log C_d + b_3 \log P_{21} + b_4 \log a_5$$
$$+ b_5 \log a_2 + b_6 \log D_2 + b_7 \log R_2 + b_8 \log R_a$$

TABLE XIV (continued)

x_i	b_i	s_b	r_{yx}	b_i	s_b	r_{yx}
k	-362.0	0.038		7.786	0.039	
P_{24}	1.967	0.159	0.771	2.001	0.164	0.767
C	-10.64	1.806	0.500	-8.551	1.687	0.445
P_{21}	0.281	0.068	0.376	0.282	0.070	0.366
a_5	76.36	26.08	0.276	6.164	1.921	0.300
a_2	171.5	63.55	0.256	3.895	13.50	0.028
D_2	444.5	163.1	0.258	4.242	7.510	0.055
R_2	-196.6	71.07	0.262	5.926	26.48	0.022
R_a	451.8	166.4	0.257			
h_2				-8.897	24.51	0.036
Multiple r		0.8965			0.8888	

Illustrations

Figure 1. Index map showing relation of San Dimas Experimental Forest to Los Angeles County.

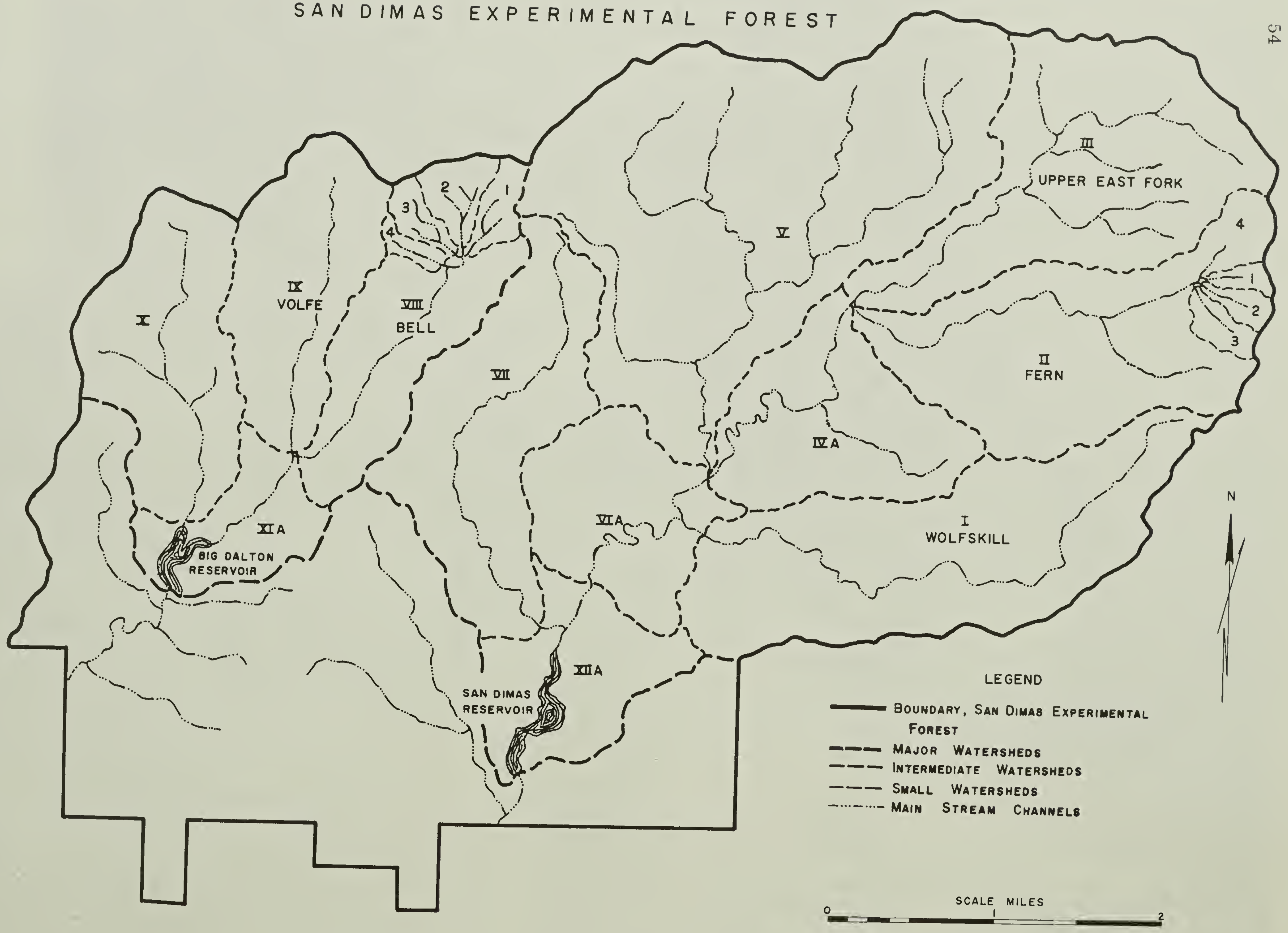


Figure 2. Index map to watersheds of San Dimas Experimental Forest.

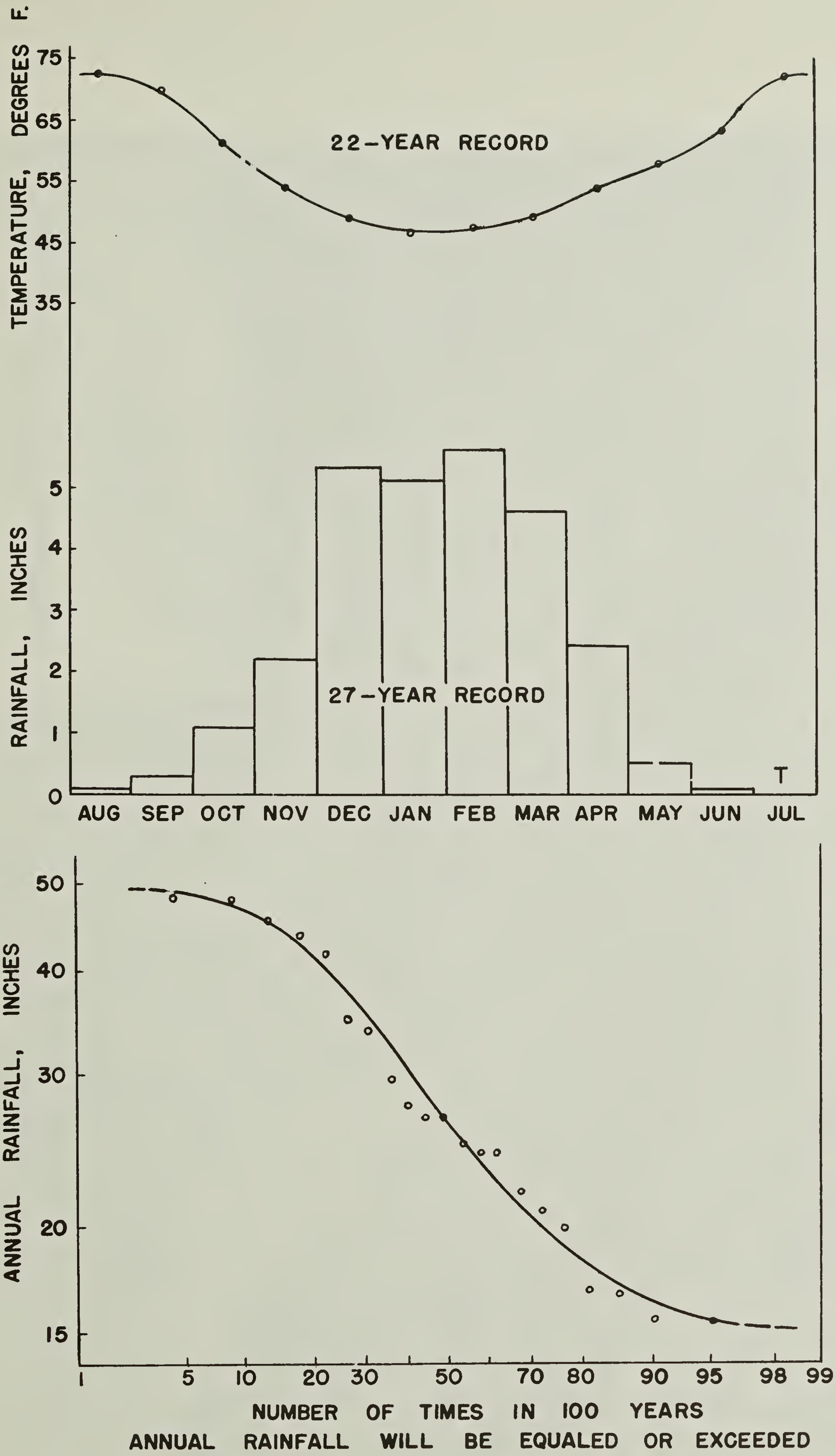


Figure 3. Precipitation and temperature data of Tanbark Flat, San Dimas Experimental Forest.

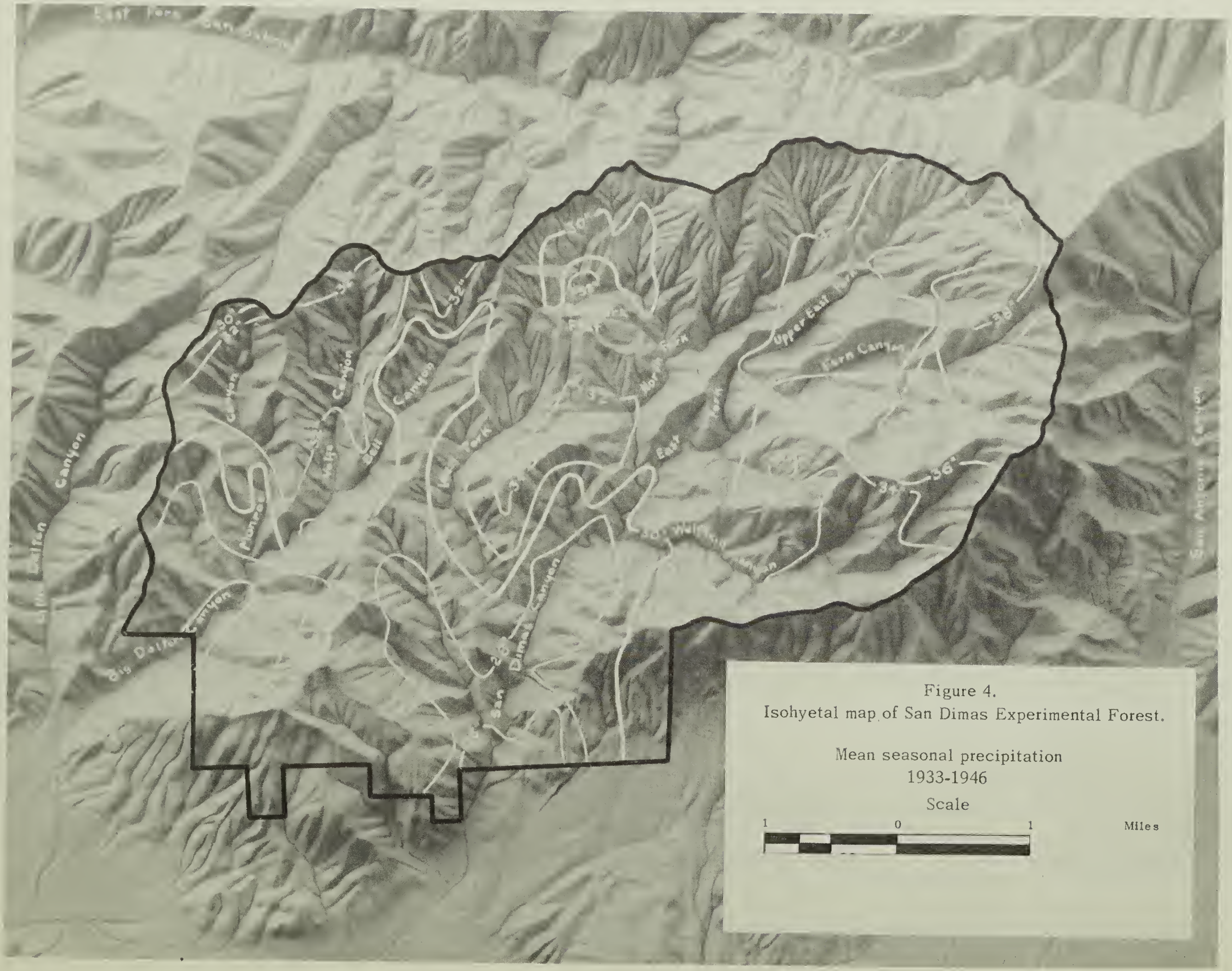


Figure 4.
Isohyetal map of San Dimas Experimental Forest.

Mean seasonal precipitation
1933-1946

Scale

Figure 5. Vegetation types of Southern California.

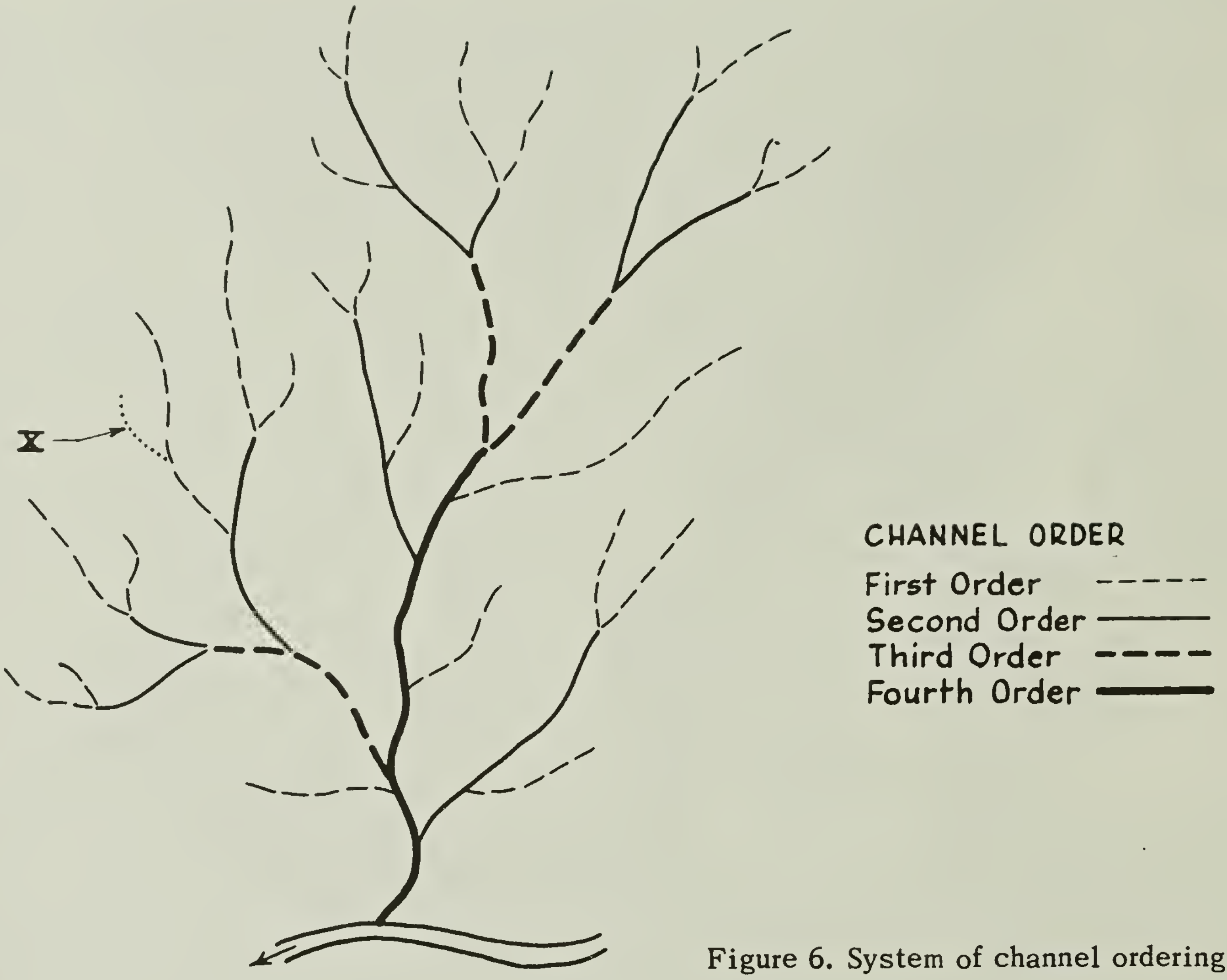
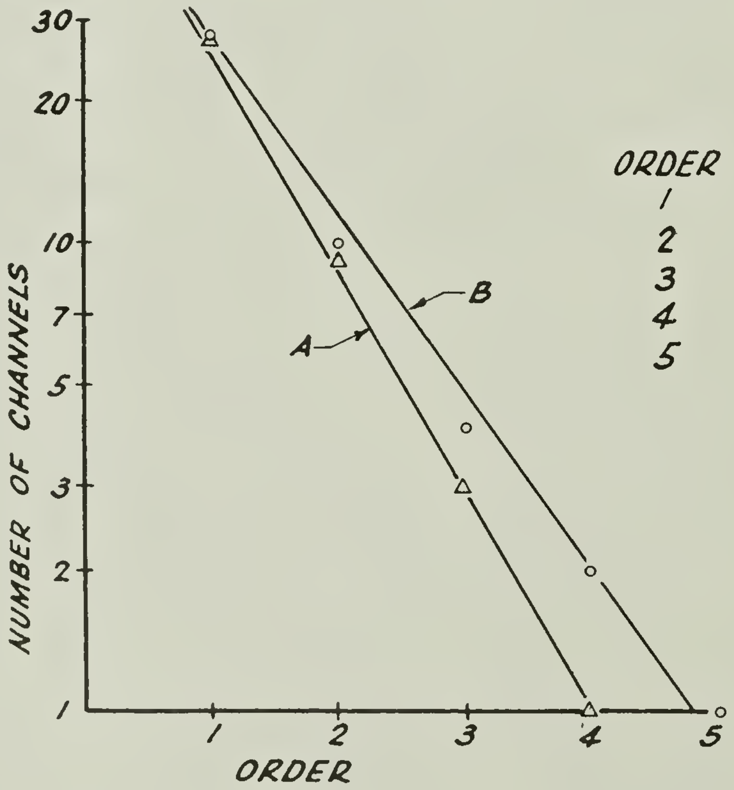


Figure 6. System of channel ordering.

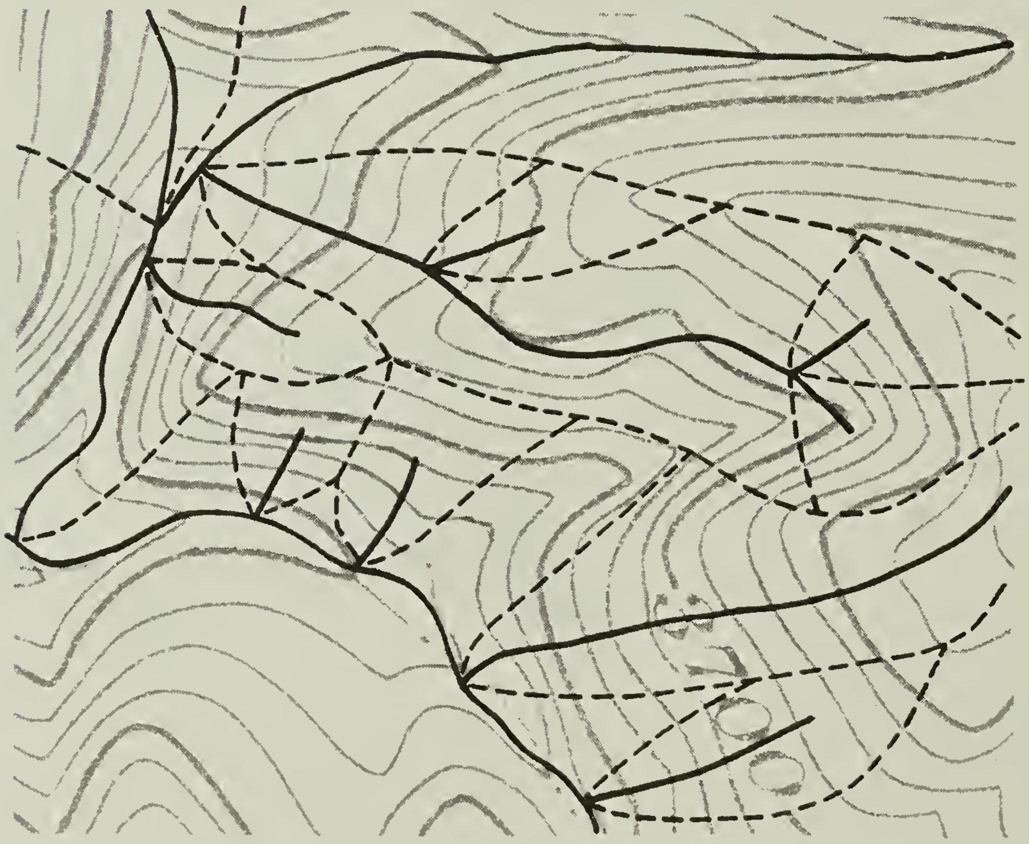


ORDER	NUMBER OF CHANNELS A	NUMBER OF CHANNELS B
1	27	28
2	9	10
3	3	4
4	1	2
5	-	1

Figure 7. Relation of stream numbers to stream order.

Figure 8. Examples of basin diameter determinations.

A. Enlargement of part of Upper East Fork map.



B. Same map showing corrected locations of channels and divides.

Figure 9. Example of relation of observed to mapped topograhic features.

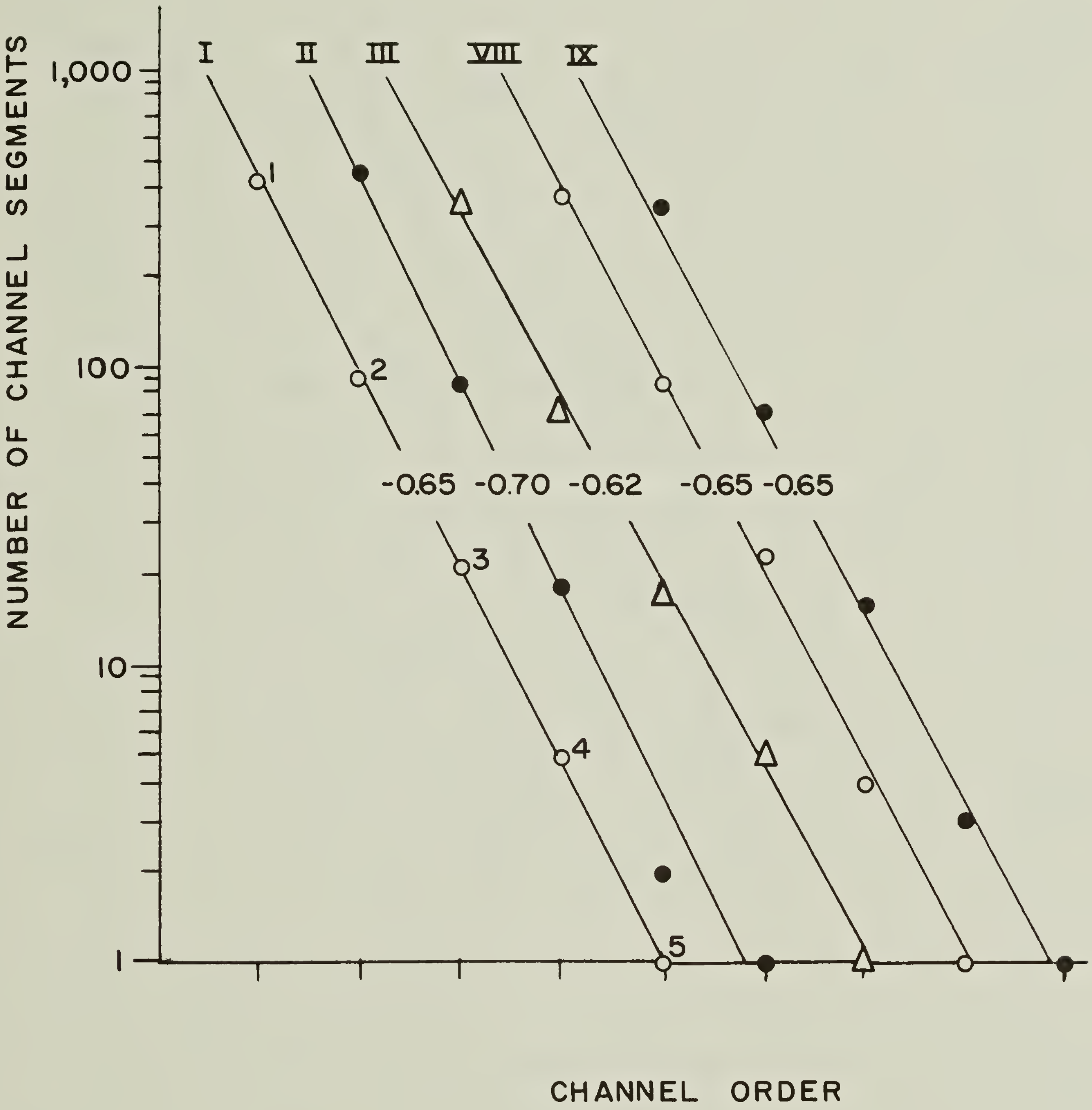


Figure 10. Relation of stream numbers to order.

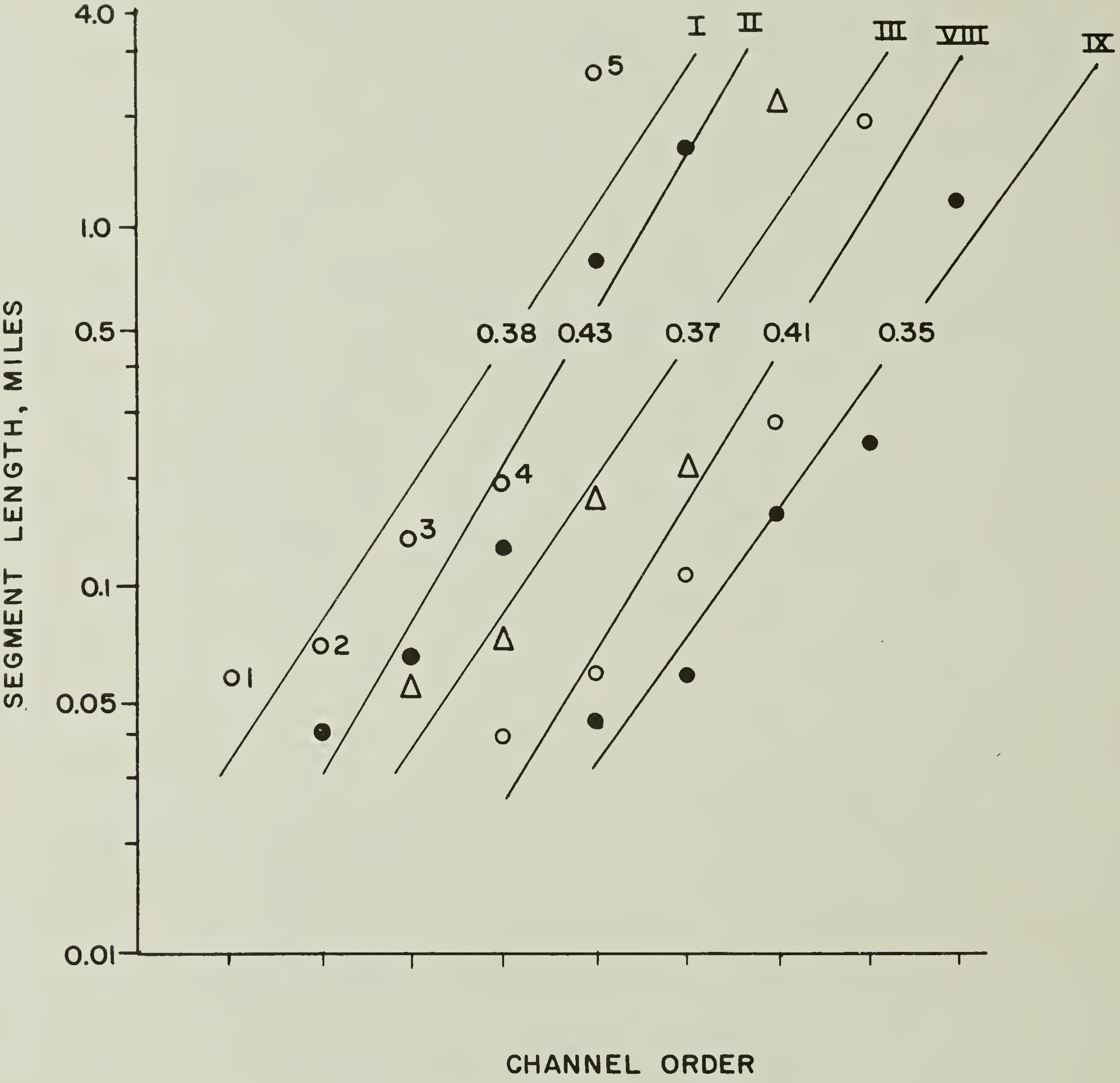


Figure 11. Relation of stream length to order.

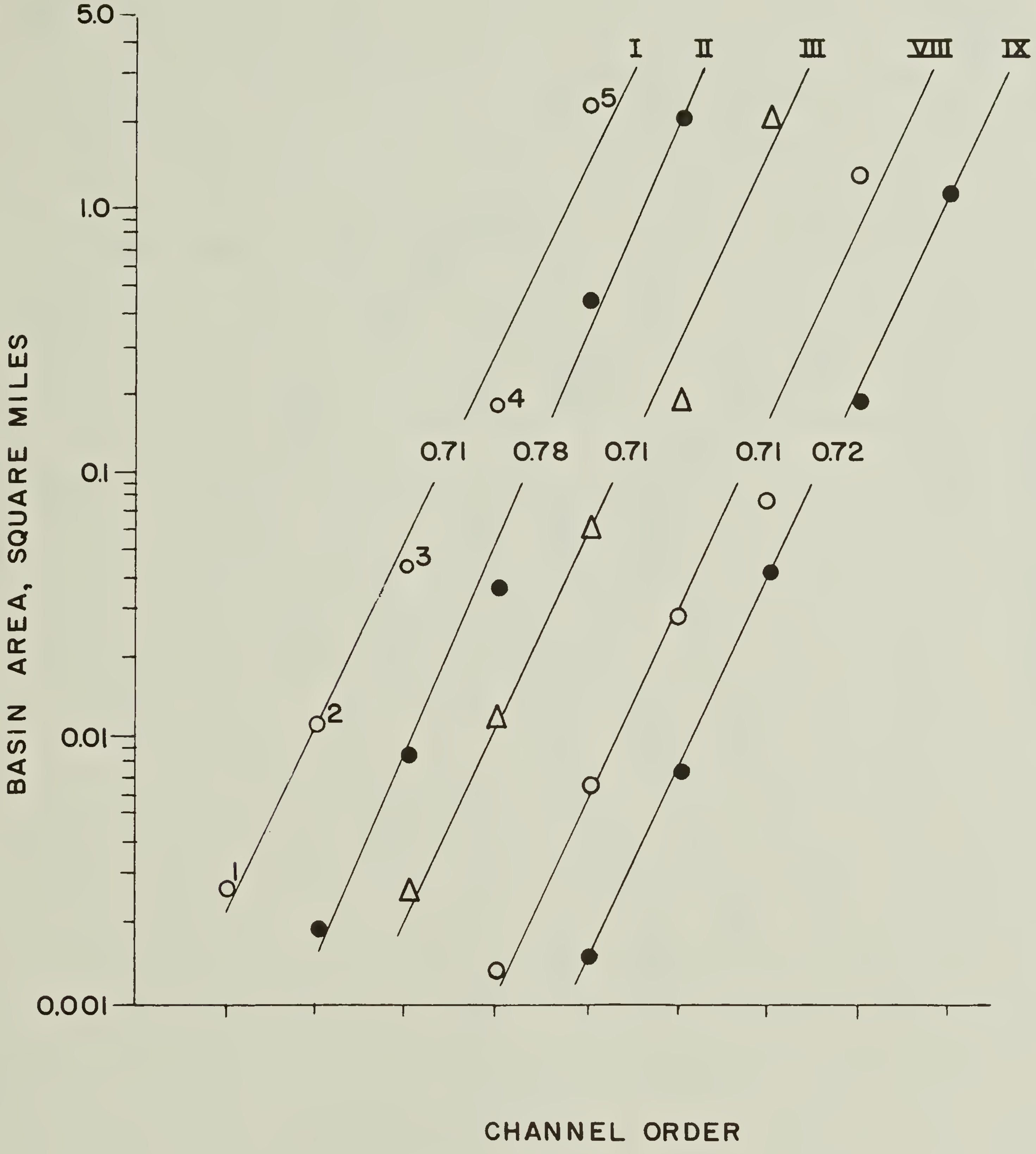


Figure 12. Relation of basin area to order.

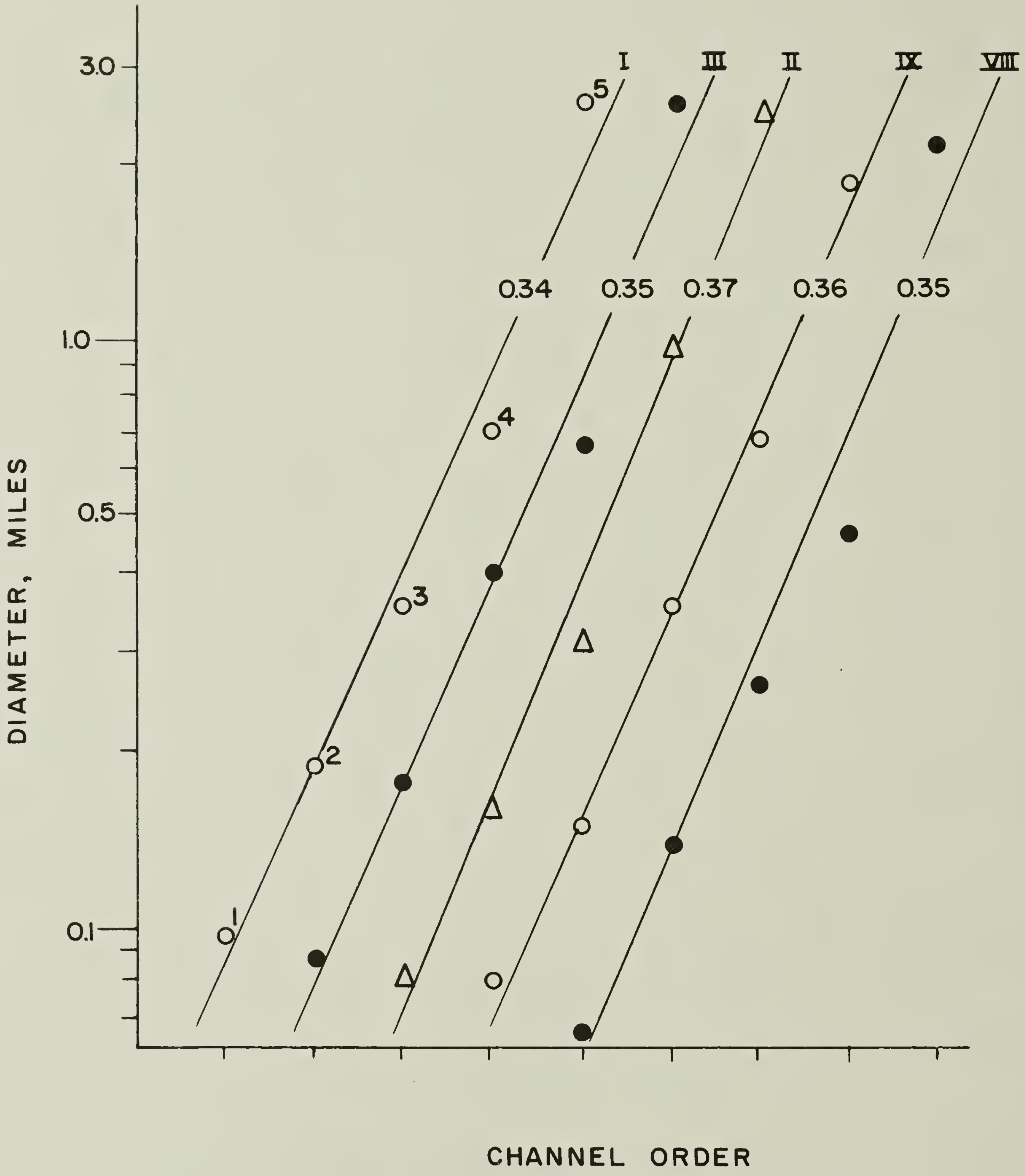


Figure 13. Relation of basin diameter to order.

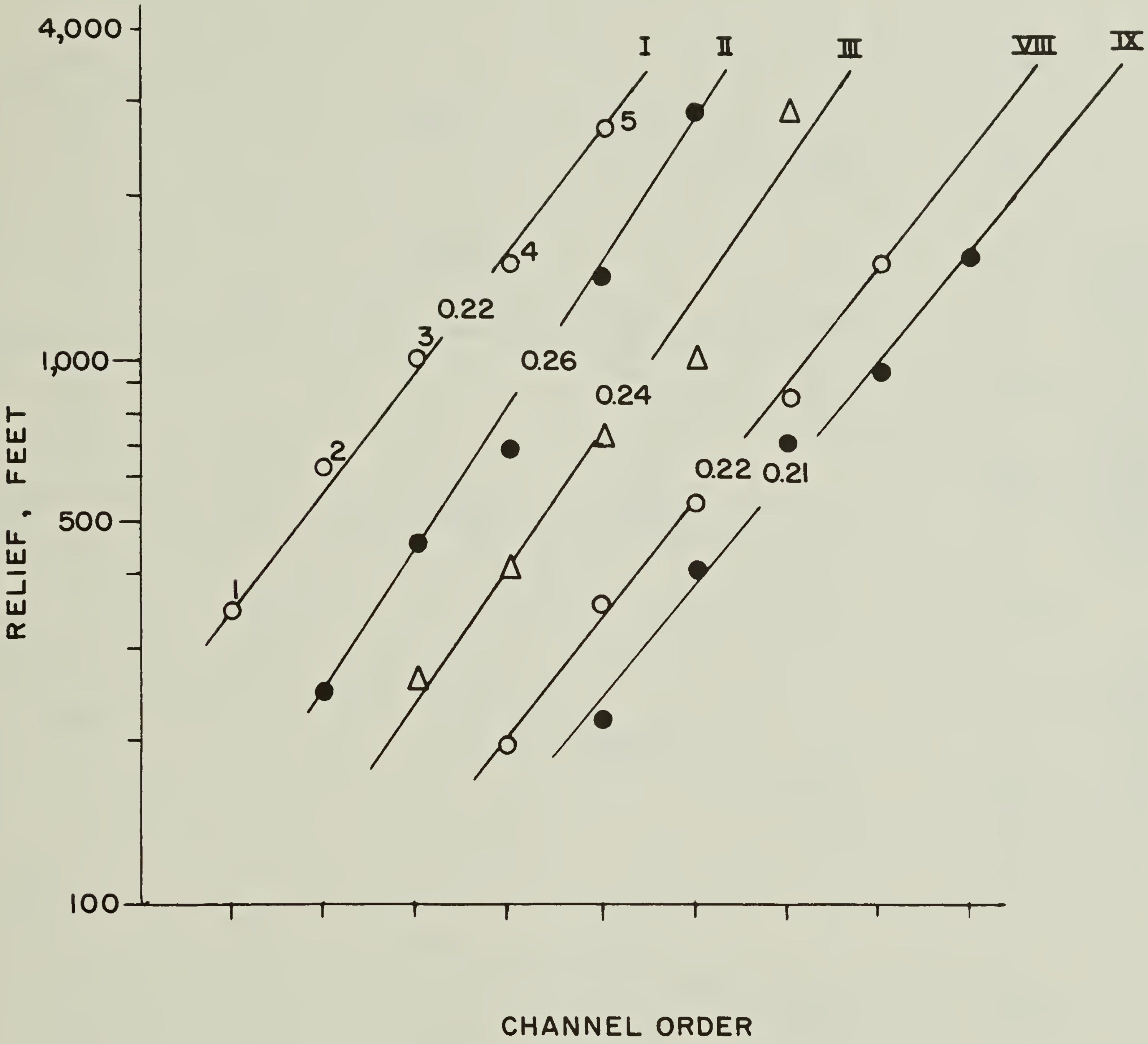


Figure 14. Relation of relief to order.

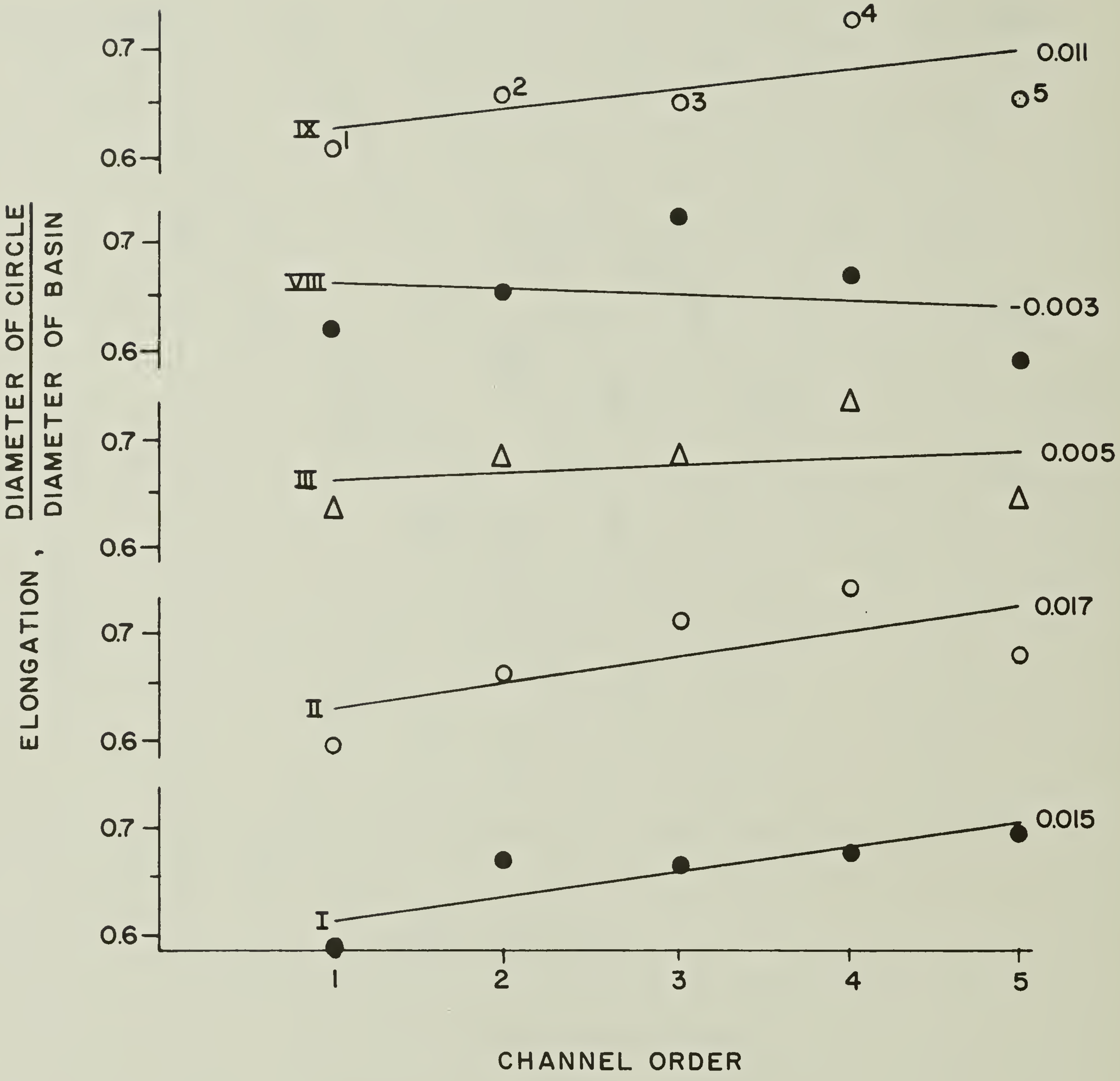


Figure 15. Relation of basin elongation to order.

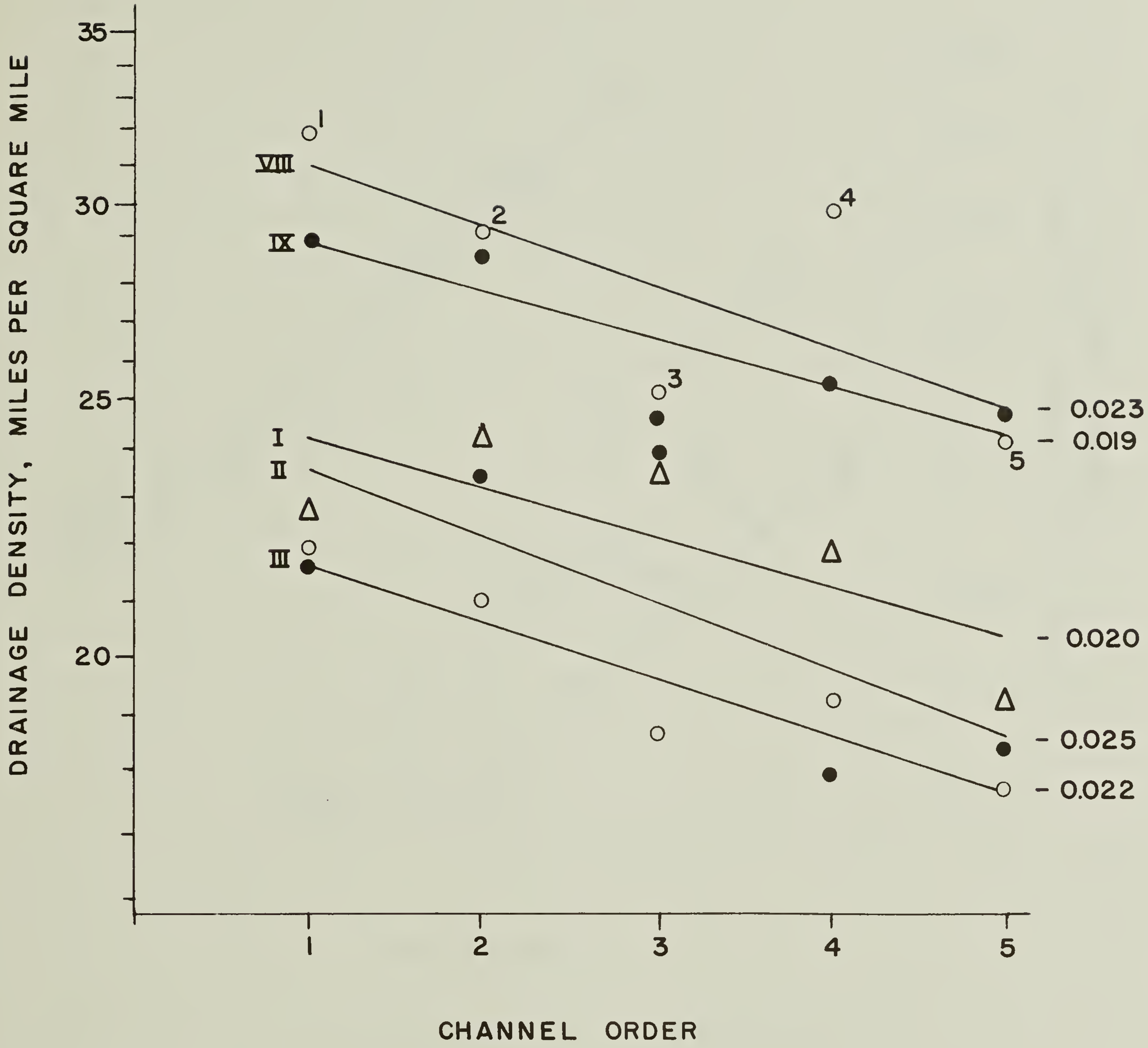


Figure 16. Relation of drainage density to order.

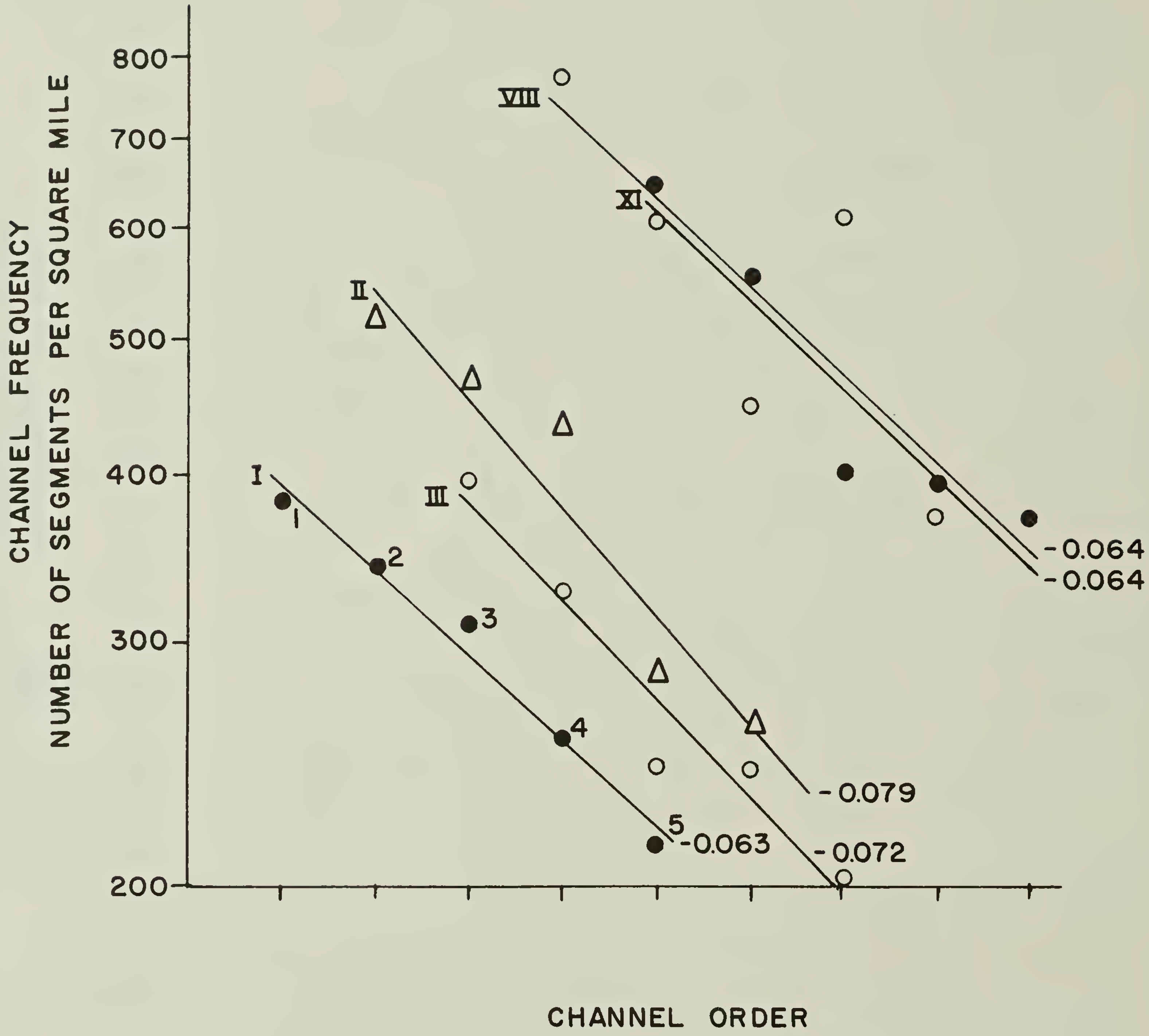


Figure 17. Relation of channel frequency to order.

Appendices

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED I, WOLFSKILL CANYON

Property		First Order Arithmetic	Log[1)]	Second Order Arith	Log	Third Order Arith	Log	Fourth Order Arith	Log
Number		409		96		21		5	
Channel length miles	x̄	.07130	.06013	.10964	.07470	.19095	.14734	.29300	.20136
	s	.04267		.09437		.13337		.20047	
	max	.2650		.479		.467		.482	
	min	.0140		.013		.028		.029	
Area sq. miles	x̄	.003485	.002640	.015633	.011423	.060990	.045195	.22424	.18074
	s	.002771		.013186		.053493		.16136	
	max	.0178		.0683		.2501		.4643	
	min	.0004		.0010		.0083		.0724	
Diameter miles	x̄	.10809	.09840	.20771	.10693	.38671	.35939	.74440	.70915
	s	.04736		.08795		.15016		.26749	
	max	.336		.483		.771		1.156	
	min	.026		.045		.148		.493	
Perimeter[2)] miles	x̄								
	s								
	max								
	min								
Elevation feet	x̄	3324.4	3250.7	3111.9	3040.2	2847.5	2785.8	2778.4	2715.7
	s	704.5		668.3		609.6		643.8	
	max	5140		4367		3935		3390	
	min	1768		1825		1828		1965	
Relief feet	x̄	377.6	340.2	671.8	635.4	1061.0	1018.8	1542.6	1504.7
	s	164.6		207.1		293.4		391.1	
	max	1088		1140		1765		2070	
	min	35		115		460		1193	
Relief ratio	x̄	.68130	.65477	.65705	.64808	.54460	.53689	.40660	.40185
	s	.18043		.18890		.08712		.06607	
	max	1.4906		1.5677		.6540		.4623	
	min	.1285		.3240		.2960		.3006	
Relative[2)] relief	x̄								
	s								
	max								
	min								
Elongation	x̄	.60385	.58927	.65387	.67217	.67130	.66748	.67803	.67646
	s	.14042		.17121		.07105		.05179	
	max	1.6453		1.4690		.7672		.7428	
	min	.3500		.3945		.5366		.6159	
Circularity[2)]	x̄								
	s								
	max								
	min								
Drainage density miles^{-1}	x̄	24.770	22.781	24.687	24.370	25.170	23.713	22.173	21.976
	s	10.005		8.091		10.858		3.361	
	max	59.00		62.00		66.79		27.27	
	min	4.38		7.92		13.44		17.95	
Channel frequency miles^{-2}	x̄	496.6	378.8	420.43	342.93	356.23	309.74	269.43	254.69
	s	382.3		343.52		205.08		109.52	
	max	2500.		3000.0		843.4		455.8	
	min	56.2		78.1		115.1		176.6	

1) Tabulated value is antilog of mean of logarithmic distribution.
2) Not measured in this watershed.

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED II, FERN CANYON

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	Log
Number		465		92		19		2	
Channel length miles	x̄	.05272	.04243	.09464	.06853	.20684	.13756	.87400	.83538
	s	.03705		.08593		.15255		.3592	
	max	.268		.472		.545		1.128	
	min	.005		.011		.005		.620	
Area sq.miles	x̄	.002711	.001952	.012501	.008685	.052500	.038388	.47810	.44413
	s	.002568		.014679		.041273		.2503	
	max	.0174		.0944		.1681		.6551	
	min	.0002		.0014		.0082		.3011	
Diameter miles	x̄	.09270	.08317	.17733	.15843	.35011	.30870	.98350	.98232
	s	.04559		.09397		.17484		.6859	
	max	.291		.573		.747		1.032	
	min	.020		.059		.131		.935	
Perimeter 3) miles	x̄	.28024	.25608						
	s	.13337							
	max	1.133							
	min	.088							
Elevation feet	x̄	4311.6	4253.0	4110.2	4042.8	4073.4	4012.5	4025.0	4025.0
	s	678.8		727.2		703.5		0	
	max	5260		5065		4909		4025	
	min	2650		2742		2912		4025	
Relief feet	x̄	287.8	246.7	515.6	456.0	790.0	695.7	1306.0	1304.8
	s	161.2		250.6		365.9		792	
	max	1015		1222		1516		1362	
	min	35		98		156		1250	
Relief ratio	x̄	.59975	.56170	.58762	.54514	.48236	.42682	.2526	.25156
	s	.22163		.24252		.26667		.1038	
	max	1.3658		1.4714		1.1340		.2758	
	min	.1155		.2249		.2172		.2294	
Relative 3) relief	x̄	.21924	.20381						
	s	.08012							
	max	.4439							
	min	.0304							
Elongation	x̄	.61527	.59939	.67885	.66363	.72795	.71617	.7735	.76552
	s	.13872		.15245		.14636		.1574	
	max	1.2613		1.2904		1.2080		.8848	
	min	.1491		.3945		.5689		.6622	
Circularity 3)	x̄	.55542	.50917						
	s	.19158							
	max	1.5303							
	min	.0078							
Drainage density miles^{-1}	x̄	24.418	21.737	24.902	23.542	24.708	24.065	18.17	18.128
	s	15.516		8.432		5.896		1.68	
	max	206.00		52.86		36.83		19.36	
	min	5.52		9.59		16.52		16.98	
Channel frequency miles^{-2}	x̄	686.4	512.3	575.14	466.72	489.93	432.56	288.5	285.32
	s	553.1		397.55		240.12		60.4	
	max	5000.		2142.9		975.6		331.2	
	min	57.5		84.7		160.6		245.8	

3) N = 150

Characteristic Values of Geomorphic Properties

WATERSHED III, UPPER EAST FORK

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	Log
Number		347		70		17		5	
Channel length miles	$\bar{x}$	.06808	.05607	.10446	.07386	.23818	.18136	.31440	.22605
	s	.04800		.08367		.16399		.22990	
	max	.334		.447		.559		.593	
	min	.014		.008		.025		.070	
Area sq.miles	$\bar{x}$	.003612	.002542	.016713	.011716	.078694	.06143	.25876	.19121
	s	.003418		.017395		.058967		.21296	
	max	.0238		.1051		.2245		.5526	
	min	.0003		.0020		.0221		.0669	
Diameter miles	$\bar{x}$	.10223	.08968	.19859	.13977	.44141	.40654	.72300	.66609
	s	.05468		.09680		.18448		.31949	
	max	.312		.475		.823		1.120	
	min	.025		.058		.199		.393	
Perimeter miles	$\bar{x}$	.26360	.23753						
	s	.12756							
	max	.834							
	min	.087							
Elevation feet	$\bar{x}$	3925.1	3882.5	3795.1	3752.7	3808.9	3800.2	3710.8	3706.7
	s	564.6		553.5		264.0		191.4	
	max	5120		4755		4243		3882	
	min	2583		2660		3272		3405	
Relief feet	$\bar{x}$	298.7	253.2	482.0	412.4	809.0	731.8	1084.0	1014.1
	s	172.2		256.0		356.4		449.0	
	max	928		1195		1495		1595	
	min	54		50		328		720	
Relief ratio	$\bar{x}$	.56400	.53475	.47058	.43896	.36182	.34090	.29223	.28835
	s	.19447		.18255		.13392		.05363	
	max	1.4529		1.0004		.6426		.3720	
	min	.2110		.1064		.1697		.2246	
Relative relief	$\bar{x}$	.21562	.20190						
	s	.08086							
	max	.7024							
	min	.0628							
Elongation	$\bar{x}$	.64773	.63129	.70000	.68639	.70635	.68856	.74355	.74077
	s	.13425		.14226		.16881		.07165	
	max	1.0832		1.1673		1.0211		.8451	
	min	.3504		.3959		.5024		.6427	
Circularity	$\bar{x}$	.58000	.56610						
	s	.12446							
	max	.9756							
	min	.2945							
Drainage density miles^{-1}	$\bar{x}$	24.030	22.062	22.093	21.022	19.234	18.727	19.726	19.265
	s	10.031		7.350		4.665		4.795	
	max	76.67		49.79		29.55		25.72	
	min	3.66		11.60		12.77		14.97	
Channel frequency miles^{-2}	$\bar{x}$	543.3	393.4	404.70	328.48	263.63	242.90	258.26	237.54
	s	455.0		276.48		107.44		111.83	
	max	3333.		1500.0		489.5		379.7	
	min	42.0		68.6		115.8		137.2	

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED VIII, BELL CANYON

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	Log
Number		386		89		24		4	
Channel length miles	$\bar{x}$	.04928	.04111	.08388	.06045	.14054	.11279	.31425	.29789
	s	.03267		.05940		.08762		.12369	
	max	.255		.229		.332		.486	
	min	.011		.004		.023		.220	
Area sq. miles	$\bar{x}$	.001681	.001315	.008668	.006664	.038683	.029583	.085350	.080223
	s	.001483		.006074		.023795		.032092	
	max	.0136		.0288		.0803		.1202	
	min	.0002		.0006		.0030		.0453	
Diameter miles	$\bar{x}$	.07302	.06728	.15330	.13976	.28400	.26390	.49075	.47467
	s	.03452		.06243		.09857		.14665	
	max	.274		.332		.450		.668	
	min	.014		.028		.094		.361	
Perimeter 4) miles	$\bar{x}$	.22783	.21292						
	s	.09651							
	max	.604							
	min	.101							
Elevation feet	$\bar{x}$	2677.1	2677.7	2529.6	2505.3	2443.8	2415.6	2551.2	2549.7
	s	341.6		351.5		381.7		103.0	
	max	3525		3535		2965		2640	
	min	2222		2270		1920		2450	
Relief feet	$\bar{x}$	213.7	194.5	380.2	354.7	577.2	557.8	870.0	861.3
	s	94.2		139.2		148.5		142.0	
	max	750		735		880		1000	
	min	40		80		290		735	
Relief ratio	$\bar{x}$	.57979	.56607	.50071	.48068	.41401	.40033	.34638	.34365
	s	.15954		.15235		.10713		.04869	
	max	1.0062		1.1685		.6017		.3856	
	min	.2296		.2658		.2268		.2793	
Relative 4) relief	$\bar{x}$	.22826	.21903						
	s	.06467							
	max	.3758							
	min	.1084							
Elongation	$\bar{x}$	.62841	.62210	.67204	.65903	.74069	.73542	.68114	.67330
	s	.13789		.14621		.09326		.12506	
	max	1.2017		1.2774		.9778		.8651	
	min	.1835		.4546		.6251		.5856	
Circularity 4)	$\bar{x}$	.51749	.50182						
	s	.12200							
	max	.7873							
	min	.2463							
Drainage density miles^{-1}	$\bar{x}$	35.526	32.114	31.122	29.360	26.310	24.804	30.190	30.060
	s	23.476		11.267		9.342		3.221	
	max	307.50		71.05		48.33		34.08	
	min	9.00		13.75		13.30		26.38	
Channel frequency miles^{-2}	$\bar{x}$	996.9	775.5	766.68	605.46	572.46	442.46	619.80	610.16
	s	802.6		676.51		505.84		126.45	
	max	5000.		5000.0		2333.3		772.6	
	min	73.5		183.5		137.0		483.4	

4) N = 53

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED IX, VOLFE CANYON

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	Log
Number		344		73		16		3	
Channel length miles	$\bar{x}$	.05087	.04495	.08730	.06304	.21388	.16796	.30300	.25638
	s	.02644		.07295		.12649		.21257	
	max	.158		.439		.443		.541	
	min	.013		.009		.018		.132	
Area sq. miles	$\bar{x}$	.001932	.001542	.009649	.007723	.049050	.042478	.21903	.19599
	s	.001437		.007175		.024857		.13321	
	max	.0083		.0479		.1033		.3728	
	min	.0003		.0013		.0129		.1386	
Diameter miles	$\bar{x}$	.07871	.07290	.16438	.15392	.37062	.35719	.68333	.68016
	s	.03084		.06851		.10023		.08182	
	max	.189		.405		.539		.774	
	min	.021		.049		.217		.615	
Perimeter 5) miles	$\bar{x}$								
	s								
	max								
	min								
Elevation feet	$\bar{x}$	2670.1	2646.3	2578.5	2553.0	2377.3	2360.0	2349.3	2348.0
	s	347.8		356.9		293.7		96.4	
	max	3250		3108		2839		2405	
	min	1900		1890		1882		2238	
Relief feet	$\bar{x}$	239.2	220.3	438.7	411.1	738.2	718.8	989.0	972.5
	s	96.3		150.1		169.2		212.6	
	max	555		835		998		1157	
	min	35		107		473		750	
Relief ratio	$\bar{x}$	.58756	.57224	.52775	.51762	.38350	.38111	.28049	.27080
	s	.13818		.11102		.04498		.08401	
	max	1.4250		1.0273		.4823		.3315	
	min	.1184		.3506		.3087		.1835	
Relative 5) relief	$\bar{x}$								
	s								
	max								
	min								
Elongation	$\bar{x}$	.61885	.60774	.67165	.65927	.66519	.65109	.74200	.73447
	s	.11571		.14020		.14842		.13231	
	max	1.0396		1.3385		1.0723		.8901	
	min	.1602		.4518		.4815		.6355	
Circularity 5)	$\bar{x}$								
	s								
	max								
	min								
Drainage density miles^{-1}	$\bar{x}$	31.724	29.152	30.101	28.852	25.577	25.413	25.682	25.655
	s	20.100		8.928		3.057		1.446	
	max	346.67		51.94		33.35		27.30	
	min	5.32		15.60		20.22		24.52	
Channel frequency miles^{-2}	$\bar{x}$	803.3	648.6	637.99	553.07	407.18	398.42	392.33	392.31
	s	554.6		417.29		90.03		4.06	
	max	3333.		3076.9		620.2		396.8	
	min	120.5		187.8		274.5		388.9	

5) Not measured in this watershed

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED II-1, FERN NUMBER ONE

Property		First Order		Second Order		Third Order
		Arithmetic	Log	Arith	Log	Arith
Number		19		3		1
Channel length miles	x̄	.02516	.01902	.05233	.04004	.359
	s	.01734		.04761		
	max	.058		.107		
	min	.005		.020		
Area sq. miles	x̄	.001563	.001262	.006867	.006095	.0544
	s	.001302		.003630		
	max	.0062		.0102		
	min	.0006		.0030		
Diameter miles	x̄	.06747	.06556	.11733	.11078	.408
	s	.01665		.04528		
	max	.107		.157		
	min	.040		.068		
Perimeter miles	x̄	.17879	.17288	.33300	.32319	1.102
	s	.04947		.09714		
	max	.313		.427		
	min	.111		.233		
Elevation feet	x̄	4947.5	4945.0	5035.3	5034.7	4610
	s	163.0		112.0		
	max	5180		5100		
	min	4730		4906		
Relief feet	x̄	202.6	196.7	306.7	301.7	727
	s	50.2		65.4		
	max	286		363		
	min	128		235		
Relief ratio	x̄	.57425	.56831	.52421	.51631	.33747
	s	.08395		.11482		
	max	.7244		.6545		
	min	.3983		.4379		
Relative relief	x̄	.22082	.21552	.17731	.17687	.12494
	s	.04636		.15173		
	max	.2974		.1910		
	min	.1248		.1610		
Elongation	x̄	.62378	.61140	.79968	.79522	.64505
	s	.13072		.09650		
	max	.9122		.9089		
	min	.4433		.7259		
Circularity	x̄	.54158	.53059	.73553	.73373	.56292
	s	.11198		.06392		
	max	.7953		.8092		
	min	.3586		.6944		
Drainage density miles^{-1}	x̄	18.186	15.077	14.091	13.885	18.272
	s	12.054		2.975		
	max	48.75		17.25		
	min	6.67		11.35		
Channel frequency miles^{-2}	x̄	928.5		631.87	583.56	422.79
	s	494.8		321.62		
	max	1667.		1000.0		
	min	172.4		405.4		

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED II-2, FERN NUMBER TWO

Property		First Order		Second Order		Third Order
		Arithmetic	Log	Arith	Log	Arith
Number		22		4		1
Channel length miles	$\bar{x}$	.02605	.02112	.05050	.03722	.444
	s	.01836		.02910		
	max	.082		.068		
	min	.006		.007		
Area sq. miles	$\bar{x}$	.001445	.001124	.005600	.004529	.0655
	s	.001263		.003214		
	max	.0060		.0083		
	min	.0005		.0013		
Diameter miles	$\bar{x}$	.07282	.06740	.10325	.10199	.486
	s	.02893		.01850		
	max	.135		.124		
	min	.032		.082		
Perimeter miles	$\bar{x}$	.17800	.16960	.31250	.29879	1.243
	s	.05923		.10142		
	max	.343		.404		
	min	.095		.187		
Elevation feet	$\bar{x}$	4975.5	4973.8	4973.2	4972.8	4585
	s	129.1		75.2		
	max	5188		5033		
	min	4750		4877		
Relief feet	$\bar{x}$	231.4	217.0	287.2	281.8	647
	s	82.7		63.7		
	max	386		357		
	min	99		217		
Relief ratio	$\bar{x}$	.61396	.60975	.52812	.52342	.25214
	s	.07522		.08023		
	max	.7935		.6037		
	min	.4934		.4326		
Relative relief	$\bar{x}$	.24698	.24231	.19078	.17866	.09858
	s	.04697		.07393		
	max	.3359		.2562		
	min	.1537		.1017		
Elongation	$\bar{x}$	.58107	.56118	.77165	.74460	.59421
	s	.16122		.23067		
	max	1.0495		1.0490		
	min	.3499		.4961		
Circularity	$\bar{x}$	.50655	.49083	.65207	.63754	.53273
	s	.11824		.15671		
	max	.6962		.8369		
	min	.2671		.4672		
Drainage density miles^{-1}	$\bar{x}$	22.489	18.796	25.286	23.541	18.611
	s	13.027		11.790		
	max	44.44		42.31		
	min	5.00		16.40		
Channel frequency miles^{-2}	$\bar{x}$	1069.0		1005.73	808.72	412.21
	s	582.5		868.97		
	max	2000.		2307.7		
	min	166.7		512.8		

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED II-3, FERN NUMBER THREE

Property		First Order		Second Order
		Arithmetic	Log	Arith
Number		13		1
Channel length miles	$\bar{x}$	.05131	.04458	.489
	s	.02632		
	max	.105		
	min	.014		
Area sq. miles	$\bar{x}$	.003338	.002435	.0856
	s	.002972		
	max	.0118		
	min	.0005		
Diameter miles	$\bar{x}$	.10054	.09753	.557
	s	.02617		
	max	.161		
	min	.060		
Perimeter miles	$\bar{x}$	.25962	.24590	1.349
	s	.09168		
	max	.488		
	min	.126		
Elevation feet	$\bar{x}$	4973.8	4972.1	4525
	s	136.5		
	max	5140		
	min	4735		
Relief feet	$\bar{x}$	303.0	296.7	990
	s	64.4		
	max	402		
	min	219		
Relief ratio	$\bar{x}$	.57930	.57606	.33662
	s	.06276		
	max	.6913		
	min	.4529		
Relative relief	$\bar{x}$	.23499	.22859	.13899
	s	.05611		
	max	.3292		
	min	.1450		
Elongation	$\bar{x}$	.58756	.57084	.59270
	s	.14740		
	max	.9101		
	min	.3723		
Circularity	$\bar{x}$	.51704	.50596	.59110
	s	.10561		
	max	.6829		
	min	.3087		
Drainage density miles^{-1}	$\bar{x}$	19.962	18.312	13.505
	s	8.371		
	max	36.00		
	min	8.90		
Channel frequency miles^{-2}	$\bar{x}$	564.9		163.55
	s	527.8		
	max	2000		
	min	84.7		

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED II-4, FERN ADDITIONALS

Property		First Order		Second Order		Third Order		
		Arithmetic	Log	Arith	Log	Arith	Log	
Number		70		13		4		
Channel length miles	$\bar{x}$	.03406	.02730	.08662	.06907	.08650	.04172	
	s	.02316		.05755		.07751		
	max	.128		.205		.182		
	min	.007		.020		.003		
Area sq.miles	$\bar{x}$	.001201	.000970	.007623	.005598	.023775	.019269	
	s	.000849		.007283		.017795		
	max	.0042		.0279		.0491		
	min	.0002		.0022		.0078		
Diameter miles	$\bar{x}$	.06404	.05999	.13546	.12582	.19850	.18091	
	s	.02364		.05343		.09660		
	max	.139		.238		.315		
	min	.030		.071		.109		
Perimeter miles	$\bar{x}$	.16466	.15604	.37562	.34908	.68150	.64921	
	s	.05469		.15893		.23663		
	max	.328		.751		.972		
	min	.069		.229		.404		
Elevation feet	$\bar{x}$	4948.0	4945.1	4853.8	4852.2	4827.2	4826.1	
	s	168.4		124.7		119.3		
	max	5184		4953		4920		
	min	4515		4550		4670		
Relief feet	$\bar{x}$	188.4	175.3	305.3	281.2	364.2	325.1	
	s	69.6		108.7		172.8		
	max	393		440		551		
	min	56		79		140		
Relief ratio	$\bar{x}$	.56609	.55342	.43821	.42325	.35151	.34038	
	s	.11182		.10749		.10496		
	max	.8092		.5619		.4953		
	min	.2165		.2107		.2433		
Relative relief	$\bar{x}$	.22120	.21277	.16177	.15256	.10838	.09485	
	s	.55613		.50654		.52604		
	max	.3486		.2365		.1594		
	min	.0593		.0603		.0362		
Elongation	$\bar{x}$	.59586	.58577	.68238	.67102	.92060	.86578	
	s	.11419		.12774		.40163		
	max	.9956		.8990		1.5108		
	min	.3637		.4592		.6112		
Circularity	$\bar{x}$	.51013	.50057	.58415	.57733	.57730	.57451	
	s	.09597		.08801		.06527		
	max	.7124		.7176		.6531		
	min	.2671		.3809		.4995		
Drainage density miles^{-1}	$\bar{x}$	30.471	28.150	29.630	28.681	30.805	30.355	
	s	12.167		7.277		6.411		
	max	64.29		42.35		40.26		
	min	8.24		14.29		26.27		
Channel frequency miles^{-2}	$\bar{x}$	1267.7		919.41	786.35	755.07	725.91	
	s	871.2		489.87		241.35		
	max	5000.		1818.2		1025.6		
	min	238.1		186.3		516.4		

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED VIII-1, BELL NUMBER ONE

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	
Number		55		9		2		1	
Channel length miles	$\bar{x}$	.03936	.03544	.09000	.04358	.03800	.03571	.531	
	s	.01879		.09176					
	max	.103		.262					
	min	.014		.002					
Area sq. miles	$\bar{x}$	.000955	.000805	.007689	.004634	.015950	.009449	.1219	
	s	.000660		.007138					
	max	.0041		.0214					
	min	.0003		.0011					
Diameter miles	$\bar{x}$	.05735	.05457	.13544	.11416	.14100	.12513	.679	
	s	.01832		.08037					
	max	.101		.259					
	min	.030		.050					
Perimeter miles	$\bar{x}$	.14807	.14275	.35433	.30531	.34050	.32374	1.669	
	s	.04185		.19763					
	max	.284		.692					
	min	.079		.136					
Elevation feet	$\bar{x}$	2916.0	2909.9	2734.1	2728.7	2947.0	2947.0	2446	
	s	189.1		183.8					
	max	3224		3006					
	min	2518		2554					
Relief feet	$\bar{x}$	203.2	197.1	441.0	363.7	346.5	332.2	992	
	s	50.9		283.3					
	max	315		893					
	min	122		177					
Relief ratio	$\bar{x}$	.69487	.68445	.64287	.60341	.51358	.50284	.27670	
	s	.13339		.24261					
	max	1.4099		1.0890					
	min	.4256		.3382					
Relative relief	$\bar{x}$	.26503	.26150	.24032	.22562	.19442	19434	.11257	
	s	.04265		.09405					
	max	.3487		.4320					
	min	.1668		.1315					
Elongation	$\bar{x}$	.59832	.58706	.67711	.67287	.87811	.87661	.58021	
	s	.12243		.07612					
	max	1.0858		.7606					
	min	.3799		.5024					
Circularity	$\bar{x}$	.50636	.49648	.63038	.62472	.94367	1.13288	.54992	
	s	.09619		.08863					
	max	.7587		.7474					
	min	.2077		.5038					
Drainage density miles^{-1}	$\bar{x}$	46.654	44.019	40.853	38.644	43.907	43.105	29.385	
	s	15.918		14.933					
	max	84.00		62.73					
	min	22.00		26.39					
Channel frequency miles^{-2}	$\bar{x}$	1425.9		1338.96	1050.84	1493.62	1283.16	549.55	
	s	714.7		996.91					
	max	3333.		2727.3					
	min	243.9		451.1					

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED VIII-2, BELL NUMBER TWO

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	Log
Number		75		16		5		2	
Channel length miles	$\bar{x}$	.03963	.03533	.05438	.02758	.08400	.06600	.23950	.23893
	s	.02074		.04765		.06626			
	max	.118		.141		.192			
	min	.012		.000		.026			
Area sq. miles	$\bar{x}$	.001040	.000824	.004750	.003490	.016080	.013103	.063100	.060596
	s	.000863		.003640		.008876			
	max	.0049		.0121		.0275			
	min	.0002		.0008		.0032			
Diameter miles	$\bar{x}$	.05896	.05536	.10912	.09896	.18100	.16962	.37800	.37800
	s	.02134		.05132		.06973			
	max	.133		.244		.283			
	min	.022		.041		.090			
Perimeter miles	$\bar{x}$	.15057	.14310	.28725	.26494	.51140	.48799	1.0880	1.0780
	s	.05022		.11685		.16108			
	max	.326		.525		.721			
	min	.068		.117		.272			
Elevation feet	$\bar{x}$	2985.8	2979.9	2940.5	2936.8	2879.4	2878.6	2657.0	2657.0
	s	187.5		149.1		76.0			
	max	3282		3078		2939			
	min	2533		2598		2753			
Relief feet	$\bar{x}$	206.0	194.0	338.4	319.8	496.0	486.2	720.0	719.5
	s	71.0		113.1		105.6			
	max	375		577		620			
	min	90		174		340			
Relief ratio	$\bar{x}$	.67254	.66377	.62146	.61209	.55195	.54296	.36079	.36050
	s	.11099		.11174		.11239			
	max	1.0743		.8163		.7155			
	min	.4486		.4479		.4149			
Relative relief	$\bar{x}$	.26178	.25678	.23286	.22863	.19081	.18872	.12831	.12640
	s	.05201		.04500		.03200			
	max	.4551		.2885		.2367			
	min	.1526		.1537		.1587			
Elongation	$\bar{x}$	.59274	.58503	.69001	.67362	.76527	.76150	.74210	.73483
	s	.09643		.15305		.08487			
	max	.9149		.9854		.8738			
	min	.4024		.3936		.6612			
Circularity	$\bar{x}$	.51601	.50551	.63221	.62483	.69815	.69145	.65530	.65524
	s	.10226		.10113		.10552			
	max	.7967		.8246		.8164			
	min	.2905		.5011		.5435			
Drainage density miles^{-1}	$\bar{x}$	46.196	42.892	41.336	39.090	37.167	36.527	32.956	32.940
	s	17.849		13.723		8.346			
	max	95.00		60.75		51.88			
	min	13.81		21.23		32.17			
Channel frequency miles^{-2}	$\bar{x}$	1496.3		1411.27	1149.97	1042.01	929.60	700.60	697.23
	s	1065.5		991.84		646.75			
	max	5000.		3750.0		2187.5			
	min	204.1		461.5		685.7			

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED VIII-3, BELL NUMBER THREE

Property		First Order		Second Order		Third Order		Fourth Order	
		Arithmetic	Log	Arith	Log	Arith	Log	Arith	
Number		39		6		2		1	
Channel length miles	$\bar{x}$	.04079	.03681	.11483	.10492	.11300	.10776	.315	
	s	.01866		.06346					
	max	.099		.243					
	min	.012		.074					
Area sq. miles	$\bar{x}$	.001062	.000933	.008900	.008028	.025850	.025372	.0979	
	s	.000558		.005269					
	max	.0026		.0195					
	min	.0003		.0056					
Diameter miles	$\bar{x}$	.06328	.06009	.17917	.17090	.24500	.24418	.545	
	s	.02033		.06769					
	max	.106		.312					
	min	.025		.134					
Perimeter miles	$\bar{x}$	.16038	.15413	.39183	.39043	.68350	.68192	1.387	
	s	.04423		.03632					
	max	.254		.438					
	min	.076		.346					
Elevation feet	$\bar{x}$	3007.9	2997.6	2965.8	2960.0	2852.0	2852.0	2469	
	s	249.0		197.3					
	max	3308		3079					
	min	2543		2467					
Relief feet	$\bar{x}$	204.9	195.6	467.2	455.9	579.5	578.0	1031	
	s	61.2		118.2					
	max	341		683					
	min	64		332					
Relief ratio	$\bar{x}$	.62418	.61650	.50838	.50523	.44834	.44832	.35828	
	s	.09755		.06067					
	max	.8672		.5767					
	min	.3869		.4146					
Relative relief	$\bar{x}$	.24479	.24034	.22547	.22115	.16054	.16053	.14078	
	s	.04464		.04651					
	max	.3428		.2953					
	min	.1302		.1486					
Elongation	$\bar{x}$	.58265	.57344	.59777	.59158	.73615	.73606	.64781	
	s	.10381		.09659					
	max	.8399		.7569					
	min	.3711		.5050					
Circularity	$\bar{x}$	.50842	.49324	.69750	.66180	.68678	.68564	.63950	
	s	.12426		.28670					
	max	.8057		1.2773					
	min	.2488		.5363					
Drainage density miles^{-1}	$\bar{x}$	42.106	39.479	32.533	32.086	29.510	29.446	28.815	
	s	15.302		5.852					
	max	86.67		39.43					
	min	15.62		25.23					
Channel frequency miles^{-2}	$\bar{x}$	1227.0		657.65	616.53	547.68	543.29	490.30	
	s	696.0		251.60					
	max	3333.		1000.0					
	min	384.6		359.0					

APPENDIX I

Characteristic Values of Geomorphic Properties

WATERSHED VIII-4, BELL NUMBER FOUR

Property		First Order		Second Order		Third Order
		Arithmetic	Log	Arith	Log	Arith
Number		13		3		1
Channel length miles	$\bar{x}$	.04107	.03451	.09367	.05175	.256
	s	.02550		.11904		
	max	.095		.231		
	min	.012		.020		
Area sq. miles	$\bar{x}$	.002071	.001703	.011200	.006683	.0617
	s	.001260		.013450		
	max	.0042		.0267		
	min	.0005		.0026		
Diameter miles	$\bar{x}$	.07336	.06921	.13600	.12323	.447
	s	.02539		.07405		
	max	.125		.218		
	min	.035		.074		
Perimeter miles	$\bar{x}$	.18850	.17905	.39833	.35201	1.191
	s	.06248		.25203		
	max	.318		.687		
	min	.0911		.222		
Elevation feet	$\bar{x}$	2772.8	2762.3	2685.7	2685.4	2349
	s	250.4		42.1		
	max	3150		2710		
	min	2386		2637		
Relief feet	$\bar{x}$	255.9	248.0	411.0	394.0	921
	s	66.9		143.8		
	max	393		560		
	min	166		273		
Relief ratio	$\bar{x}$	.68536	.67877	.61277	.60551	.39023
	s	.09953		.11169		
	max	.8983		.6987		
	min	.5405		.4865		
Relative relief	$\bar{x}$	.26570	.26236	.21739	.21197	.14646
	s	.04281		.05686		
	max	.3455		.2649		
	min	.1834		.1544		
Elongation	$\bar{x}$	.67828	.67275	.75372	.74857	.62703
	s	.09191		.10598		
	max	.9031		.8458		
	min	.5522		.6379		
Circularity	$\bar{x}$	.68364	.66734	.67815	.67776	.54660
	s	.17819		.02838		
	max	1.2482		.7109		
	min	.5203		.6606		
Drainage density miles^{-1}	$\bar{x}$	21.676	20.267	23.771	23.086	18.023
	s	7.379		6.831		
	max	34.44		30.38		
	min	7.89		16.74		
Channel frequency miles^{-2}	$\bar{x}$	726.4		704.56	595.38	275.53
	s	522.6		445.88		
	max	2000.		1153.8		
	min	238.1		262.2		

APPENDIX I

Characteristic Values of Geomorphic Properties

FIFTH ORDER VALUES LARGE WATERSHEDS

Watershed Property	I	II	III	VIII	IX
Channel length miles	2.839	1.870	2.254	2.011	1.209
Area sq. miles	2.4915	2.2038	2.1790	1.3574	1.1809
Diameter miles	2.5602	2.4639	2.5622	2.2157	1.8640
Elevation feet	1765	2565	2565	1880	1880
Relief feet	2695	2900	2560	1520	1610
Relief ratio	.19937	.22291	.18923	.12993	.16358
Elongation	.69569	.67984	.65008	.59333	.65782
Drainage density miles^{-1}	19.266	18.501	17.811	24.406	24.907
Channel frequency miles^{-2}	213.53	262.73	201.93	371.30	370.06

APPENDIX I

Characteristic Values of Geomorphic Properties

WEIGHTED MEANS AND EXTREME EXTREMES

Property	Order	1st	2nd	3rd	4th	5th
Channel length miles	$\bar{x}$	.05833	.09615	.19365	.36584	2.036
	max	.334	.479	.559	.593	2.839
	min	.005	.004	.005	.029	1.870
Area sq. miles	$\bar{x}$	.002692	.012611	.054941	.22998	1.8825
	max	.0238	.1051	.2501	.6551	2.4915
	min	.0002	.0006	.0030	.0453	1.1809
Diameter miles	$\bar{x}$	.09126	.18047	.36106	.7089	2.3332
	max	.336	.573	.823	1.156	2.562
	min	.014	.028	.094	.361	1.864
Perimeter miles	$\bar{x}$	.26469				
	max	1.133				
	min	.087				
Elevation feet	$\bar{x}$	3423.1	3228.3	3078.7	3039.4	2131.0
	max	5260	5065	4909	4025	2565
	min	1768	1825	1828	1965	1765
Relief feet	$\bar{x}$	285.3	503.6	785.9	1168.0	2257.0
	max	1088	1222	1765	2070	2900
	min	35	50	156	720	1520
Relief ratio	$\bar{x}$	.60439	.55516	.44149	.32771	.18100
	max	1.4906	1.5677	1.1340	.4623	.2229
	min	.1155	.1064	.1697	.1835	.1299
Relative relief	$\bar{x}$	.21783				
	max	.7024				
	min	.0304				
Elongation	$\bar{x}$	.62188	.67397	.70470	.71609	.65535
	max	1.6453	1.4690	1.2080	.8901	.6957
	min	.1491	.3945	.4815	.5856	.5933
Circularity	$\bar{x}$	.56727				
	max	.9756				
	min	.0078				
Drainage density miles^{-1}	$\bar{x}$	27.909	26.606	24.388	23.349	20.978
	max	346.67	71.05	66.79	34.08	24.91
	min	3.66	7.92	12.77	14.97	17.81
Channel frequency miles^{-2}	$\bar{x}$	703.2	562.88	428.09	361.67	283.91
	max	5000	5000	2333	772.6	371.3
	min	42	68.6	115.1	137.2	201.9

APPENDIX II

Percent Probability of Observed Departure from Normality

Watershed I, Wolfskill Canyon

ORDER	1		2		3		4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	--0.1 1)	Chi	--0.1	Chi	10-5 65	Chi K-S	92	K-S
Log chan. length	5-2.5	Chi	5-2.5	Chi	70 93	Chi K-S	85	K-S
Area	--0.1	Chi	--0.1	Chi	24	K-S	76	K-S
Log area	0.5-0.1	Chi	10-5	Chi	82	K-S	99	K-S
Diameter	--0.1	Chi	2.5-2	Chi	23	K-S	98	K-S
Log diameter	8-5	Chi	65-55	Chi	94	K-S	99.8	K-S
Perimeter								
Log perimeter								
Elevation	--0.1	Chi	--0.1	Chi				
Log elevation	--0.1	Chi	--0.1	Chi				
Relief	--0.1	Chi	97.5-95	Chi				
Log relief	1-0.5	Chi	40-30	Chi				
Relief ratio	10-5	Chi	2.5-2	Chi				
Log relief ratio	--0.1	Chi	70-60	Chi				
Relat. relief								
Log relat. relief								
Elongation	-0.1	Chi	-0.1	Chi				
Log elongation	5-2.5	Chi	--0.1	Chi				
Circularity								
Log circularity								
Drain. density	-0.1	Chi	45-40	Chi				
Log drain. density	5-2.5	Chi	35-30	Chi				
Channel freq.	--0.05	Chi	--0.1	Chi				
Log channel freq.	0.5-0.1	Chi	20-15	Chi				

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1) -0.1 should be read as "less than one tenth percent"; --0.1 as "much less than one tenth percent".

APPENDIX II

Percent Probability of Observed Departure from Normality

Watershed II, Fern Canyon

ORDER	1		2		3		4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	--0.1	Chi	--0.1	Chi	2-1 62	Chi K-S	Not determinable, N = 2	
Log chan. length	2-1	Chi	80-75	Chi	35-30 32	Chi K-S	"	"
Area	--0.1	Chi	--0.1	Chi	92	K-S	"	"
Log area	-0.1	Chi	25-20	Chi	95	K-S	"	"
Diameter	--0.1	Chi	-0.1	Chi	28	K-S	"	"
Log diameter	15-10	Chi	60-50	Chi	44	K-S	"	"
Perimeter	-0.1	Chi						
Log perimeter	45-35	Chi						
Elevation	--0.1	Chi	--0.1	Chi				
Log elevation	--0.1	Chi	-0.1	Chi				
Relief	--0.1	Chi	30-25	Chi				
Log relief	15-10	Chi	45-35	Chi				
Relief ratio	--0.1	Chi	0.5-0.1	Chi				
Log relief ratio	10-5	Chi	50-40	Chi				
Relat. relief	15-10	Chi						
Log relat. relief	30-20	Chi						
Elongation	--0.1	Chi	10-5	Chi				
Log elongation	5-2	Chi	20-15	Chi				
Circularity	15-10	Chi						
Log circularity	--0.1	Chi						
Drain. density	--0.1	Chi	30-25	Chi				
Log drain. density	38-32	Chi	45-40	Chi				
Channel freq.	--0.05	Chi	-0.1	Chi				
Log channel freq.	-0.05	Chi	65-60	Chi				

APPENDIX II

Percent Probability of Observed Departure from Normality

Watershed III, Upper East Fork

ORDER	1		2		3		4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	--0.1	Chi	-0.1	Chi	20-10 24	Chi K-S	87	K-S
Log chan. length	5-2.5	Chi	20-10	Chi	10-5 87	Chi K-S	66	K-S
Area	--0.1	Chi	--0.1	Chi	42	K-S	62	K-S
Log area	-0.1	Chi	50-40	Chi	65	K-S	89	K-S
Diameter	--0.1	Chi	2-1	Chi	56	K-S	99	K-S
Log diameter	5-2.5	Chi	65-55	Chi	83	K-S	97	K-S
Perimeter	--0.1	Chi						
Log perimeter	60-50	Chi						
Elevation	--0.1	Chi	10-5	Chi				
Log elevation	--0.1	Chi	10-5	Chi				
Relief	--0.1	Chi	-0.1	Chi				
Log relief	100-99.5	Chi	20-15	Chi				
Relief ratio	--0.1	Chi	-0.1	Chi				
Log relief ratio	60-55	Chi	50-40	Chi				
Relat. relief	-0.1	Chi						
Log relat. relief	100-99.9	Chi						
Elongation	15-10	Chi	20-15	Chi				
Log elongation	30-25	Chi	30-25	Chi				
Circularity	40-30	Chi						
Log circularity	2-1	Chi						
Drain. density	-0.1	Chi	30-25	Chi				
Log drain. density	45-40	Chi	60-55	Chi				
Channel freq.	--0.05	Chi	--0.1	Chi				
Log channel freq.	-0.05	Chi	1-0.5	Chi				

APPENDIX II

Percent Probability of Observed Departure from Normality

Watershed VIII, Bell Canyon

ORDER	1		2		3		4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	--0.1	Chi	0.5-0.1	Chi	50-40 45	Chi K-S	90	K-S
Log chan. length	10-5	Chi	5-2.5	Chi	20-10 85	Chi K-S	88	K-S
Area	--0.1	Chi	2-1	Chi	80	K-S	99.9	K-S
Log area	-0.1	Chi	65-55	Chi	44	K-S	99.8	K-S
Diameter	--0.1	Chi	15-10	Chi	86	K-S	97	K-S
Log diameter	2.5-2	Chi	90-85	Chi	29	K-S	87	K-S
Perimeter	-0.1	Chi						
Log perimeter	70-60	Chi						
Elevation	-0.1	Chi	-0.1	Chi				
Log elevation	--0.1	Chi	-0.1	Chi				
Relief	-0.1	Chi	2.5-2	Chi				
Log relief	10-5	Chi	25-20	Chi				
Relief ratio	5-4	Chi	1-0.5	Chi				
Log relief ratio	--0.1	Chi	80-75	Chi				
Relat. relief	20-15	Chi						
Log relat. relief	5-4	Chi						
Elongation	0.5-0.1	Chi	-0.1	Chi				
Log elongation	--0.1	Chi	10-8	Chi				
Circularity	90-85	Chi						
Log circularity	20-15	Chi						
Drain. density	--0.1	Chi	5-2.5	Chi				
Log drain. density	20-10	Chi	60-50	Chi				
Channel freq.	--0.05	Chi	--0.1	Chi				
Log channel freq.	0.5-0.1	Chi	25-20	Chi				

Percent Probability of Observed Departure from Normality

Watershed IX, Volfe Canyon

ORDER	1		2		3		4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	--0.1	Chi	-0.1	Chi	20-10 86	Chi K-S	91	K-S
Log chan. length	10-5	Chi	80-75	Chi	70-50 69	Chi K-S	98	K-S
Area	--0.1	Chi	-0.1	Chi	99.9	K-S	64	K-S
Log area	2.5-2	Chi	60-50	Chi	59	K-S	66	K-S
Diameter	-0.1	Chi	60-50	Chi	87	K-S	94	K-S
Log diameter	5-2.5	Chi	70-60	Chi	58	K-S	95	K-S
Perimeter								
Log perimeter								
Elevation	--0.1	Chi	15-10	Chi				
Log elevation	--0.1	Chi	1-0.5	Chi				
Relief	--0.1	Chi	80-75	Chi				
Log relief	18-12	Chi	75-70	Chi				
Relief ratio	-0.1	Chi	5-1	Chi				
Log relief ratio	2-1	Chi	5-3	Chi				
Relat. relief								
Log relat. relief								
Elongation	-0.1	Chi	-0.1	Chi				
Log elongation	5-3	Chi	1-0.5	Chi				
Circularity								
Log circularity								
Drain. density	--0.1	Chi	2.5-1	Chi				
Log drain. density	40-35	Chi	5-3	Chi				
Channel freq.	--0.05	Chi	-0.1	Chi				
Log channel freq.	2.5-2	Chi	30-20	Chi				

APPENDIX II

Percent Probability of Observed Departure from Normality

Watersheds II-1, 2, 3, and 4, Fern Small Watersheds, First Order Only

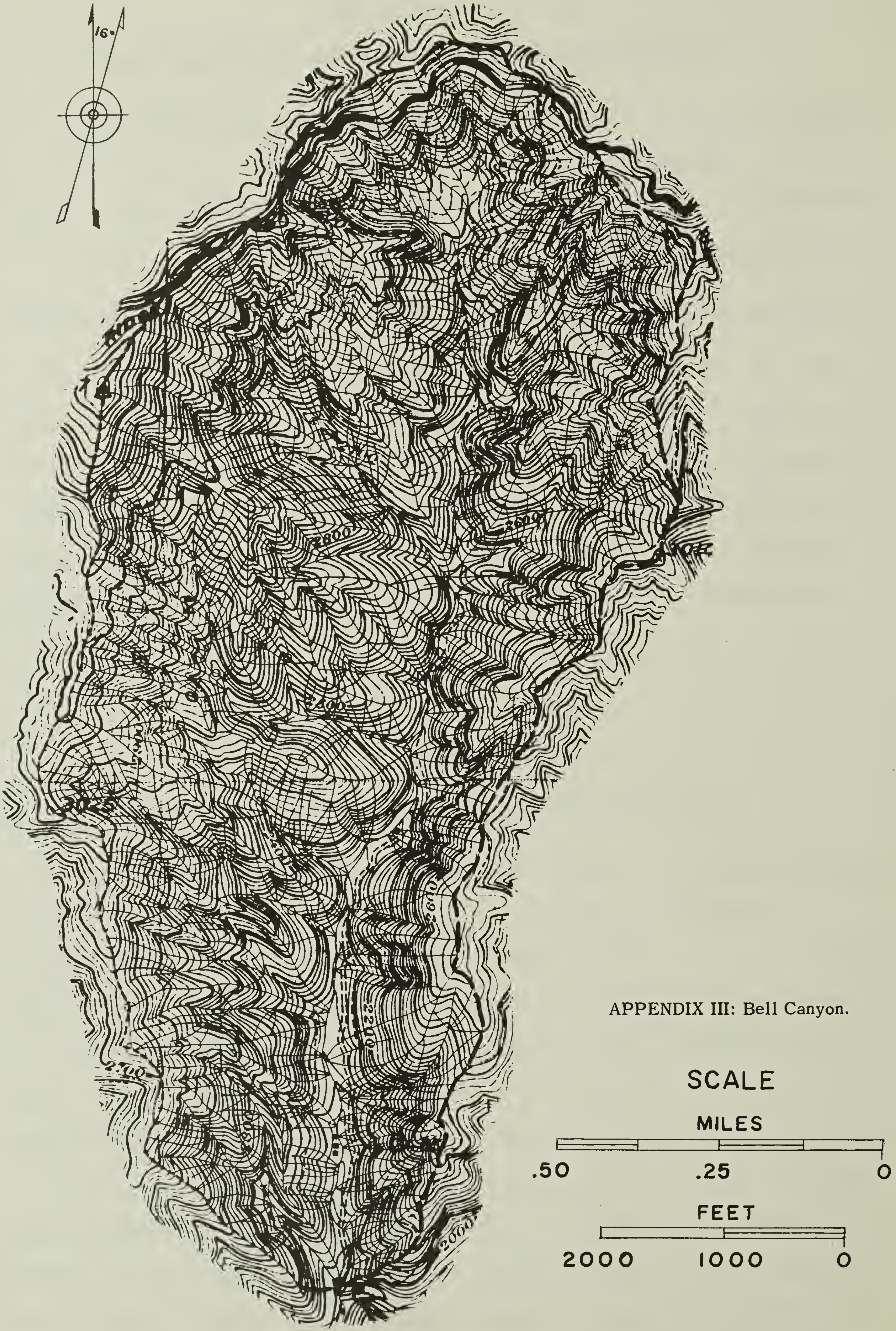
WATERSHED	II-1		II-2		II-3		II-4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	10-5 65	Chi K-S	20-10 16	Chi K-S	88	K-S	-0.1	Chi
Log chan. length	30-20 77	Chi K-S	20-10 70	Chi K-S	80	K-S	40-30	Chi
Area	23	K-S	5.7	K-S	46	K-S	0.5-0.1	Chi
Log area	88	K-S	28	K-S	95	K-S	85-80	Chi
Diameter	96	K-S	78	K-S	96	K-S	30-25	Chi
Log diameter	98	K-S	93	K-S	98	K-S	50-40	Chi
Perimeter	90	K-S	35	K-S	80	K-S	50-45	Chi
Log perimeter	98	K-S	63	K-S	75	K-S	99.5-99	Chi

APPENDIX II

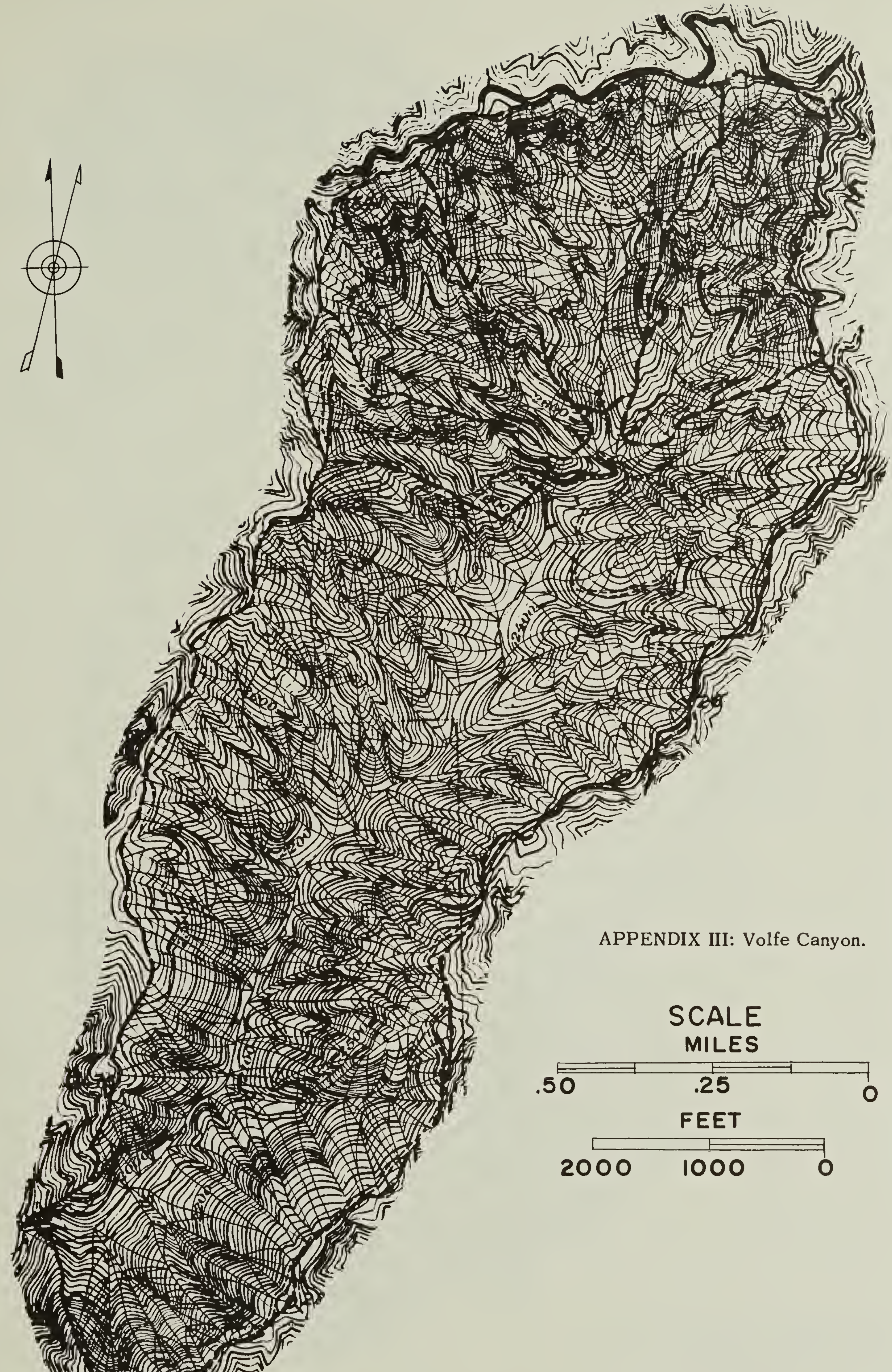
Percent Probability of Observed Departure from Normality

Watersheds VIII-1, 2, 3, and 4, Bell Small Watersheds, First Order Only

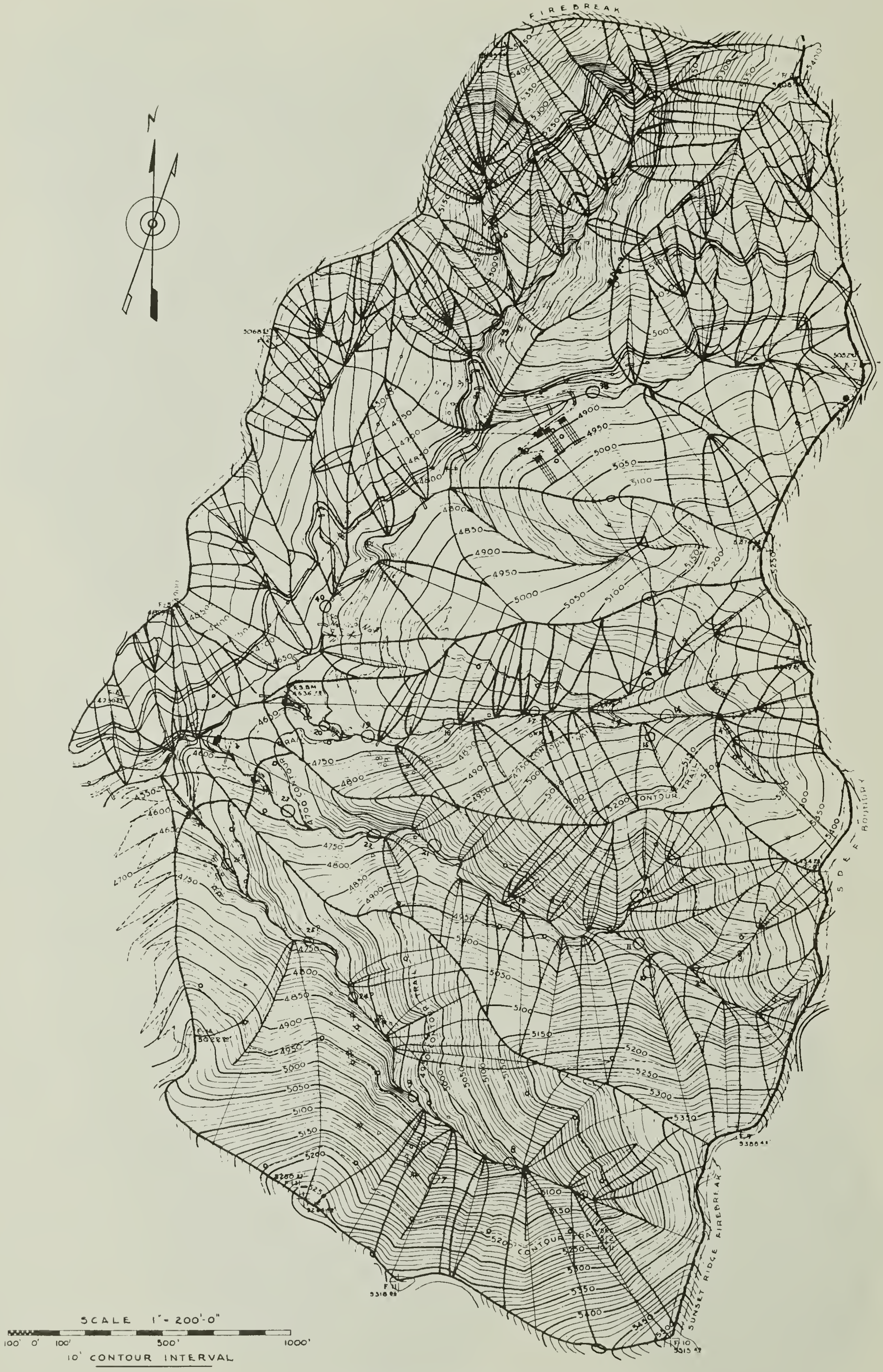
WATERSHED	VIII-1		VIII-2		VIII-3		VIII-4	
PROPERTY	Prob.	Test	Prob.	Test	Prob.	Test	Prob.	Test
Channel length	0.5-0.1	Chi	0.5-0.1	Chi	20-10	Chi	83	K-S
Log chan. length	20-10	Chi	95-90	Chi	15-10	Chi	98	K-S
Area	--0.1	Chi	--0.1		25-20	Chi	51	K-S
Log area	-0.1	Chi	0.5-0.1	Chi	10-9	Chi	72	K-S
Diameter	50-45	Chi	45-35	Chi	2-1	Chi	97	K-S
Log diameter	95-90	Chi	90-80	Chi	1-0.5	Chi	98	K-S
Perimeter	10-5	Chi	15-10	Chi	15-10	Chi	92	K-S
Log perimeter	30-25	Chi	85-80	Chi	30-25	Chi	97	K-S



APPENDIX III: Bell Canyon.



APPENDIX III: Volfe Canyon.



APPENDIX III: Fern Small Watersheds.

COEFFICIENTS OF CORRELATION, WITH UNEXPLAINED DISCHARGE AS DEPENDENT VARIABLE

Independent Variable	Simple Correlation	Multiple Correlation, Independent Variables						
		a_5	d_5	a_5, a_2	d_5, a_2	d_5, d_2	d_5, h_2	d_5, D_2
a_5	0.387							
d_5	0.441							
a_2	0.222	.4267	.4603					
d_2	0.251	.4110	.4476					
h_2	0.241	.3907	.4421	.4274	.4764	.4886		
D_2	0.233	.4286	.4885	.4396	.4889	.4890	.4745	
C_2	0.256	.4140	.4596	.4643	.4607	.4759	.4728	.4889
R_2	0.159	.3883	.4513	.4278	.4747	.4699	.4703	.4890
R_b	0.046	.3879	.4438	.4776	.4606	.4481	.4444	.4885
R_1	0.288	.4274	.4531	.4279	.4630	.4539	.4594	.4887
R_a	0.015	.3956	.4428	.4888	.4684	.4530	.4438	.4885
R_d	0.232	.4116	.4499	.4848	.4787	.4665	.4499	.4886

Independent Variable	Multiple Correlation, Independent Variables			
	d_5, d_2, D_2	a_5, a_2, D_2	d_5, d_2, D_2, R_2	a_5, a_2, D_2, R_2
h_2	.4890	.4890	.4892	.4892
R_2	.4890	.4892		
R_b	.4890	.4893	.4891	.4891
R_1	.4890	.4854	.4892	.4892
R_a	.4890	.4892	.4892	.4892
R_d	.4890	.4896	.4900	.4892

APPENDIX III: Upper East Fork.

APPENDIX III: Bell Small Watersheds.

APPENDIX III: Fern Canyon.

APPENDIX III: Wolfskill Canyon.

SCALE

Miles

50 25 0

Feet

2000 1000 0