Erosion and Sediment Yields in the Transverse Ranges, Southern California

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SYMBOLS

A	Area of a drainage basin.
a	Area above a certain reference altitude within a drainage basin.
C	Runoff coefficient.
Dd	Drainage density.
DR	Dispersion ratio; a measure of soil erodibility.
ER	Elongation ratio.
FF	Fire factor.
H	Total relief of a drainage basin; highest altitude minus lowest altitute.
h	Altitude of a contour line above outlet of drainage basin.
I	Precipitation intensity.
K	Precipitation factor defined as: 10-day $\times$ (24-hour precipitation)^2.
L	Watershed length.
ΣL	Total stream length.
L_μ	Length of stream or stream channel of order μ.
MAP	Mean annual precipitation.
P	Precipitation.
Q_{50}	Peak discharge with a recurrence interval of 50 years.
Q_{cfs}	Peak discharge in cubic feet per second.
Q_{csm}	Peak discharge in cubic feet per second per square mile.
Rb	Bifurcation ratio.
Rr	Relief ratio.
S_A	Sediment-area factor.
S_M	Sediment-movement factor.
S_y	Sediment yield.
S_y'	Sediment yield per unit area.
SA	Surface-aggregation ratio; a measure of soil erodibility.
SF	Proportion of basin underlain by slope failures.
T_1	Transport-efficiency factor.
TC	Total time of concentration.
VI	Vegetation index.
Z	Land-use coefficient.
θg	Ground-slope angle.
μ	Stream order; unbranched tributaries are designated as first order; their confluence forms a stream of second order; and so forth.

CONVERSION FACTORS

Factors for converting English units to metric units are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric*
° F (degrees Fahrenheit)	5/9(F−32)	° C (degrees Celsius)
ft (feet)	3.048×10^{-1}	m (meters)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
in (inches)	2.540×10	mm (millimeters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
yd^3 (cubic yards)	7.646×10^{-1}	m^3 (cubic meters)
yd^3/acre (cubic yards per acre)	1.889	m^3/hm^2 (cubic meters per square hectometer)
yd^3/mi^2 (cubic yards per square mile)	2.952×10^{-1}	m^3/km^2 (cubic meters per square kilometer)

EROSION AND SEDIMENT YIELDS IN THE TRANSVERSE RANGES, SOUTHERN CALIFORNIA

By KEVIN M. SCOTT and RHEA P. WILLIAMS

ABSTRACT

Major-storm and long-term erosion rates in mountain watersheds of the western Transverse Ranges of Ventura County are estimated to range from low values that will not require the construction of catchments or channel-stabilization structures to values as high as those recorded anywhere for comparable bedrock erodibilities.

A major reason for this extreme variability is the high degree of tectonic activity in the area—watersheds are locally being uplifted by at least as much as 25 feet (7.6 meters) per 1,000 years, yet the maximum extrapolated rate of denudation measured over the longest available period of record is 7.5 feet (2.3 meters) per 1,000 years adjusted to a drainage area of 0.5 square mile (1.3 square kilometers). Evidence of large amounts of uplift continuing into historical time includes structurally overturned strata of Pleistocene age, active thrust faulting, demonstrable stream antecedence, uplifted and deformed terraces, and other results of base-level change seen in stream channels. Such evidence is widespread in the Transverse Ranges, and aspects of the landscape, such as drainage-net characteristics and hillslope morphology, are locally more a function of tectonic activity than of denudational process. Many of the 72 study watersheds are located on frontal escarpments of mountain blocks cut by recently active thrust faults, along which the upper part of the drainage basin has overthrust either the lower part of the basin or the adjacent valley area.

To define erosion rates in 35 small watersheds in the western Transverse Ranges, a group of 37 similar watersheds with sediment yields measured in debris basins was selected from the eastern Transverse Range in Los Angeles County. Sediment yields from this group of watersheds during the record-breaking 1969 storms ranged from relatively low rates to values equivalent to reduction of the entire land surface of a watershed by more than 2 inches (51 millimeters).

Correlation of the measured erosion rates to the watersheds with unknown rates required definition of the chief factors that control the erosion rates. Numerous types and combinations of variables measuring physiography, soil erodibility, slope stability, hydrologic factors, wildfire effects, vegetation, and land use were analyzed by regression. A slope-stability variable retained in regression at significant levels was the proportion of watershed drainage area underlain by slope failures, a logical measure of increased erodibility caused by uplift.

The importance in the area of debris flows, mudflows, and mass movements—forms of sediment transport not involving normal aqueous entrainment—is also a reflection of the active tectonic setting of the Transverse Ranges. Implicit in the detailed study of selected physiographic and slope-failure variables was the logical assumption that correlation with the probability of transport by these exotic but quantitatively important sedimentation processes would be achieved.

So prominent and widespread was evidence of debris flows in the small study watersheds after the 1969 storms, that it was possible to formulate a model for the dispersal of sediment in such watersheds: Lateral supply of sediment to stream channels is a relatively continuous process, accomplished in significant part during the dry season by dry sliding, in addition to wet-season contributions from overland flow and mass movements. During periods without major storms, stream channels undergo more-or-less time-continuous fill. Then, during a storm of high recurrence interval, channel-bed material is mobilized and dispersed in large part by debris flows—coarse granular slurries, some of which are induced by mass movements triggered by the storm. Channels undergo substantial net scour, accomplished by removal of bed material in debris flows and by scour during recession flow. Valley-side slopes are undercut by bank erosion, and a new cycle of channel infilling by hillslope processes is initiated.

INTRODUCTION

The vast urban area of southern California has developed progressively outward from intermontane flatlands to alluvial fans formed around the bases of precipitous, fault-block mountain ranges. Continued population pressure has extended urbanization up the fans and, in recent years, almost into the mouths of the rugged mountain watersheds, which periodically disgorge their storm runoff and loads of coarse sedimentary detritus to the surfaces of the fans.

The results of flooding in areas of urban expansion may be catastrophic when neither proper zoning nor flood-control measures exist. However, the problems due simply to rising floodwater in existing channels have been of historically lesser importance relative to the problems caused by a group of complex geomorphic processes common to the region. Processes that have caused extensive damage on alluvial fans, for example, include lateral scour in existing channels, the formation of new channels by sudden redirection of flow at the fan apex (Scott, 1973), and inundation by debris flows and mudflows (Scott, 1971). When unimpeded, channels in the noncohesive fan deposits that are themselves the products of former storms are free to migrate unpredictably throughout the roughly semicircular arc of the fan. Numerous other processes related to major storms are active on hillslopes and in the confined bedrock channels of the watersheds themselves.

The prevention of damage from these causes is one of the most important environmental-geomorphic problems in the area today. At present, the most economical solution often is the construction of debris basins at the mouths of watersheds with high flooding potential and erosion rates. These structures trap sedimentary detritus and divert storm discharges into lined channels. A major criterion for both justifying and designing the basins is the amount of detritus that will be eroded during a major storm.

The object of this study is to estimate major-storm and long-term erosion rates for planning purposes in the western Transverse Ranges (fig. 1). The study basically is an analysis of the variables that affect the quantities of sediment eroded from small, steep drainages in an area that is as diverse as any in the world with respect to the tectonic, geologic, and geomorphic controls on erosion rates.

The term "erosion" is used here in the established general sense to include both weathering and the transportation of weathered products, which consist predominantly of detrital alluvium and colluvium in the study area. Sediment yields are the volumes of sediment retained in impoundment structures over a given period or during a certain magnitude of storm. Erosion rate is used here synonymously with sediment yield per unit watershed area in some contexts, with the qualification that absolute values of erosion rates can be derived from sediment yields only by measurement of the dissolved products of weathering, and with a correction for trap efficiency of the impoundments. Both corrections are minor throughout most of the study area.

PREVIOUS WORK

The sediment system of mountain watersheds like those in southern California is unique compared with the sediment system of watersheds for which sediment-measurement procedures have been developed. Direct measurements of sediment discharge in surface flow are not feasible for sediment-yield analysis in the study watersheds because, among

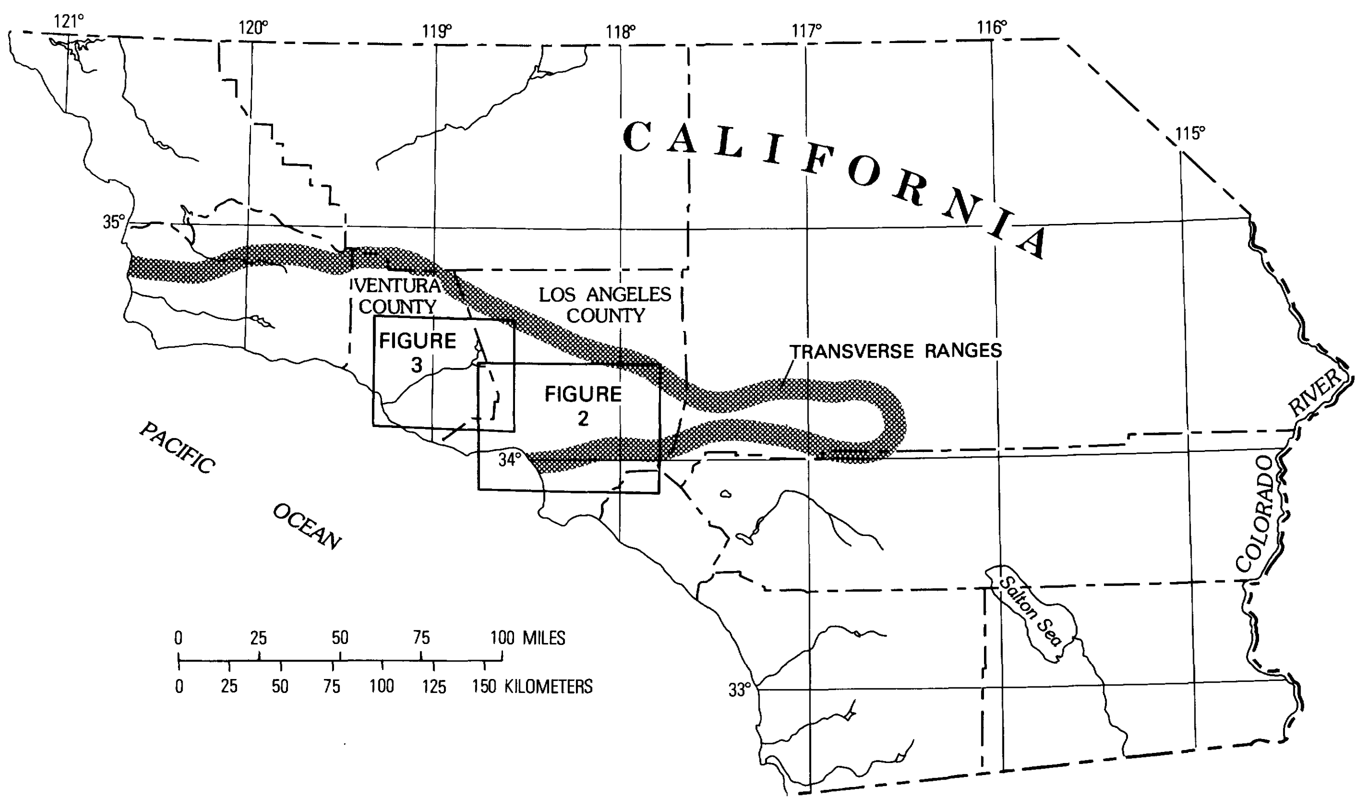

FIGURE 1.—Location of the Transverse Ranges and the principal areas of study.

other reasons, of the scarcity and short duration of such flows. Use of standard sedimentation procedures in mountain watersheds may be objected to for many reasons, such as the subjectivity in calculation of bedload when bed material is in extremely coarse size ranges. Other problems unique to quantitative sedimentation study of these watersheds will be discussed throughout the report.

In addition to application of bedload functions and rating curve–flow duration extensions of direct measurements of sediment discharge, methods by which sediment yields are determined indirectly have been widely used. The most common of these involves the calculation of the amount of eroded soil, using one of several classical soil-loss equations, followed by sediment routing by means of sediment-delivery ratios. However, soil-loss equations are products of agricultural research, and this approach should be confined to areas with zonal soil development. It has not proved useful in southern California.

Sediment volumes that have accumulated in reservoirs and debris basins are the only reliable source of sediment-yield data in the mountain watersheds of southern California. Erosion rates determined from these accumulations must be transferable to other watersheds if any conclusion of more than local interest is desired. It is the transfer value of the erosion rates, the watershed variables by which the rates may be correlated, and the assessment of the limits beyond which the rates no longer apply that are the crux of any such attempt. Past studies in the Transverse Ranges have attempted the widespread application of a single set of criteria calculated from a limited group of data.

In a typical regression analysis using graphical techniques, Ferrell (1959) estimated erosion rates in Los Angeles County, mainly in the frontal San Gabriel Mountains, to derive criteria for debris-basin design. The resulting equation was

$$S_y' = \frac{35{,}600\ Q_{csm}^{1.67} Rr^{0.72}}{(5+VI)^{2.67}}$$

where S_y' is sediment yield, in cubic yards per square mile, Q_{csm} is peak discharge, in cubic feet per second per square mile, Rr is relief ratio, and VI is a vegetation index. The standard error of estimate is 0.386 log units (+143, −59 percent).

What is essentially a regression of sediment yield against a series of variables—slope, drainage density, hypsometric-analysis index, and 3-hour rainfall—was developed by Tatum (1965). Basic to the analysis was the concept of an ultimate erosion rate, the idea that under conditions of a 100-percent burn followed by a major storm there is a maximum rate of erosion to which correction factors for the above variables can be applied. Data were obtained from watersheds in the eastern Transverse Ranges.

Although the inflow of sediment into an impoundment is a stochastic process, attempts to develop a stochastic model for prediction of sediment yields have thus far foundered in practicality on several critical but necessary assumptions. As will be clear from subsequent discussion, the extreme character and diversity of the subject watersheds would virtually preclude modeling, even were procedures standardized.

A reconnaissance of all existing impoundments and many stock pounds in September 1970 led inescapably to the conclusion that previous attempts at erosion-rate analysis would not apply to the western Transverse Ranges, primarily because of the limited nature of the sample populations from which the previous criteria were derived. At the time of the 1970 reconnaissance, the effects of the recordbreaking 1969 storms were still visible, and large differences in erosion rates between adjacent parts of the Transverse Ranges were distinct. The differences were in most cases related to complex differences in watershed characteristics, and not simply to variations in storm intensity.

PURPOSE, SCOPE, AND METHODS

The most logical approach to estimation of erosion rates in the Transverse Ranges is empirical correlation of actual sediment yields on the basis of watershed characteristics (see Anderson and Wallis, 1965). This study will use the same type of data as the studies by Ferrell (1959) and Tatum (1965)—actual sediment yields from debris basins in the eastern Transverse Ranges in Los Angeles County—but will attempt to modify the predictive results to a more variable range of conditions, especially to those that exist in the western Transverse Ranges of Ventura County. Objections to extension of the previous studies can be met in the following ways:

1. The sample of watersheds with known erosion rates will specifically include watersheds with characteristics similar to those of watersheds in the western Transverse Ranges. Sample size and selection will still be sufficient to assure diversity of parameters in most other respects.
2. All possible watersheds from areas of sedimentary rocks in the normally granitic-meta-

morphic eastern part of the ranges will be included in the analysis. This broader range of bedrock and soil characteristics should include many of the conditions in the western part of the ranges. The chief difficulty in comparing watersheds in the two areas is this general difference in rock type. Anderson (1949a, p. 622) met a similar problem in correlating peak discharges but found that functions relating discharge to watershed variables were remarkably similar in areas of both sedimentary and granitic-metamorphic rock types. Anderson's result, though encouraging with respect to hydrologic behavior of the two types of terrain, points out the need for other variables to explain the large observed differences in erosion rates.

3. A larger number of variables than analyzed in previous studies will be considered, not only for reasons given in 2 but also because of the known importance of additional factors. Substantial new data became available as a result of the 1969 storms.
4. Variable selection will be based on logic and the results of other studies in southern California, as well as statistical inference. It is not possible to consider all the potential variables on a purely statistical basis, and it is at this point that sedimentation theory and the known response of watersheds elsewhere can be used for determination of variables.

The net end product of the study is the development of criteria by which the erosion potential of selected mountain watersheds in the western Transverse Ranges in Ventura County can be determined. Specifically, the foci of the study are as follows:

1. Estimates of erosion rates from a major storm (approximate 50-year recurrence interval) are prepared as an aid to the planning and design of debris basins or zoning regulations. Differences between rates under burned and unburned conditions are assessed to the maximum extent possible.
2. Estimates of long-term erosion rates are made to assist in planning cleanout costs and selecting debris-disposal areas. Long-term rates estimated under present conditions also establish a natural base against which the effects of future environmental changes can be compared.
3. Modes of coarse-sediment transport such as debris flow and mudflow, and their effects on erosion rates, are evaluated. Previous study (Scott, 1971) has indicated that such processes may be the dominant means of sediment transport in some small watersheds in southern California.

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THE ENVIRONMENT

LOCATION AND PHYSICAL FEATURES

The 72 drainage basins discussed in this report are in the Transverse Ranges in Ventura and Los Angeles Counties, Calif. (fig. 1). Most of the 37 drainages with known erosion rates are in the eastern Transverse Ranges in Los Angeles County (fig. 2); the 35 watersheds for which rates are determined by indirect methods are in the western Transverse Ranges in Ventura County (fig. 3).

The group of watersheds studied in Los Angeles County drains into both the Los Angeles and the San Gabriel River systems. Both steepness of terrain and erosion rates generally are high in watersheds along the front of the San Gabriel Mountains, and are by local standards relatively low to moderate in other parts of the area selected for correlation of erosion rates.

The watersheds in Ventura County are located in each of the three major drainages that flow to the ocean: The Ventura River, the Santa Clara River, and Calleguas Creek. Terrain and erosion rates decrease in severity from north to south within the county, so that the watersheds in the Ventura River drainage have the highest erosion rates, and those in the Calleguas Creek drainage have the

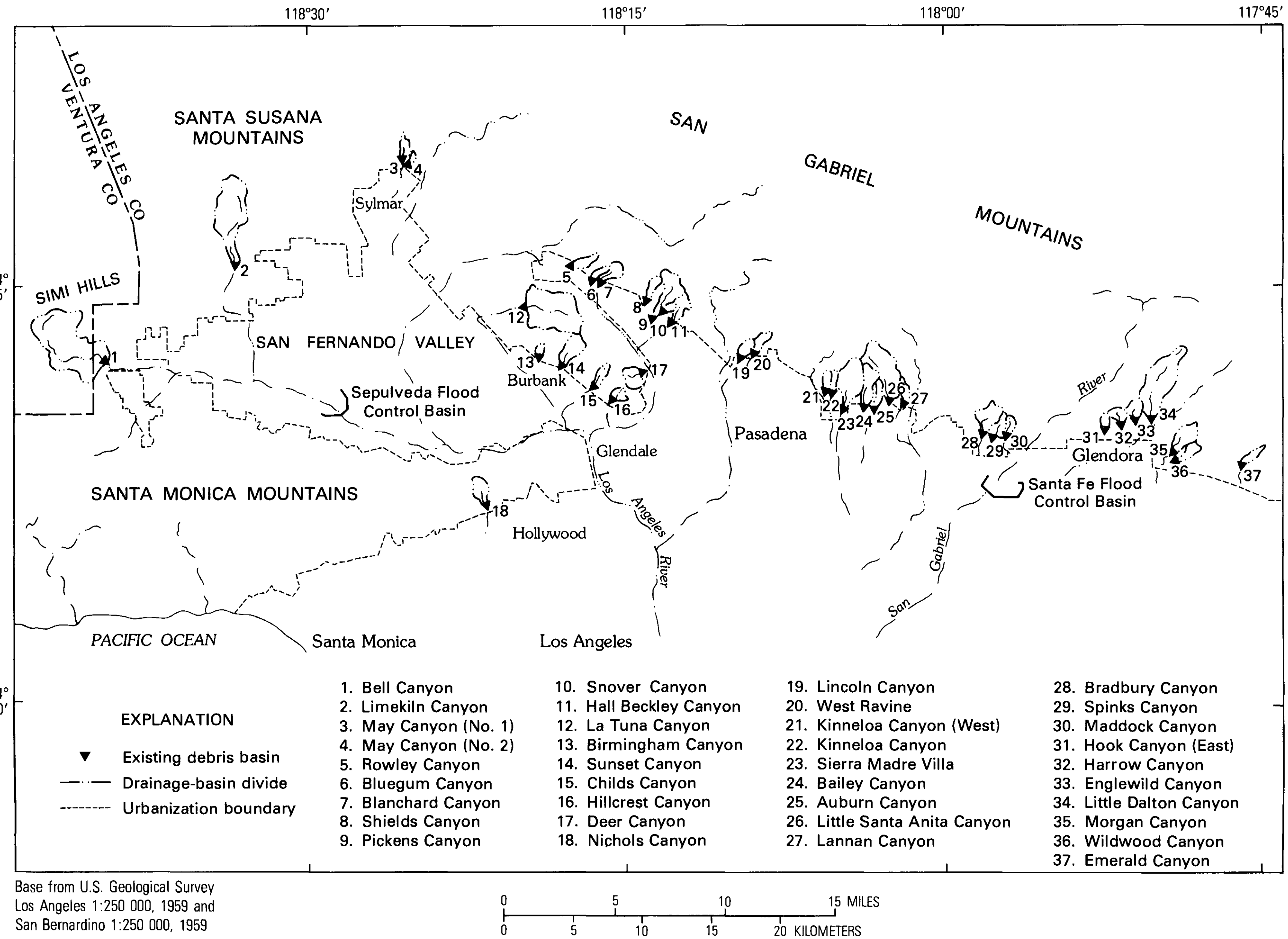

FIGURE 2.—Location of drainage basins in the eastern Transverse Ranges, Los Angeles County.

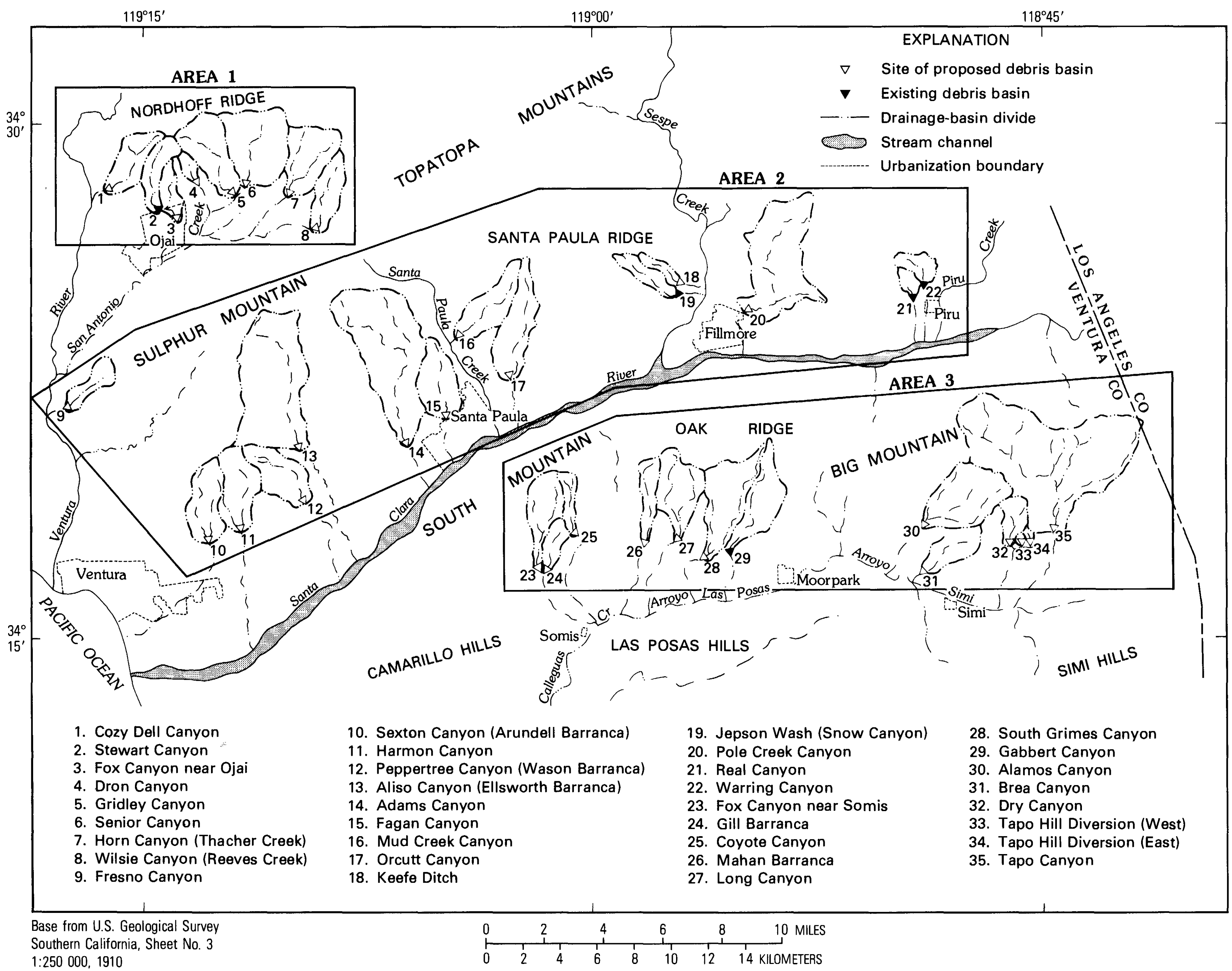

FIGURE 3.—Location of drainage basins in the western Transverse Ranges, Ventura County.

lowest. The large, diverse Santa Clara River drainage contains watersheds with vastly differing rates of erosion; those studied, however, are generally intermediate in intensity.

No large, easily delineated mountain ranges exist within the Transverse Range system in Ventura County. Rather, the area is a complex of discontinuous ranges with local names (fig. 3).

The altitude range of watersheds studied is 310 to 4,485 ft (94 to 1,367 m) above mean sea level in Ventura County and 500 to 5,440 ft (152 to 1,658 m) in Los Angeles County.

All the watersheds discussed in this report debouch into areas that are inhabited or have development potential. Sites of existing and proposed debris basins are commonly near the point at which streams leave the mountain terrain and flow out upon the alluvial fans. The natural change in channel is from a confined, bedrock channel with little alluviation to an ephemeral wash formed in the deposits of the fans. No significant surface flow occurs in any of the study watersheds except during and after storms.

BEDROCK GEOLOGY

Watersheds in both Ventura and Los Angeles Counties are underlain by a great variety of bedrock lithologies. Generally, however, watersheds in Ventura County are underlain by sedimentary sequences that are from Cretaceous to Holocene in age, and those in Los Angeles County are dominated by igneous and metamorphic assemblages mainly of Mesozoic age. This distribution is not exclusive, and a number of basins were found in Los Angeles County that are at least partly underlain by sedimentary rock types. Otherwise, correlation of erosion rates from one area to another could possibly have been less significant.

Even if the lithologic differences were mutually exclusive in the two areas, correlation would still have been possible if variables reflecting surface erodibility were correctly assessed. The U.S. Forest Service (1953, app. 2, p. 12–13) applied a regression analysis developed with sediment yields in igneous-metamorphic terrain to yields from sedimentary terrain in Ventura County and found that little change in the discharge function or cover factor was necessary. Marked differences in the equation constant were found and were attributed to geologic and soil differences.

CLIMATE AND VEGETATION

The Transverse Ranges, like most of southern California, have a Mediterranean-type climate. At the low and intermediate altitudes considered here, summers are dry and warm; winters are wet and cool. Summer high temperatures in the 90's F (32°–37° C) are common. Winter temperatures are only occasionally below freezing.

Approximately 90 percent of the annual precipitation occurs in the 6 months from November to April. The rest of the year is just one long dry spell. In any one year there may be almost no precipitation, or there may be five times the mean annual precipitation. Mean annual precipitation in the study watersheds ranges from a low of 15 in (381 mm) at a site in the Simi Hills to 28 in (711 mm) in several watersheds along the front of Nordhoff Ridge north of Ojai.

Although light snowfalls occur above altitudes of 3,000 ft (914 m), snow is not a significant factor in hydrologic analysis of the watersheds. Less than 0.1 percent of the study-watershed area in Los Angeles County is above an altitude of 5,000 ft (1,524 m), a common lower limit used to assess effects of snow cover on runoff in the area. No part of any watershed studied in Ventura County is above 5,000 ft (1,524 m).

Hillslopes on steep mountain fronts are covered with a dwarf forest of chaparral, an association of xerophytic shrubs and stunted tree forms that reflects the semiarid climate. The dense, highly flammable chaparral gives way to a sage or sage-chamise association on lower slopes, especially in the Santa Clara River basin. This brush association in turn grades to grassland, which is dominant in many parts of the low rolling hills in the Calleguas Creek drainage.

Individual adjacent watersheds vary greatly in cover density. To this natural areal variation is added the variation through time caused by wildfire (fig. 4) and changes in land use. Figure 4 shows the post-wildfire development of many lowest order stream channels, formed by the natural tendency to approach the hillslope configuration required for more efficient transport of the erosional products made available by removal of vegetation. These rills and first-order streams will heal in time as the restoration of vegetation increases the hydraulic roughness and decreases the surface erodibility.

Wildfire effects on vegetation, as they pertain to increased erosion potential, can be predicted and quantified; changes in cover related to land use can only be estimated with great subjectivity. Fortunately, this latter problem is largely academic when applied to areas with high erosion rates. Hillslope-stability problems attendant to construc-

FIGURE 4.—Fire-denuded hillslope in Hook Canyon watershed. Date of fire: August 24, 1968; date of photograph: July 10, 1969. Major storms occurred in both January and February 1969.

tion will prevent any significant degree of urbanization or manmade change in most watersheds with relatively moderate to high erosion rates. In addition, chaparral is neither penetrable nor palatable to grazing animals when it occurs in the density normal to watersheds with high erosional potential. Thus, except for wildfire destruction of cover, no other changes in cover can be predicted, or are important, in areas that have high yields, as do many of the watersheds in the Transverse Ranges.

FLOOD HISTORY—THE 1969 STORMS

Major storms, like those of March 1938 and January and February 1969, have followed a generally similar pattern that can be expected to recur in future major storms. The storm of January 18–27, 1969, was typical: The circulation pattern and stagnation of a low-pressure center in the Pacific permitted intense streaming of northeastward-moving, moisture-laden air as a succession of storm fronts. Precipitation was light until January 19 when intensity increased sharply. Heavy precipitation occurred throughout most of January 19–26, was interrupted by a brief respite on January 22, and then climaxed on January 25.

The January 1969 storm generally produced peak discharges equal to or greater than those of the 1938 storm in Ventura County and western Los

Angeles County. The 1938 storm had been the greatest storm of recent times, at least since the legendary floods of 1862, and its peak discharges and sediment yields have been widely used as standards of flood magnitude and as criteria for impoundment structures. A much larger quantity of sediment-yield data resulted from the 1969 storm. Only eight debris basins in Los Angeles County were available for sediment measurements in 1938; more than 70 existed in 1969. The suitability of January 1969 storm yields as a basis for future planning of sediment-retention structures is discussed later in this report.

In both the 1969 storm periods, surface saturation occurred well before the most intense precipitation. Similar antecedent conditions existed during the 1938 storm and can logically be assumed to recur during any future major storm.

GENERAL GEOMORPHIC HISTORY

Surface form of the study watersheds reflects a Quaternary history that is unusual in its combination of complexity and youthfulness.

Tectonic activity was intermittent throughout the late Pleistocene epoch, especially following an interval of earlier Pleistocene marine deposition. The folded Pleistocene sedimentary deposits were uplifted and now border the Santa Clara River valley on the north. This period of mountain building produced much of the bedrock structure seen in the region, even in terrain of Mesozoic age. Putnam (1942, p. 712) believed that local summit levels record a significant episode of erosion following the middle-Pleistocene orogeny. Although this interpretation is unlikely, late Pleistocene time was marked by alternating periods of alluviation and valley cutting, shown by paired terraces which are juxtaposed and incised at a variety of levels. The relative importance of tectonic activity and climatic change in the formation of these terraces is not known. Uplift was extensive and variable in intensity throughout the area, however, and was doubtless an important component in the process.

The latest period of alluviation was profound and probably corresponds with similar episodes of alluviation noted by many workers throughout the southwestern United States. In parts of the Calleguas Creek drainage basin, alluvium, including colluvial or weathered-mantle materials, extends from stream channel to within a few feet of hillslope crests, forming a broadly rounded terrain with few rock outcroppings even though the weathered mantle is thin and soil development is poor. In much of the study area, erosion has been too active or hillslopes steepened too rapidly by tectonic activity for evidence of former alluvial cycles to be preserved.

Channel entrenchment indicates that the latest period of alluviation has ended. Renewed incision has been caused, or at least accelerated, by historical changes in climate and land use.

Vertical-walled valley trenches reveal thick alluvium composed predominantly of silt-size sediment (0.004–0.0625 mm). This material is finer than the present or past bed material and represents a substantial source of sediment that will add to future sediment yields if the erosion cycle is further accelerated. Although the material is fine grained, it is largely noncohesive, and this property, combined with its occurrence in thick deposits adjacent to active channels, indicates a considerable and continuing potential erosion hazard.

WATERSHED FORM AND PROCESS

RELATION OF GEOMORPHIC HISTORY TO TECTONICS

The Transverse Ranges, named for their anomalous east-west trend relative to the rest of the Coast Ranges in California, reflect earth structure at the largest scale. Although the actual dynamics are unknown, the range system was formed by the interaction of an east-west oceanic fracture zone with the San Andreas fault, a continental transform fault marking a major plate boundary. One effect of the interaction of the two fault systems has been extensive and rapid local uplift. The episodes of alluviation reflect periods of greater or lesser intensity in the tectonic processes, in concert with changes in climate. Historical movement on major faults in the area illustrates the activity of the processes today and their effects on the study watersheds.

The dominating influence on uplift of the Transverse Ranges is a recently recognized, 110-mi (177-km) system of thrust faulting that extends along the fronts of the ranges from Ventura eastward along the Santa Clara River valley, across San Fernando Valley, and along the abrupt southern front of the San Gabriel Mountains. The eastern 55-mi (89-km) segment of the system is known as the Sierra Madre fault zone (Proctor and Payne, 1972, p. 220). Movement on this zone at the front of the San Gabriel Mountains has resulted in watersheds so rugged and youthful that some drainages near

Glendora are little more than avalanche chutes (Scott, 1971, p. 242).

These extremely rugged watersheds are produced by extreme rates of uplift. In the newly completed Glendora water-diversion tunnel, a minimum of 700 ft (213 m) of throw is observed along the fault at the point where the basement complex has been thrust over probable Holocene deposits (oral commun., R. J. Proctor, 1972). This apparent separation is equivalent to a probable rate in excess of 70 ft (21 m) per 1,000 years. The attitude of the thrust at this point is one of shallow dip, but elsewhere the same zone is steeply dipping, thus probably accentuating rates of uplift.

The central part of the thrust complex, the San Fernando fault system, was responsible for the San Fernando earthquake of February 9, 1971. A sudden vertical displacement of more than 3 ft (0.9 m) occurred in valley alluvium along the base of the westernmost San Gabriel Mountains. Several of the watersheds in this study occur on the uplifted block. An older scarp of the same magnitude on the same zone has been identified as probably dating from 1769 (written commun., M. G. Bonilla, 1972). A scarp 10 ft (3 m) in height occurs in young alluvium east of Glendora and has also been correlated with the 1769 quake (Proctor and Payne, 1972, p. 221).

West of the San Fernando Valley, the thrust system splays into a series of faults, the relations of which are poorly known. The San Cayetano thrust, the best known of the group, either bisects or underlies several of the study watersheds in Ventura County, including Mud Creek Canyon, Orcutt Canyon, Jepson Wash, Keefe Ditch, Pole Creek Canyon, Real Canyon, and Warring Canyon. The fault dips north along the north side of the central Santa Clara River valley, parallel in strike but opposed in dip to the Oak Ridge thrust on the south side of the valley. So recent is movement on this pair of faults that Sharp (1954, p. 23) believed that the Santa Clara River valley was "primarily a fault valley and not a secondary product of erosion." The San Cayetano thrust is noteworthy for its recent activity, shown by displacement of oil-well casings in holes penetrating the fault zone, and faulted late-Quaternary terraces that have been back-tilted toward their source.

Watersheds in the Transverse Ranges have also been uplifted by folding. The Ventura River is antecedent at least to the extent that it has preserved its course across terrain being uplifted in the form of a broad flexure. The antecedence is shown by the convex-upward longitudinal profiles of river terraces described by Putnam (1942, fig. 8). Warping of the terraces is coincident with a major anticline that is normal to the river course and that involves a large thickness of Pliocene and Pleistocene sedimentary rocks. Folding probably is continuing at the present.

Deposits of late Pleistocene age are in a steeply inclined attitude at many localities in the area, and are actually overturned at several—to within 50° of complete overturn in Orcutt Canyon, a study watershed. In fact, the structural deformation of deposits of the youngest geological time periods in the Transverse Ranges is without known parallel in North America.

It is clear, from the above evidence, that tectonic processes are generally important and in local areas exceed erosional processes in their role in landscape formation. The significance of this conclusion to erosional analysis is that, in such a steep area, gravitional force acts directly on sediment particles in various forms of mass movement, plastic flow, and viscous fluid flow, rather than indirectly through entrainment in normal stream runoff. Correlation of erosion rates would be impossible without assessment of factors reflecting the relative amounts of uplift between watersheds. It is, of course, the differences in tectonic activity in the recent geologic past, and not the possible future tectonic effects, that will most influence erosion rates within the time span with which this study is concerned.

MASS MOVEMENTS AND SEDIMENTATION PROCESSES

ROCKFALLS AND SLIDES

The downslope movement of sediment as individual particles is locally an important erosional process in the Transverse Ranges. Talus deposits, formed by rapid downslope movement of individual particles or dry or unsaturated masses of particles (granular flow may occur), form laterally to stream channels at the base of steep hillslopes. Frontal watersheds in the San Gabriel Mountains and those north of Ojai in Ventura County contain many such deposits, which are finer grained than the talus characteristically associated with igneous or metamorphic rocks. The process supplies detritus to stream channels, where it must await a major flood before further transportation can occur.

In most cases, talus accumulations are associated with either rockslides or debris slides (mass-movement terminology after Highway Research Board; Varnes, 1958). Where the bedrock is poorly con-

FIGURE 5.—Mud Creek watershed viewed from the drainage divide. Large slumps are visible at left and on opposite hillslope. Terrace in foreground is the top of a slump unit abuting a basal plane of failure. Note intense erosion along toes of the slope failures.

solidated fine-grained sedimentary rock of the Pico Formation, as in the Mud Creek watershed (fig. 5), mass movement may take the form of a slump. Although the view of Putnam (1942, p. 727–728), that "nearly every square foot of surface on hillslopes underlain by upper Pico clay shale is in motion downslope, or has moved in the very recent geologic past" is somewhat extreme, so active is this type of sliding in this appropriately named drainage, that Mud Creek itself usually contains high concentrations of silt- and clay-size material at low flow. This sediment reflects the nearly continuous activity at the snouts of large slumps. The sedimentary bedrock yields much silt and clay when fractured during slumping, concomitant with development of permeability to allow water to percolate through the masses and remove the material and transport it to the stream.

Large-scale slumps with little downslope movement affect the bedrock of the study watersheds north of Glendora. Although contributing little sediment directly to the stream channels, the slope failures are an index of the extreme hillslope instability of these watersheds.

Soil slips, small slides that involve only material above the bedrock surface (Bailey and Rice, 1969, p. 172), are common throughout the Transverse Ranges. They are the most visible aftereffects of major storms like those in 1969. The saturated soil mantle fails and moves downslope to the drainage network where it supplies sediment directly to existing runoff. In some cases in 1969, movement continued downstream as a debris flow or mudflow. U.S. Forest Service studies in the eastern Transverse Ranges (summarized in Bailey and Rice, 1969, p. 176) found erosion rates due only to soil slippage of 81 yd^3/acre (153 m^3/hm^2) in converted grass areas and 11 yd^3/acre (20.8 m^3/hm) in brush areas, measured during a single storm in 1965. Renewal of slippage in 1969 produced 14 times as much erosion in brush areas and 5.4 as much in grass areas due to this cause as occurred in 1965 (Rice and Foggin, 1971, p. 1496).

ROCK-FRAGMENT FLOWS

Dry granular flowage on slopes during the dry season is the dominant form of sediment transport on hillslopes in many watersheds along the front of the San Gabriel Mountains, in the Ojai area, and in the drainage of the Santa Clara River. This type of movement is the end member in the continuum of movement with individual particles at the other extreme, and is a more poorly sorted form of the sand runs or gravel runs observed in aggregate processing. It is largely confined to particles of pebble size (4–64 mm) and smaller. The process is known locally as dry sliding (fig. 6) and has been quantitatively evaluated by Anderson, Coleman, and Zinke (1959) and by Krammes (1960) in cases of brush-fire denudation.

DEBRIS FLOWS

Where bedrock weathers to particles predominantly coarser than silt size (0.004–0.0625 mm), change from slumps, rockslides, and debris slides to channelized debris flows may occur during movement. More commonly, these and other types of mass movement do not change directly to flows, but in-

FIGURE 6.—Eroded dry-sliding deposits in Englewild Canyon. Vertical depth of erosion during 1969 storms is indicated by the height of the pedestaled fragments. Date of photograph: July 9, 1969. Length of ruler is 6 in (15.2 cm).

stead provide source material and act as triggering mechanisms for, or undergo transformation to, debris flows at the time of major storms.

Evidence of debris-flow movement was widespread following the 1969 storms throughout the Transverse Ranges. Debris flows occurred in the following study watersheds: Cozy Dell Canyon, Stewart Canyon, in a tributary of Senior Canyon, Orcutt Canyon, Jepson Wash, May Canyon (No. 1), La Tuna Canyon, Sierra Madre Villa, in a tributary of Little Santa Anita Canyon, Hook Canyon (East), Harrow Canyon, Englewild Canyon, and in several tributaries of Little Dalton Canyon.

Diagnostic features of debris-flow activity in small watersheds included fronts of coarse detritus, which formed transverse to the direction of flow, lateral levees of coarse (>2 mm), poorly sorted material along channel sides, and the characteristic form and texture of the depositional phases of the flows. Actual flows were occasionally observed where they debouched from mountain fronts. In most cases, however, debris flows were not directly observed, because of downstream dilution to less viscous flow before leaving the mountain front, or because of the presence of a two-phase flow in which normal water flow occurred as an upper layer to a debris slurry in the manner documented by Scott (1971, p. 247).

A number of interesting historical reports support the evidence of debris flow concomitant with flood discharges in larger drainages of the Transverse Ranges during major floods. Reports include the appearance of boulders at the surface of what seemed to be normal water discharge, and standing trees seen moving downstream. To this can be added the plight of an individual, submerged and pinned upright against his car by floodwaters, who was buried to his shoulders by a wavelike mass of sediment and who survived to describe the experience. Clearly, however, the process of debris flow is of markedly less quantitative importance the larger the drainage area and the more subdued the relief.

Evidence of debris flows or viscous surges of sediment-water slurry associated with storm runoff was also present in some larger watersheds. In 1969 coarse fill occurred in downstream reaches of Sespe Creek (fig. 3), a 251-mi^2 (650 km^2) watershed. Evidence from buried vegetation indicates that the fill was continuous, both across the channel and to a point 0.8 mi (1.3 km) away from the mountain front. Fill ceased at that point as if a pronounced front, 4–5 ft (1.2–1.5 m) in height, existed across the channel. The front was subsequently cut by recession flow. Though the presence of such fronts is not total proof of debris flow (see Scott and Gravlee, 1968, p. 20–22), when combined with the character of the deposits—the size, sorting, and continuous nature of the fill—the evidence is strong. Deposits of the filled reach differed from most of those farther downstream in that they were coarser and more poorly sorted.

So prominent and widespread was evidence of debris flows in the small watersheds after the 1969 storms that it is possible to formulate a model for the dispersal of sediment in such watersheds: Lateral supply of sediment to stream channels is a relatively continuous process, accomplished during the dry season by dry sliding and in the wet season by mass movements and overland flow. During periods between major storms, stream channels undergo more-or-less time-continuous fill. Then, during a major storm, channel bed material is mobilized and dispersed in large part by debris flows, some of which are induced by mass movements triggered by the storm. Channels undergo much net scour, accomplished by incorporation of bed material in the debris flows and by scour during recession flow. Valley-side slopes are undercut by bank erosion, paving the way for a new cycle of channel infilling.

This model is probably most applicable to watersheds less than 5 mi^2 (13 km^2) in size. It is empirically obvious, but not quantitatively demonstrable, that debris flows account for the bulk of coarse-sediment (>2 mm) dispersal in such watersheds. It is, of course, with catchment of the coarse sediment that debris-basin planning is most concerned.

MUDFLOWS

The modal class in size distributions of the 1969 Glendora debris flows was the 8–16 mm range (Scott, 1971, table 2). In the continuum of flow types, as grain size decreases and when mud content (<0.0625 mm) exceeds 10 percent dry weight of the contained sediment, the muddy, viscous appearance of the mixture will usually result in designation as a mudflow. Although no widely accepted distinction between mudflows and debris flows exists, the limit of 10-percent mud used here achieves an adequate working distinction in the Transverse Ranges.

Mudflows occurred in 1969 where thick deposits of fine-grained alluvium became saturated near the end of each storm period. Because of the sealing effect of the finer sediment, mudflows were able to continue in movement well beyond the mountain fronts. Two such 1969 flows in the Transverse

Ranges were described by Scott (1971, p. 246), but in neither case does a parallel situation exist in any study watershed. In contrast, loss of fluidity by infiltration halted most of the more coarsely grained debris flows in the fan channels within a short distance of mountain fronts.

Mudflows commonly occur in watersheds which are underlain by fine-grained sedimentary rocks and which have been burned by recent wildfire. Mudflows occurred in December 1971 in small watersheds of an area burned in October 1971 20 mi (32 km) northwest of Ventura. Witnesses described these flows of surges of what appeared to be mud covered with water backed up behind a moving boulder front. High water marks of the storm period were formed by the initial surge of mud in each channel. Succeeding surges were of an equally short duration but were accompanied by less pronounced boulder fronts.

Only small, localized mudflows occurred in 1969 in the watersheds shown in figures 2 and 3, probably because of a lack of recent burns in the susceptible watersheds. A few shallow slumps continued as mudflows, but in no known case in the study watersheds did movement progress much beyond the foot of the failed slope. However, a definite mudflow potential exists in the Mud Creek watershed mentioned above. Many active slumps bordering Mud Creek could change to rapid earthflows or mudflows after long periods of saturation or a change in ground-water conditions. Such flows could continue down channels and could be destructive to development downstream. There is also potential for channel blockage by a slump, followed by release of a surge.

RELATIVE IMPORTANCE OF SEDIMENT-TRANSPORT PROCESSES

The preceding emphasis on mass movement and related processes should not give the impression that movement of sediment as bedload or suspended sediment in normal stream runoff is necessarily of subordinate importance. The significant point is that, compared with sediment-transport processes operating on a year-to-year basis in these unstable watersheds (and in stable watersheds at all times) the processes operative in small watersheds in the Transverse Ranges in a major storm are markedly different. Many kinds of mass movements can be triggered, sediment may sluff from precipitous hillslopes at record-setting rates, and debris flows and mudflows may pour down steep canyon bottoms, mobilizing and incorporating most channel-bed material in their path.

Throughout this discussion, emphasis has been placed on transport of the coarse sediment fractions which constitute the volumetric bulk of the sediment produced in these watersheds. Even during a major storm most of the silt and clay (<0.0625 mm) and part of the sand (0.0625–2 mm) would continue to be transported as suspended sediment in flood discharge.

SLOPE FAILURES AS RELATED TO DEBRIS FLOWS AND MUDFLOWS

An inspection of all watersheds after the 1969 storms showed that the frequency and size of debris flows in a given watershed was directly related to the amount of slope failure in the watershed. If this was the case, were the flows triggered in part by the slope failures? This possibility was investigated by Scott (1971, p. 243–244) in watersheds above Glendora. In one place the relation was definitely established by tracing debris-flow levees to their point of origin. In others the relation was very suggestive but not beyond doubt. It was not doubtful, however, that slope failures were an important source of sediment to the flows, indicated by abrupt increases in height of debris-flow levees at the sites of slides. Conversely, some slope failures were triggered or enlarged by bank erosion by the flows.

The slope failures that generated some of the debris flows and accounted for surges in others were small and generally involved only surficial or highly fractured material. Many were soil slips. In the Glendora watersheds, these small slope failures were not directly related to the large slumps and block glides that were present in all the watersheds. However, the number and extent of these larger slope failures did appear to be related to watershed stability and thus indirectly to sediment yields.

HOW 1969 SEDIMENTATION PROCESSES RELATE TO DETERMINATIONS OF EROSION RATES

Study of the results of the 1969 storms in the Transverse Ranges led to several conclusions important to the determination of erosion rates (Scott, 1973).

First, sediment-yield rates for design storms must be based on yields from actual major storms of similar recurrence interval. The noteworthy differences in the way mountain watersheds respond to major versus minor storms could result in actual major-storm rates being greater than would have been expected from an analysis based on data from lesser storms.

Secondly, peak discharges based on indirect determinations of discharge in watersheds like the study watersheds should not be used as a variable by which to correlate sediment yields. There are several reasons to doubt the reliability of some discharge measurements in small watersheds after major storms. The possible presence of debris flow or mudflow at the time high water marks were formed, and the unknown degree of change in channel cross section after passage of a peak are two such reasons. Processes of scour and fill are especially variable and unpredictable in the heterogeneous sediment in which stream channels of semiarid regions are formed.

These observations lead to another important consideration. Sediment yields and channel processes are clearly time-evolutionary. Many of the channel changes and unusual processes would not have occurred, or would have been less pronounced, had not abundant bed material been available for transport in channels. Channels that before the storms were choked with detritus were scoured to bedrock by storm runoff and removal of bed material in debris flows (fig. 7), and such was probably also true during the 1938 storms. For equivalent conditions to produce equivalent sediment yields, a similar quantity of bed material would have to be available. Consequently, sediment-yield studies from a storm closely preceded by another major storm may be of limited practical value. For this reason, sediment yields from the second 1969 storm (in February) were relatively low, and the storm could not be used for correlation purposes.

Most importantly, it is obvious that erosion rates in the area are directly dependent on the geological youthfulness—the interplay of relief and erodibility—of the terrain in each watershed. The following analysis of watershed characteristics is in part a search for a combination of variables that will assess the effect of watershed instability on sediment yields. Possibilities include geomorphic variables, measures of soil erodibility, or a variable that defines the areal extent of slope failures. This is particularly important in analysis of highly variable sediment yields, because in the type of analysis commonly used, multiple regression, most of the standard error generally is due to neglect of significant factors (or to incorrect model formulation), not to errors in measurement.

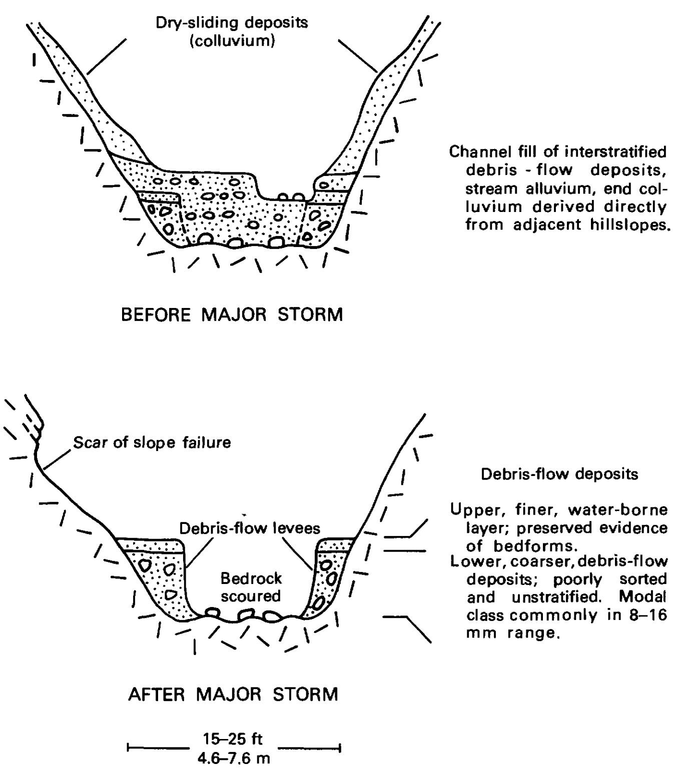

FIGURE 7.—Diagrammatic cross sections of typical bedrock-channel deposits in an area of high erosion rates in the Transverse Ranges.

METHODS OF DATA ANALYSIS

Because of its quick and effective applicability to the problem (Shen, 1972), multiple linear regression was selected as the technique by which erosion rates would be correlated from one set of watersheds to another (see criticism of factor analysis by Matalas and Reiher, 1967). Basically, multiple regression creates a linear mathematical equation of the relation between a dependent variable, in this case sediment yield, and a group of explanatory independent variables, the watershed characteristics that control the amount of sediment eroded. Results of previous studies have shown that hydrologic events are most nearly linearly related to watershed characteristics with logarithmic transformation of all variables.

Many logical series and combinations of watershed variables were analyzed by means of a program for stepwise regression (Dixon, 1968). In this procedure, the independent variables are progressively added, with calculation of the regression equation, standard error of estimate, and effectiveness of the most significant independent variables as each is added in order of its significance. A variable may be significant at an early stage of the computation but may be deleted after other variables are added.

This step-by-step analysis allowed for rigorous study of the effects of the variables, their interaction with variables already entered, and the progressive changes in accuracy of the relations. Variables were grouped and ordered according to their logical effects on sediment yield.

Where independent variables are themselves correlated, regression coefficients can be unstable and most statisticians believe that correlation might be spurious. To reduce this possibility, a simple partial correlation matrix was prepared and, in the case of correlation between two similar variables, only that variable giving the greatest reduction in standard error was included. There are, however, those who believe that if, as in this study, the purpose is to derive a regression formula that predicts the dependent variable accurately rather than to interpret individual regression coefficients, bias due to intercorrelation may actually be advantageous (Snedecor and Cochran, 1967, p. 395).

No absolute cause and effect is necessarily implied by correlation of the variables. The method simply provides an optimum fit of selected variables in the form of a predictive equation where success is reflected in a measure of the accuracy of the relation—the standard error of estimate. Using the regression equations for prediction at a number of sites, two-thirds of the estimates would be within the range of the standard error from the true value, and 95 percent would be within a range of twice the standard error. The assumption of normality of the residuals is necessary for tests of significance, but not for other standard properties of regression estimates.

PHYSIOGRAPHIC CHARACTERISTICS

Many physiographic variables have been developed in attempts to define the shape of watersheds. The number is probably well in excess of 100, and many are claimed to relate watershed shape to erosion rate more significantly than simple measures like basin size and channel slope.

An opportunity existed in data compiled by Ferrell (1959) to test a number of these variables in the Transverse Ranges. Using a selected group of seven watersheds, each with three sediment accumulations, physiographic variables were correlated with 21 separate sedimentation events (table 1), including some resulting from the major 1938 storm. Variables were regressed against sediment yield as the dependent variable. Discharge and a vegetation factor were included as additional independent variables. The discharges in these analyses are actual measurements in large part and are not subject to the uncertainties described in previous sections.

Two stepwise multiple regressions were computed to compare the relative ability of each physiographic variable to explain the residual error after two important variables with known significance had already been included:

1. Total sediment yield (S_y) as the dependent variable regressed against peak discharge (Q_{cfs}), the vegetation index (VI) of Ferrell (1959), and the group of physiographic variables. The result, after insertion of Q_{cfs} and VI, is

   $$\text{Log } S_y = 3.720 + 0.921 \log Q_{cfs} - 1.267 \log VI.$$

   The standard error of estimate is 0.387 log units (+143, − 59 percent).

2. Sediment yield per square mile (S_y') as the dependent variable regressed against peak discharge per unit area (Q_{csm}), vegetation index, and the group of physiographic variables. The result, after insertion of Q_{csm} and VI, is:

   $$\text{Log } S_y' = 3.655 + 1.070 \log Q_{csm} - 1.488 \log VI.$$

   The standard error of estimate is 0.388 log units (+145, −59 percent).

Considerable care in data selection was necessary to insure that basins in the analysis were similar in respect to variables not included, such as soil erodibility, lithologic type, slope stability, and urbanization. Calculation of the vegetation index involves a subjective weighting procedure after both cover density and subareas dominated by each of eight vegetation types are determined from aerial photography. It includes the effects of wildfire.

Physiographic variables in the analysis were confined to those found significant in correlations with erosion rates in southern California and similar areas (Ferrell, 1959; Lustig, 1965; Anderson and Wallis, 1965; Tatum, 1965; and Scott, Ritter, and Knott, 1968). Several potentially useful variables, such as Anderson's variable (1949b, p. 571), area of main channel of the watershed, were excluded because of inapplicability to small, steep watersheds of this study. Variables included are as follows:

Hypsometric-analysis index: The index is a measure of the distribution of land surface within a basin—the relation of horizontal cross-sectional drainage area to altitude; a plot of these variables defines the hypsometric curve (Langbein and others, 1947, p. 140). Relative height, h/H (altitude of a given contour above basin outlet/basin relief), is plotted against relative area, a/A

(area in basin above a given contour/total drainage area). The index used by Tatum (1965, p. 886) is the relative height at the point $a/A = 0.5$.

Mean ground-slope angle ($\bar{\theta}g$): Measured by Ferrell (1959, p. 67) as the average slope between successive contours, corrected for the relative proportion of total area occupied by each contour interval.

Mean stream length: The sum of stream lengths of all orders divided by the total number of streams. Data were obtained from Ferrell (1959) who utilized only streams delineated on topographic maps. Future determinations of stream length should be made by the contour method of Morisawa (1957) in which the drainage net is sketched by inserting streams wherever V-shaped contours are present.

Total stream length (ΣL): Total length of all streams in the watershed. The factor is highly area dependent but should more accurately reflect the degree of watershed dissection, implying greater sediment yield, than simple drainage area.

Mean bifurcation ratio ($\bar{R}b$): The mean of the ratios of the number of streams of each order to the number of streams of the next higher order. Ferrell (1959, p. 68) weighted his data by multiplying each bifurcation ratio of each successive pair of orders by the total number of streams involved in the ratio. Strahler (1957, p. 914) noted that, although the bifurcation ratio seems a useful dimensionless number to define a drainage system, it is highly stable except where powerful geologic controls exist.

Transport-efficiency factor (T_1): Defined as $T_1 = \bar{R}b \times \Sigma L$, the product of the mean bifurcation ratio and total stream length. Found by Lustig (1965, p. 18) to be the factor showing the best correlation with sediment yield of any of the physiographic variables in his study of reservoir sedimentation in southern California. It is an adjustment of total stream length to reflect the character of the drainage pattern.

Sediment-area factor (S_A): Another of Lustig's more significant factors; defined as $S_A = A/\cos \bar{\theta}_g$, the ratio of drainage area to the cosine of the mean ground-slope angle. As suggested by Lustig (1965, p. 13) the ground-slope angle was determined at 100 points in each watershed, in this study by means of a grid overlay.

Sediment-movement factor (S_M): The product, $S_M = S_A \times \overline{\sin \theta_g}$, of the sediment-area factor and the mean of the sines of the ground-slope angles (Lustig, 1965, p. 17). In theory it is a measure of the downslope forces acting on the weathered mantle of a watershed.

Mean basin exposure: The azimuth of the average direction of slope in the basin Ferrell (1959, p. 67) outlined all major slope exposures, determined the slope direction of each, and summed the values proportionally by size of area to obtain the mean value. The range of values in the sample watersheds is probably too small to show the real effects of this variable.

Elongation ratio (ER): A ratio produced by dividing the diameter of a circle with an area equal to that of the watershed by the maximum watershed length measured in a straight line parallel to the main channel.

Relief ratio (Rr): The ratio of watershed relief and overall basin length (see Schumm, 1956, p. 612). Studies of Schumm (1954, p. 217) indicated strong correlation of relief ratio with sediment yields from small drainage basins on the Colorado Plateau. Relief ratio was selected by Ferrell (1959) on this basis as the physiographic variable to be used in estimation of sediment yields in Los Angeles County.

Area under the area-altitude (hypsometric) curve: The area beneath the hypsometric curve previously described.

Mean channel slope: Average slope of the drainage path between the highest and lowest points in a watershed, measured along the main drainage channel.

Ratio of surface area to planimetric area: The relation between the surface area and the drainage area as planimetered from a map. Surface area is the product of the plane area between contour lines and the secant of the slope between the same two contour lines (Farrell, 1959, p. 67).

Drainage density (Dd): The ratio of the sum of channel lengths to planimetric drainage area. As noted by Strahler (1957, p. 916), stream density apparently increases in watersheds of greater erodibility and reaches a maximum in areas of badland topography.

Standard deviation from uniform slope: A measure of the variation of the slope of the main channel from a straight line drawn from the headwaters of a stream to its outlet. It is apparently similar to the coefficient of variation of flowpaths (Wallis, 1965, p. 50).

Elongation ratio and the area under the area-altitude (hypsometric) curve are the variables that

TABLE 1.—*Summary of physiographic variables, discharges, and sediment data for selected watersheds in eastern Transverse Ranges of Los Angeles County*

[Data in part after Ferrell (1959) and Tatum (1965)]

Drainage basin (Number corresponds with location in fig. 2)	Drainage area A (mi²)	Hypsometric-analysis index	Mean ground-slope angle θ_g (degrees)	Length of streams of order μ (ft)	Mean stream length (ft)	Total stream length ΣL (mi)	Mean bifurcation ratio Rb	Transport-efficiency factor T_1	Sediment-area factor S_A	Sediment-movement factor S_M	Mean basin exposure (azimuth in degrees)	Elongation ratio ER
Shields Canyon (8)	0.23	0.51	39.4	$\Sigma L_1=$ 262 $\Sigma L_2=$ 399 $\Sigma L_3=$ 761 $\Sigma L_4=$ 3,315	318	0.90	6.58	5.92	0.30	0.19	187.2	0.593
Pickens Canyon (9)	1.70	.47	39.4	$\Sigma L_1=$ 345 $\Sigma L_2=$ 345 $\Sigma L_3=$ 1,535 $\Sigma L_4=$ 4,439 $\Sigma L_5=$ 2,301	423	1.72	6.35	10.92	2.20	1.40	206.6	.783
Hall Beckley Canyon (11)	.68	.50	41.1	$\Sigma L_1=$ 287 $\Sigma L_2=$ 416 $\Sigma L_3=$ 751 $\Sigma L_4=$ 3,000 $\Sigma L_5=$ 3,050	346	1.42	5.26	7.47	.90	.59	201.6	.751
Birmingham Canyon (13)	.17	.42	34.0	$\Sigma L_1=$ 166 $\Sigma L_2=$ 295 $\Sigma L_3=$ 487 $\Sigma L_4=$ 650 $\Sigma L_5=$ 2,196	203	.72	6.94	5.00	.20	.11	210.6	.673
Sunset Canyon (14)	.43	.48	38.7	$\Sigma L_1=$ 296 $\Sigma L_2=$ 486 $\Sigma L_3=$ 983 $\Sigma L_4=$ 1,382 $\Sigma L_5=$ 420	350	.68	5.65	3.84	.55	.34	222.3	.841
West Ravine (20)	.25	.40	27.5	$\Sigma L_1=$ 205 $\Sigma L_2=$ 362 $\Sigma L_3=$ 552 $\Sigma L_4=$ 1,590 $\Sigma L_5=$ 2,603	260	1.01	6.52	6.59	.27	.12	202.5	[1].672
Little Santa Anita Canyon (26).	2.39	.48	36.2	$\Sigma L_1=$ 337 $\Sigma L_2=$ 698 $\Sigma L_3=$ 1,266 $\Sigma L_4=$ 3,982 $\Sigma L_5=$ 10,800	425	3.24	6.32	20.48	3.06	1.81	169.0	.632

[1] Value for ER was determined by Farrell (1959) from topographic maps older and of smaller scale than modern editions and is not comparable to value used in a following analysis. Included for consistency of data sources in this analysis.

explain the greatest amount of residual variance after discharge and vegetation factors are included in the regressions.

Elongation ratio is seen in the following sections to correlate positively with sediment yield; that is, the less elongate a watershed the higher the sediment yield. This conclusion is compatible with an element of sediment-transport theory—the likelihood of a given particle being eroded from a basin is generally inversely proportional to its distance from the basin outlet. In California, however, other data suggest that a low elongation ratio (an elongate watershed) reflects a degree of structural instability, as in a valley cut in directionally sheared or faulted bedrock. The highest sediment yields from large drainage basins in California are from elongate fault-line valleys in the Eel River basin. Also, the highest recorded yields from very small watersheds occur in elongate basins in the San Gabriel Mountains (for example, the Rainbow Drive watershed; Scott, 1971). Geologic assessment of local basins in the size range of those in this study indicates, however, that few, if any, contain fault-line valleys.

The use of area under the area-altitude curve as a variable has been criticized because it is based on a single value rather than the entire population of a statistic (Wallis, 1965, p. 45). Criticism of its use is logical for areas of constructional topography, such as the volcanic terrain of the Wallis example.

SOIL ERODIBILITY

A major control of erosion rate in a watershed normally is the erodibility of the soils in that watershed. Soil erodibility, in terms of differences among the azonal mountain soils of watersheds that have high erosion rates, is not generally a part of soil mapping. Routine soil survey involves the categorization of soils by characteristics of subsurface weathering horizons that may have little relation to the erodibility of the surface layer. Analysis of soil erodibility, therefore, must be a special study.

Mapping of mountain soils on the basis of erodibility of the surface layer is not feasible. A valid but less time-consuming approach must be substituted. The method used here is to key soil erodibilities to lithologic types; that is, by using values of the erodibility of soils developed on each rock type

TABLE 1.—*Summary of physiographic variables, discharges, and sediment data for selected watersheds in eastern Transverse Ranges of Los Angeles County*—Continued

[Data in part after Ferrell (1959) and Tatum (1965)]

Drainage basin (Number corresponds with location in fig. 2)	Relief ratio Rr	Area under area-altitude (hypsometric) curve (in ^{2})	Mean channel slope (percent)	Ratio of surface area to planimetric area	Drainage density (Dd)	Standard deviation from uniform slope	Vegetation index (VI)	Peak discharge Q_{cfs} (ft^3/s)	Peak discharge Q_{csm} ((ft^3/s)/mi^2)	Sediment yield S_y (yd^3)	Sediment yield per unit area (erosion rate) S_y' (yd^3/mi^2)
Shields Canyon (8).	0.445	44.78	36.5	1.30	29.6	16.6	1938: 12.04 1943: 14.89 1952: 16.22	1938: 82 1943: 82 1952: 37	1938: 358 1943: 358 1952: 160	1938: 31,000 1943: 4,940 1952: 7,770	1938: 135,000 1943: 21,500 1952: 33,800
Pickens Canyon (9).	.268	50.80	21.0	1.31	21.8	14.8	1938: 11.30 1943: 17.76 1952: 14.31	1938: 503 1943: 632 1952: 218	1938: 296 1943: 372 1952: 128	1938: 141,000 1943: 41,000 1952: 7,760	1938: 83,000 1943: 24,100 1952: 5,500
Hall Beckley Canyon (11).	.307	49.07	25.0	1.33	31.5	16.6	1938: 12.79 1943: 19.41 1952: 22.16	1938: 223 1943: 241 1952: 101	1938: 328 1943: 354 1952: 149	1938: 79,600 1943: 39,000 1952: 13,200	1938: 117,000 1943: 57,400 1952: 19,400
Birmingham Canyon (13).	.278	45.81	24.4	1.21	51.6	20.3	1954: 1.62 1955: 1.62 1955: 3.10	1954: 2 1955: 2 1955: 4	1954: 12 1955: 12 1955: 23	1954: 5,370 1955: 5,590 1955: 2,670	1954: 31,600 1955: 32,900 1955: 15,700
Sunset Canyon (14).	.333	51.47	28.9	1.28	39.3	17.2	1938: 17.00 1943: 18.00 1952: 19.00	1938: 106 1943: 138 1952: 67	1938: 247 1943: 321 1952: 155	1938: 6,620 1943: 1,180 1952: 3,440	1938: 15,400 1943: 2,750 1952: 8,000
West Ravine (20).	.309	36.08	23.6	1.13	42.4	22.0	1938: 16.66 1943: 20.13 1952: 21.27	1938: 76 1943: 90 1952: 29	1938: 305 1943: 361 1952: 117	1938: 30,500 1943: 6,870 1952: 3,230	1938: 122,000 1943: 27,500 1952: 12,900
Little Santa Anita Canyon (26).	.291	48.07	20.6	1.24	43.4	14.1	1938: 19.12 1943: 20.08 1954: 13.32	1938: 743 1943: 707 1954: 219	1938: 311 1943: 296 1954: 92	1938: 61,700 1943: 22,000 1954: 55,400	1938: 25,800 1943: 9,200 1954: 23,200

and proportioning these values to the percentage of exposure of that rock type, a mean value of soil erodibility for a watershed can be determined.

Such an analysis ties erodibility to only one of the soil-forming factors—parent material. Because of tectonic activity, however, the Transverse Ranges are the penultimate in youthful terrain where parent material is logically the dominant soil-forming factor. Other workers (Anderson, 1954; André and Anderson, 1961; and Wallis, 1965) have found that erodibility indices related to geology correlate well with erosion rates in areas where the factor of parent material is of lesser importance. André and Anderson (1961, table 3) showed that parent material explained a larger amount of the variation in erodibility between samples than did any other soil-forming factor for soils of northern California.

Soil erodibility is measured by a variety of indices, most of them applicable primarily to agricultural soils. Most of the indices applied to mountain terrain are proportional to the silt content of the soils or to the degree of aggregation of fine particles into larger aggregates. Two measures of erodibility shown to correlate significantly with erosion rates in previous studies in mountain areas were measured for each major rock type in the study area. They are defined as follows:

Dispersion ratio (*DR*): The ratio, expressed as a percentage, of the percentage of measured silt- and clay-size particles in an undispersed soil to the percentage of the same sizes after dispersion (Middleton, 1930, p. 3)

Surface-aggregation ratio (*SA*): The ratio, expressed as a percentage, of the surface area of particles coarser than silt divided by the value of aggregated silt plus clay. Surface area is obtained by treating the particles as spheres with a specific gravity of 2.65 and assigning mean diameters to the sand, granule, and pebble classes. Aggregated silt plus clay is the percentage of dispersed silt- and clay-size particles minus the percentage measured before dispersion (Anderson, 1954, p. 272). Basically, this index is the ratio between the amount of surface area needing binding in order to form a cohesive, erosion-resistant soil to the amount of cohesive fine material available to accomplish the binding.

Silt and clay content of the soils was measured by hydrometer, using techniques suggested by Bouyoucos (1936, p. 225–226) and Anderson (1954, p. 277). Size distribution of the coarser-than-silt fraction in each sample was then determined by wet sieving.

The number of samples collected from each rock type was proportional to the variability in lithology in each of the geologic units. For example, the metamorphic assemblages (pK), alluvium (Qal), and terrace deposits (Qt) were judged to be highly variable, and multiple samples of soils from these units were collected in both Ventura and Los Angeles Counties. Each sample consisted of three penetrations of the top 6 in (152 mm) of the surface layer with a coring device. At least three samples were collected per unit under conditions as nearly uniform as possible—natural vegetation on slopes of 20–30 percent facing south or southwest.

Both the dispersion ratio and surface-aggregation ratio were included in the final analysis. The values (table 2) compose a set of reference data that can be used to quantify soil erodibility throughout the area. The data are, of course, applicable only to the azonal soils of mountain and foothill areas.

SLOPE FAILURE

The extent of slope failure was calculated as the proportion of the drainage area underlain by failures in each of the 72 study watersheds. Talus and dry-sliding deposits were excluded; slides, slumps, block glides, and soil slips were included. Calculations were made with grid overlays on aerial photographs and geologic maps. Where landslide maps of adequate accuracy and scale existed, as in parts of the San Gabriel Mountains (see references in Morton and Streitz, 1969), this mapping was used as a standard for the delineation of map units. Elsewhere, criteria used for the field recognition (fig. 8) and aerial-photograph interpretations of slope failures were those outlined by Ritchie (1958) and Liang and Belcher (1958).

The methods for determination of this variable are by nature subjective. Nevertheless, this objection is negated by applying the same standards to all the watersheds. Extension of the analysis to additional watersheds in the western Transverse Ranges should first involve study of maps or photographs of basins that have a large number of landslides and for which values of the slope-failure variable are given in this report. Watersheds in the Glendora area (East Hook Canyon, Harrow Canyon, or Englewild Canyon), for which published or available maps exist (see references in Morton and Streitz, 1969), are ideal for this purpose.

Simple correlation of the slope-failure variable with the two retained physiographic variables and most of the other physiographic variables was at a relatively low level. It is possible that a slope-failure variable is a more sensitive indicator of erosion rates in areas where such rates are high. The logic (in addition to statistical significance) behind inclusion of this variable in the final analysis is established by the close association of extensive mass movement and debris-flow transport and, in turn, between debris-flow transport and high erosion rates.

HYDROLOGIC FACTORS

The selection of hydrologic factors related to erosion rates in southern California has been limited only by the number of studies. Therefore, the approach selected is in part pragmatic; as in the case of physiographic factors, variables selected will be those that correlate most significantly with actual sediment yields in the area.

Erosion rates are of greatest practical value if a recurrence interval can be established for major-storm contributions. Unfortunately, the recurrence intervals of rainfall, discharge, and sediment yields rarely coincide. Because sediment records are much too sparse for determining actual recurrence frequencies, a precipitation or runoff variable for which a more reliable recurrence interval can be determined must be used to compare major-storm sediment yields. Values of variables for a 50-year design storm can then be compared with data for a storm like that of January 1969. The uncertainty in relating sedimentation, discharge, and rainfall frequencies is understood to apply but is pragmatically necessary.

PRECIPITATION

The true total rainfall over a basin is difficult to assess because of the interaction of orographic effects, wind, temperature, evaporation, geographic alinement of watersheds, and other basin characteristics. Extreme local meteorologic differences can, however, be negated by regionalization of data. Also, uncertainties will exist when a frequency is assigned to any actual storm, even when data are reliable. The true return period is not statistically established because of the short period of record at Transverse Range stations. Thus, a theoretical 50-year precipitation may not be representative of

TABLE 2.—*Dispersion and surface-aggregation ratios as related to all geologic units in debris-producing areas of Ventura County and in selected drainage basins in Los Angeles County. Map symbols are those used by Kundert (1955)*

Lithologic type	Map symbol	Dispersion ratio (*DR*)		Surface-aggregation ratio (*SA*)	
		Mean	Confidence liimts at 0.95 probability	Mean	Confidence limits at 0.95 probability
Quaternary alluvium—highly variable, poorly sorted sand and gravel in or near modern stream courses	Qal	56	±18	132	±76
Quaternary terrace deposits—poorly sorted sandy gravel capping uplands or lateral to and above modern stream courses	Qt	50	±10	111	±27
Pleistocene nonmarine deposits—predominantly lacustrine silt and clay with a few gravel lenses	Qc	57	±6	103	±25
Pleistocene marine deposits—medium- to well sorted sand and silt with thin intercalations of gravel; well exposed in foothills behind Ventura	Qm	33	±2	103	±11
Pliocene nonmarine sedimentary rocks—poorly indurated siltstone, sandstone, and minor conglomerate; erodes to badland topography, indicating areas of high sediment yield	Pc	53	±4	121	±12
Middle and lower Pliocene marine sedimentary rocks—well-bedded siltstone, shale, and sandstone with conglomerate lenses; one of the predominant rock units underlying the Santa Clara River valley; locally synonymous with the Pico Formation, discussed in section on mass movements	Pml	48	±5	79	±8
Upper Miocene nonmarine sedimentary rocks—siltstone, shale, sandstone, and conglomerate	Muc	44	±3	69	±9
Upper Miocene marine sedimentary rocks—thinly bedded siltstone, shale, and sandstone; better indurated than any younger rocks	Mu	52	±3	66	±9
Miocene volcanic rocks—intrusives and flows of variable composition with agglomerates, tuffs, and breccias	Mv	52	±6	140	±42
Middle Miocene nonmarine sedimentary rocks—similar lithology to Muc	Mmc	40	±5	66	±18
Middle Miocene marine sedimentary rocks—lithology similar to Mu; a major rock type throughout Ventura County	Mm	41	±1	62	±10
Lower Miocene marine sedimentary rocks—lithology generally similar to Mm, Mu; more shale than in younger marine units	Ml	46	±3	70	±8
Oligocene nonmarine sedimentary rocks—generally thin-bedded shale and sandstone distinguished by colorful shades of red and yellow; a major rock unit in western Ventura County	ϕc	55	±4	75	±12
Eocene marine sedimentary rocks—interbedded shaly siltstone, and sandstone; sandstone predominates throughout much of the unit and forms resistant ridges with small potential for sediment yield	E	34	±2	77	±6
Paleocene marine sedimentary rocks—poorly exposed shale and sandstone	Ep	30	±10	57	±26
Upper Cretaceous marine sedimentary rocks—massive indurated sandstone with minor interbeds of shale; moderately resistant with low erosion potential	Ku	38	--	59	--
Granitic rocks of Los Angeles County, age indefinite—massive intrusives of intermediate composition; high degree of deuteric alteration and postintrusion faulting and fracturing create potential for high sediment yields	gr	36	±6	121	±35
Granitic rocks in Ventura County, of Jurassic age—lithologically similar to gr of Los Angeles County; less altered and fractured than equivalent rocks in Los Angeles County	Jgr	40	±1	108	±42
Pre-Cretaceous marine metasedimentary rocks of Los Angeles County—an assemblage of phyllite, schist, and gneiss, commonly containing small intrusives; high degree of alteration and fracturing create potential for high sediment yields	pK	47	±5	139	±30
Pre-Cretaceous marine metasedimentary rocks of Ventura County—gneiss predominates in an assemblage also including phyllites and schists; a few small intrusives; less altered and fractured than equivalent rocks in Los Angeles County	pK	36	±4	145	±43

FIGURE 8.—Typical Transverse Range slump showing features used to identify slope failures, from top right to bottom left: Crown of slide (A); main scarp (B); transverse cracks (C); toe of slide (D). Road at left is offset along a longitudinal failure zone within the slump.

an actual storm, whereas a variable that expresses actual storm precipitation will be a valid physical descriptor, will be meteorologically realistic, and still be representative of a major storm, such as that of January 1969.

Any inventory of precipitation requires a knowledge of the meteorologic conditions that prevail during the corresponding periods of high discharge. It has been suggested that each storm is an entity in itself and will not be repeated; however, one storm pattern can be distinguished repeatedly in southern California coastal regions—the extratropical cyclonic storm previously described that develops off the Pacific coast and causes major floods as the storm moves inland. All major erosion-producing storms in the Transverse Ranges can be assumed to be of this type. Comparable storms can be assigned a probable frequency and magnitude. Although large variations in rainfall occur and measurement deficiencies exist, storms of this type can be fitted reasonably well by a generalized isohyetal pattern. This pattern in January 1969 was found to coincide closely with the pattern of mean annual precipitation. Such coincidence should be expected because mean annual precipitation is influenced by the same factors affecting the major storms and a large proportion of the mean annual precipitation results from storms of this type.

Rainfall variables in the analysis included January 18–27, 1969, total-storm precipitation; 24-hour maximum January 1969 precipitation; 50-year 24-hour maximum precipitation; 50-year, 1-hour precipitation; and mean annual precipitation. Values were obtained for each drainage basin from isohyetal maps prepared by local agencies, the National Weather Service, and the Geological Survey. Definition by the various sources was consistent throughout the region except for the Ojai area of Ventura County, where values of the 50-year 24-hour maximum and the 1969 24-hour maximum rainfall were poorly defined.

Mean annual precipitation was evaluated for each drainage basin on the basis of 90 years of record in Los Angeles County and 50 years of record in Ventura County. A comparison of map values of mean annual precipitation and the averaged yearly figures obtained from the National Weather Service showed good agreement.

Precipitation variables were studied to determine what intensities and durations would provide the best correlation. Sediment yields from several storms were plotted graphically against different precipitation variables, with corrections to eliminate the effects of watershed burns. The results indicated that 7- to 10-day total precipitation and 24-hour rainfall intensity are critical factors. The factor selected, K, is defined as 10-day $\times$ (24-hour precipitation)^2 and is analogous to the discharge function of Nelson (1970). The variable K is a measure of antecedent conditions as well as the peakedness of rainfall during the period in which sediment contributions by the unusual modes of transport described in previous sections are highest.

Frequency analyses of several long-term precipitation records were then evaluated (table 3) to determine a corresponding storm with a 50-year frequency of occurrence to adjust part of the 1969 data.

TABLE 3.—*Depth-duration comparison of 50-year precipitation and nearest actual precipitation at stations in the Transverse Ranges*

Station name	Duration	Depth (in) and K factor			
		50-year precipitation[1]	Nearest actual precipitation	(year)	January 1969 precipitation
Ojai	Monthly	23.3	23.8	(1969)	23.8
	10-day	20.6	20.1	(1914)	22.3
	24-hour	8.12	8.0	(1969)	8.0
	K	1,270	1,430	(1969)	1,430
Santa Paula	Monthly	16.9	17.2	(1962)	17.6
	10-day	14.7	14.7	(1962)	16.1
	24-hour	6.03	5.09	(1938)	5.01
	K	480	404	(1969)	404
Fillmore	Monthly	19.9	22.1	(1969)	22.1
	10-day	18.0	20.53	(1969)	20.5
	24-hour	6.52	6.40	(1952)	5.86
	K	690	705	(1969)	705
Santa Barbara	Monthly	16.9	17.2	(1916)	15.6
	10-day	14.0	13.3	(1969)	13.3
	24-hour	5.41	5.53	(1943)	3.96
	K	362	388	(1943)	208
Ventura	Monthly	14.3	14.0	(1907)	8.7
	10-day	11.1	12.7	(1962)	7.8
	24-hour	4.70	4.62	(1943)	2.75
	K	216	202	(1956)	58.9
Mount Wilson	10-day	34.3	35.3	(1969)	35.3
	24-hour	13.8	12.0	(1969)	12.0
	K	6,010	5,080	(1969)	5,080

[1] Values obtained from frequency curve.

PEAK DISCHARGE

A high correlation between sediment discharge and peak flow can be expected to exist. Sediment data from several large drainages in southern California indicate that 87 to 99 percent of the coarse material is transported during 1 percent of the time (written commun., C. G. Kroll, 1973). A comparison of 50-year and January 1969 peak discharges will aid in determining the degree of usefulness of the 1969 storm as a possible design storm.

Nelson (1970) has shown good results in relating annual suspended-sediment discharges to a variable that includes both annual runoff and annual peak discharge. Unless actually measured, however, peak discharge and annual runoff are extremely difficult to estimate for small basins like the study watersheds. An additional complication is that there is no universally accepted method to estimate discharges in this area. The Pearson type III probability distribution and multiple regression have some acceptance. For example, Benson (1964) used multiple regression to relate peak discharge of a given frequency to assorted variables in order to estimate a flood-frequency curve. Anderson (1957) summarized a number of studies in which regression analysis was used to relate peak discharge to watershed variables.

Peak-discharge equations have been developed in southern California, but most have a limited range of application or are too general to define 1969 peak discharges for small watersheds. The 50-year peak-discharge equation with the smallest standard error (Crippen and Beall, 1970, p. 32) is:

$$Q_{50} = 40A^{0.80}MAP^{0.85}$$

where A is drainage area, in square miles, and MAP is mean annual precipitation, in inches. The standard error of estimate is 0.243 log units (+75, −43 percent). Table 4 indicates the applicability of this equation to gaged watersheds in Los Angeles and Ventura Counties.

Combinations of variables were applied in this study to 89 gaging stations in southern California to determine the 1969 peak discharge at ungaged sites. The equation with the smallest standard error is:

$$Q_{cfs} = 0.453A^{0.84}P^{0.99}MAP^{1.22}$$

where P is the January 18–27 storm precipitation, in inches, and other variables are as previously defined. The standard error of estimate is 0.265 log

TABLE 4.—*Fifty-year peak discharges at selected stream-gaging stations in Los Angeles and Ventura Counties*

Station No.	Station name	Drainage area *A* (mi²)	Mean annual precipitation *MAP* (in)	Values of 50-year peak discharge (frequency curve) (ft³/s)	Calculated 50-year peak discharge from equation of Crippen and Beall (1970) (ft³/s)
11–0805	East Fork San Gabriel River near Camp Bonita	85.0	31	32,300	21,700
11–0840	Rogers Creek near Azusa	6.6	30	2,920	3,210
11–0845	Fish Creek near Duarte	6.4	30	2,810	3,160
11–0865	Little Dalton Creek near Glendora	2.7	29	1,870	1,560
11–0930	Pacoima Creek near San Fernando	28.5	25	9,140	9,000
11–0980	Arroyo Seco near Pasadena	16.6	28	7,530	6,430
11–1000	Santa Anita Creek near Sierra Madre	9.7	33	5,010	4,820
11–1005	Little Santa Anita Creek near Sierra Madre	1.8	35	362	1,340
11–1010	Eaton Creek near Pasadena	6.5	29	1,910	3,120
11–1040	Topanga Creek near Topanga Beach	18.0	23	8,650	5,805
11–1105	Hopper Creek near Piru	23.6	22	9,950	6,940
11–1115	Sespe Creek near Wheeler Springs	49.5	29	14,800	15,900
11–1130	Sespe Creek near Fillmore	251.0	28	54,300	56,500
11–1135	Santa Paula Creek near Santa Paula	40.0	28	19,100	13,000
11–1160	North Fork Matilija Creek at Matilija Hot Springs	15.6	31	7,920	6,670
11–1175	San Antonio Creek at Casitas Springs	51.2	23	24,700	21,400
11–1180	Coyote Creek near Ventura	41.2	25	19,900	12,100
11–1185	Ventura River near Ventura	188	27	61,350	43,500

units (+84, −46 percent). The range of data used was: area, 4.65–644 square miles; mean annual precipitation, 10–35 inches; storm precipitation, 7.5–35 inches; and peak discharge, 280–68,800 cubic feet per second.

It was assumed that, if precipitation of the depth and duration experienced in the Transverse Ranges in January 1969 was repeatable in nature, the general equation for 89 stations might apply to a similar storm, the March 1938 storm. The results from 24 stations with 1938 data were in error by an average of 61 percent. Table 5 compares 50-year peak discharges determined from frequency curves to 1938 and 1969 peak discharges.

Final analysis of the hydrologic variables showed that neither 50-year nor January 1969 peak discharge as determined by multiple regression was significant in estimating 1969 sediment yields. This conclusion may result from a bias population of high discharges. It may also result from the large initial error in the determination of peak discharge.

TOTAL TIME OF CONCENTRATION

The time required for water to flow from the most remote part of a basin to the outlet is the total time of concentration. Although the factor has numerous definitions and may not be precisely measurable, it can be useful if measured with a consistent procedure. It is a variable that may be helpful in explaining the hydraulics of channel networks.

At least nine definitions of time of concentration exist (Espey, Morgan, and Masch, 1966, p. 39), most of which employ a graphical measure of the time delay between the rainfall hyetograph and the

TABLE 5.—*Comparison of 1938 and 1969 peak flow to the 50-year peak flow in Ventura County*

Station No.	Station name	Drainage area *A* (mi²)	1938 peak discharge (ft³/s)	Ratio to 50-year peak discharge	January 1969 peak discharge (ft³/s)	Ratio to 50-year peak discharge
11–1085	Santa Clara River at Los Angeles-Ventura County line.	644	---	---	68,800	0.76
11–1096	Piru Creek above Lake Piru	372	35,000	0.68	20,800	.41
11–1100	Piru Creek near Piru	437	35,600	1.04	---	---
11–1105	Hopper Creek near Piru	23.6	8,000	.80	8,400	.84
11–1115	Sespe Creek near Wheeler Springs	49.5	---	---	9,700	.66
11–1130	Sespe Creek near Fillmore	251	56,000	1.03	60,000	1.10
11–1135	Santa Paula Creek near Santa Paula	40.0	13,500	.71	16,000	.84
11–1145	Matilija Creek above reservoir, near Matilija Hot Springs.	50.7	---	---	19,600	.54
11–1155	Matilija Creek at Matilija Hot Springs	54.6	15,900	.69	20,000	.87
11–1160	North Fork Matilija Creek at Matilija Hot Springs.	15.6	5,580	.70	8,440	1.06
11–1175	San Antonio Creek at Casitas Springs	51.2	---	---	16,200	.66
11–1176	Coyote Creek near Oak View	13.2	---	---	8,000	.92
11–1180	Coyote Creek near Ventura	41.2	11,500	.58	---	---
11–1185	Ventura River near Ventura	188	39,000	.64	58,000	.95

runoff hydrograph. The definition of the Los Angeles County Road Department (unpub. data, 1969), when compared with observed velocities and indirect determinations of discharge in larger basins, is the most adequate in the Transverse Ranges. It is

$$TC=Z\left(\frac{L^3}{H}\right)^{0.2}$$

where Z is a land-use coefficient; L is watershed length, in feet; and H is watershed relief, in feet.

FIRE EFFECTS

No analysis of erosion rates in southern California is complete without consideration of the effects of wildfires. The serious nature of the problem is indicated by the fact that watersheds discussed in this report, which are in national forests, have a Federal fire-control budget per unit area more than 10 times the national average. And for the steep, fluelike mountain basins that debouch directly into habitated areas and therefore are in direct contact with human activity the costs are even higher.

The fires are a function of the characteristic summer dry season and dry fire-fanning winds caused by periodic reversal of the normal onshore flow pattern. Chaparral is rich in flammable resins and waxy leaf coatings which are consumed with an intensity that has been described as one of the most difficult wildland fire-control problems in the world. Although fires of human origin have tripled in 15 years, the overall rate of watershed burn has remained relatively constant in Los Angeles County since 1907 at about 1 percent per year, with a recurrence interval at an average point in brush cover of approximately 26 years. Improvements in firefighting technology have thus far kept pace with an increased number of fires by more effectively limiting their spread.

Existing fire records for the basins studied outside of national forests in Ventura County are of too short an interval (1963 to date) to define an accurate burn rate. Compilation of all data from this short period in the study watersheds indicated an average annual burn rate of 0.42 percent. Only three of the watersheds were touched by the widespread burns of September 1970. Longer records within national forest areas indicate that a substantially higher rate, above 1.00 percent, is more applicable.

A definitive study of the effects of wildfires on erosion rates by Rowe, Countryman, and Storey (1954) established relations between estimated discharges and sediment yields for many drainage basins in southern California. Tatum (1965, p. 888) used some of these data to obtain a general relation defining the progressive reduction of sediment yields in the 10-year interval following a burn. This relation, based upon data from flood-control reservoirs, indicates a ratio of the yield in the year following a total-watershed burn to the yield 10 or more years following the burn of 34.5. Records in debris basins in the study area show that this ratio is too high for the smaller basins for which sediment yields must be determined in the western Transverse Ranges. Unpublished U.S. Forest Service data (Rowe, Countryman, and Storey, 1949) indicate that the ratio ranges at least from 11.9 to 35.0 for watersheds in the western Transverse Ranges in Ventura County.

This variability in response to burns led to the decision to include a fire factor as a separate independent variable, rather than apply a correction factor to data for either totally burned or unburned conditions. The effect of burns was approached in the following manner: For all watershed burns occurring during the 12 years preceding the storm catchment being analyzed, the percentage of nonrecovery of vegetative cover (100 percent of recovery) was multiplied by the percentage of watershed burned. This gave a variable correlating positively with erosion rate, with a theoretical range of 0–100, and with a range of 0–88 in the watersheds with known erosion rates. Recovery rates were calculated from prorated area of burn and from vegetation type with relations developed by Horton (U.S. Forest Service, 1953, p. 8 and table 6); Rowe, Countryman, and Storey (1954, fig. 1); and Ferrell (1959, fig. E–2).

Watersheds with a fire factor of 88 included several with a 100-percent burn only 6 months before the January 1969 storm. Only a total burn immediately followed by a storm would yield an index of 100.

The effect of fire is highly variable. Seasonal timing of both burns and storms, vegetative type, and the changing technology of fire- and erosion-prevention measures will all interact to prevent exact forecasts of burn effect on erosion rates. By using the results of previous studies of fire effects on discharge and yield of suspended sediment (see references by Anderson and Wallis, 1965), however, it should be possible to make a meaningful forecast based on the size of the burn and the time interval between burn and storm.

COVER AND LAND USE

The effect of vegetation type and cover density was assessed by means of variables indicating the proportion of drainage area in grass, in brush, and

TABLE 6.—*Data for selected drainage basins with January 1969 sediment yields in Los Angeles and eastern Ventura County*

Drainage basin (number corresponds with location in fig. 2)	Drainage area *A* (mi²)	Geologic units exposed in drainage basin Symbols from Kundert (1955) Listed in order of predominance	Slope failures *SF* (acres/mi²)	Elongation ratio *ER*	Surface aggregation ratio *SA*	Dispersion ratio *DR*	Grass cover 1968 photographs (acres/mi²)	Brush cover 1968 photographs (acres/mi²)	Barren 1968 photographs (acres/mi²)
Bell Canyon (1)	7.00	Ku, Mm, Mu	19	0.727	61	40	305	113	33
Limekiln Canyon (2)	3.69	Mm, Qc, Qt, Mu, Qal	10	.485	83	48	340	66	25
May Canyon (No. 1) (3)	.70	pK, Qc	32	.656	136	50	170	274	66
May Canyon (No. 2) (4)	.09	Qc, pK	20	.521	120	53	145	315	73
Rowley Canyon (5)	.58	gr, Qal	43	.646	110	41	92	272	80
Bluegum Canyon (6)	.19	gr, Qal	55	.478	108	40	105	399	70
Blanchard Canyon (7)	.50	gr, Qal	55	.654	108	40	114	425	73
Snover Canyon (10)	.23	gr, Qc, Qal	51	.712	108	41	89	445	62
La Tuna Canyon (12)	5.34	pK, gr, Qal	19	.795	127	45	120	373	28
Childs Canyon (15)	.31	gr, Qal	49	.556	108	40	95	430	40
Hillcrest Canyon (16)	.35	gr, Qal	20	.804	108	40	87	444	21
Deer Canyon (17)	.59	gr, Qal	39	.810	108	40	92	406	53
Nichols Canyon (18)	.94	gr, Mm, Mv, Ku, E	7	.664	94	41	40	215	21
Lincoln Canyon (19)	.50	gr, Qc, Qal	53	.798	108	42	37	450	82
West Ravine (20)	.25	gr, Qal, Qc	44	.495	108	41	33	430	70
Kinneloa Canyon (West) (21)	.16	pK	63	.564	139	47	62	421	88
Kinneloa Canyon (22)	.20	pK	43	.567	139	47	60	433	63
Sierra Madre Villa (23)	1.46	gr, pK, Qal	61	.593	127	46	58	410	90
Bailey Canyon (24)	.60	gr, pK, Qal	32	.575	115	42	72	440	53
Auburn Canyon (25)	.19	gr, pK, Qal	15	.547	114	42	72	445	52
Little Santa Anita Canyon (26)	2.39	gr, Qal	72	.632	109	40	60	412	87
Lannan Canyon (27)	.25	gr, pK, Qc, Qal	30	.513	112	41	53	463	44
Bradbury Canyon (28)	.68	gr, Qal	42	.705	108	40	63	455	43
Spinks Canyon (29)	.44	gr, Qal	19	.619	108	40	58	460	35
Maddock Canyon (30)	.25	gr, Qal	22	.705	108	40	49	453	35
Hook Canyon (East) (31)	.18	gr, Oal	165	.704	108	40	30	397	105
Harrow Canyon (32)	.43	gr, Qc, Qal	82	.974	109	42	29	375	97
Englewild Canyon (33)	.40	gr, Qc, Qal	70	.768	109	41	31	386	110
Little Dalton Canyon (34)	3.31	gr, Qc, Qal	114	.548	109	41	40	450	83
Morgan Canyon (35)	.60	Mv, Oc, Qal, Qt	80	.723	137	52	150	380	30
Wildwood Canyon (36)	.65	Mv, Mm, Qc, Qal	20	.650	111	48	135	295	20
Emerald Canyon (37)	.16	Mv, Qc, Qal	15	.370	138	48	202	375	15

under barren conditions. Values were determined for the group of watersheds in Los Angeles County by means of grid overlay of aerial photographs taken late in 1968 so as to reflect conditions at the time of the January 1969 storms. All these variables were dropped from the final analysis because of a lack of statistical significance. The lack of significance logically was due to greater importance of the fire factor in determining cover density and erosion rates.

The chief change in land use, both observed and expected, is transfer of natural terrain to urban development. Lower parts of a number of the study basins in the eastern Transverse Ranges have been urbanized, sufficiently to evaluate the effect on erosion rates. The variable that was used to measure the amount of urbanization did not prove significant at a level at which the resulting regression was stable. The cause was obvious—because of slope-stability problems only the lower parts of basins with moderate and high erosion rates can become urbanized. By far the larger part of the sediment is derived, and will continue to be derived, from the steep, undeveloped upper parts of such watersheds.

RESULTS OF ANALYSIS

PREDICTIVE EQUATIONS

Sediment yields from the January 18–27, 1969, storm were selected as the dependent variable in the final regression analyses for predictive purposes. Reasons for restricting the analysis to this single storm are many. Primarily, data are more plentiful, more representative of future conditions, and include a greater range of conditions than are found in any other set of storm data. No other recent storm is comparable in the number of conditions which should be attached to a design storm in the area and which are satisfied by the January 1969 storm. These include a typical antecedent condition, a typical storm pattern, a duration corresponding to the critical duration for maximum sedi-

TABLE 6.—*Data for selected drainage basins with January 1969 sediment yields in Los Angeles and eastern Ventura County* —Continued

Drainage basin (Number corresponds with location in fig. 2)	Urbanization 1968 photographs (acres/mi²)	Fire history		Fire factor January 1969 *FF*	Total time of concentration *TC* (min)	January 1969 precipitation		*K* factor (10 day × (24-hour precipitation)²)	Mean annual precipitation *MAP* (in)	Sediment yield Jan. 18–27, 1969 S_y (yd³)
		Date latest pre-1969 burn	Percent of watershed burned			Jan. 18–27 (in)	Max. 24 hr (in)			
Bell Canyon (1)	25	Oct. 1967	100	65	96.6	16.0	4.5	324	15.0	23,700
Limekiln Canyon (2)	122	Mar. 1964	25	3	54.6	17.0	4.8	392	18.5	15,200
May Canyon (No. 1) (3)	0	Nov. 1966	100	52	30.3	20.0	5.0	500	22.0	40,600
May Canyon (No. 2) (4)	0	Nov. 1966	100	52	25.0	20.0	5.0	500	23.0	2,900
Rowley Canyon (5)	215	Sept. 1913	100	0	48.1	20.0	7.0	980	22.0	2,000
Bluegum Canyon (6)	0	June 1964	<10	3	43.1	25.0	8.3	1722	23.0	1,060
Blanchard Canyon (7)	23	Nov. 1933	100	0	52.2	25.0	8.3	1722	24.0	9,780
Snover Canyon (10)	32	Nov. 1933	75	0	43.6	28.0	10.5	3087	26.5	8,600
La Tuna Canyon (12)	25	Oct. 1952	100	0	76.3	15.0	5.5	454	19.5	37,300
Childs Canyon (15)	5	Mar. 1964	100	17	29.8	17.0	5.8	572	18.5	3,760
Hillcrest Canyon (16)	13	Mar. 1964	100	17	26.3	17.0	5.8	572	18.5	8,000
Deer Canyon (17)	11	Mar. 1964	100	17	39.3	19.0	6.5	803	19.5	30,400
Nichols Canyon (18)	357	No history	0	0	21.4	16.0	6.0	576	17.5	3,450
Lincoln Canyon (19)	5	July 1968	10	8	24.7	25.0	9.5	2256	23.5	16,600
West Ravine (20)	60	Oct. 1935	100	0	34.5	27.0	8.5	1951	25.0	13,700
Kinneloa Canyon (West) (21)	6	No history	0	0	24.0	27.0	9.5	2437	25.0	16,500
Kinneloa Canyon (22)	0	No history	0	0	25.9	27.0	9.5	2437	25.0	13,500
Sierra Madre Villa (23)	52	Oct. 1961	50	5	31.4	26.0	9.5	2346	26.0	106,000
Bailey Canyon (24)	29	Oct. 1961	50	5	30.2	28.0	11.0	3388	25.0	27,600
Auburn Canyon (25)	3	Oct. 1961	50	5	25.9	28.0	10.5	3087	26.0	6,830
Little Santa Anita Canyon (26)	0	Dec. 1953	100	0	32.4	32.0	13.0	5408	27.5	102,000
Lannan Canyon (27)	8	Dec. 1953	100	0	22.9	27.0	11.0	3267	23.0	3,420
Bradbury Canyon (28)	0	Oct. 1958	75	2	28.8	23.0	8.5	1662	25.0	39,100
Spinks Canyon (29)	10	Oct. 1958	75	2	28.2	22.0	8.0	1408	24.0	13,400
Maddock Canyon (30)	0	Oct. 1958	100	2	24.6	22.0	8.0	1408	25.0	7,800
Hook Canyon (East) (31)	0	Aug. 1968	100	80	25.4	21.0	7.5	1181	23.0	[1] 25,200
Harrow Canyon (32)	0	Aug. 1968	100	80	38.6	25.0	8.0	1600	23.5	52,600
Englewild Canyon (33)	0	Aug. 1968	100	80	33.5	25.0	8.5	1806	24.0	44,800
Little Dalton Canyon (34)	15	July 1960	100	2	46.1	28.0	10.5	3087	27.0	256,000
Morgan Canyon (35)	6	July 1960	100	2	35.5	19.0	7.5	1069	22.5	9,900
Wildwood Canyon (36)	6	July 1957	100	2	38.0	18.0	7.5	1012	22.0	7,890
Emerald Canyon (37)	7	Aug. 1968	25	20	44.1	17.0	7.0	833	22.0	790

[1] Estimated.

ment yield (historical storms of duration longer than 10 days do not produce greater sediment yields), and a sufficient interval since the preceding major storm to allow a normal degree of sediment accumulation in channels.

Most importantly, the storm was of a magnitude for which the response of the watersheds to the complex variety of erosional processes could be assumed to be similar to that of a theoretical event of 50-year recurrence interval. Given this assumption, theoretical 50-year erosion rates for planning purposes can be estimated from the predictive equations by substitution of hydrologic variables of equivalent frequency.

It is necessary to establish a design fire condition when using the resulting equations for predictive planning purposes. For the general condition, a fire factor of 20 is assumed, corresponding to a 100-percent burn 4.5 years previous to the storm. An estimated post-burn interval of either 4 or 5 years has been used in previous hydrologic studies in the area and is based on decision theory. The figure of 4.5 years reflects the seasonal offset of burn and storm periods.

Data for watersheds with known erosion rates from the eastern Transverse Ranges in Los Angeles County are presented in table 6.

Regression equations resulting from stepwise analysis of the data of table 6 were selected from a large number of possibilities on statistical criteria. The equations included

$$\log S_y = -3.524 + 0.929 \log A + 1.671 \log ER + 0.246 \log SF + 0.249 \log FF + 5.666 \log MAP \quad (1)$$

S_y is sediment yield of the January 1969 storm, in cubic yards; A is drainage area, in square miles; ER is elongation ratio; SF is area of slope failures, in acres per square mile; FF is fire factor; and MAP is mean annual precipitation, in inches. The standard error of estimate is 0.278 log units (+90, −47 percent); the multiple correlation coefficient is 0.894.

TABLE 7.—*Data for drainage basins above proposed and selected existing debris-basin sites in Ventura County. Only the watershed variables shown in this report to be significantly related to major-storm sediment yields are included*

Drainage basin (Number corresponds with location in fig. 3)	Drainage area A (mi²)	Geologic units exposed in drainage basin Symbols from Kundert (1955) Listed in order of predominance	Slope failures SF (acres/mi²)	Elongation ratio ER	Fire factor January 1969 FF	Total time of concentration TC (min)	K factor (1969) (10 day × (24-hour precipitation)²) K	K factor (50 yr) K
Area 1								
Cozy Dell Canyon	(1) 1.71	E, Qal	58	0.583	0	55	[1] 1920	[1] 3308
Stewart Canyon	(2) 1.98	E, Qt, Qal	83	.592	2	58	[1] 1372	[1] 2913
Fox Canyon near Ojai	(3) .68	E, Qt, Qal	70	.500	0	49	[1] 1056	[1] 2601
Dron Canyon	(4) .34	E, Qal	90	.553	0	35	[1] 1056	[1] 2601
Gridley Canyon	(5) 4.05	E, Qal	58	.656	0	69	[1] 1728	[1] 2978
Senior Canyon	(6) 5.60	E, Qal	32	.864	0	66	[1] 1728	[1] 3267
Horn Canyon	(7) 3.27	E, Qal	32	.729	0	51	[1] 1274	[1] 3146
Wilsie Canyon	(8) 2.65	E, ϕc, Qal	77	.565	0	64	[1] 1274	[1] 3146
Area 2								
Fresno Canyon	(9) 1.27	Mm, Mu, Pml, Qal, Qt	6	.537	0	67	828	1294
Sexton Canyon	(10) 2.67	Pml, Pu, Qm, Qal	13	.645	4	74	240	714
Harmon Canyon	(11) 3.03	Pml, Pu, Qm, Qal	13	.664	0	72	324	784
Peppertree Canyon	(12) 2.22	Pu, Pml, Qal	13	.657	0	73	425	833
Aliso Canyon	(13) 11.37	Pml, Pu, Mu, Mm, Qal	6	.773	0	96	726	1614
Adams Cayon	(14) 8.36	Pml, Mu, Mm, Pu, Qc, Qal	13	.600	0	111	1098	1835
Fagan Canyon	(15) 3.01	Pml, Qc, Pu, Qal	19	.675	0	81	792	1590
Mud Creek Canyon	(16) 2.43	Pml, E, Qt	96	.596	64	58	971	2164
Orcutt Canyon	(17) 3.38	Pml, Qt, E, Qc, Pu, Qal	51	.523	64	68	792	2200
Keefe Ditch	(18) .61	Qc, E, Qt, Qal	77	.506	0	40	929	1704
Jepson Wash	(19) 1.31	Qc, E, Qal, Qt	64	.471	15	53	971	1781
Pole Creek Canyon	(20) 7.65	Mm, Qal, Ml	6	.616	3	99	666	1433
Real Canyon	(21) .25	Mm, Pu, Qal	45	.627	21	33	469	992
Warring Canyon	(22) 1.08	Mm, Pu, Pml, Qal	45	.782	47	50	469	992
Area 3								
Fox Canyon near Somis	(23) 2.41	Pml, Qc, Mm, Mv, Pu, Ml, Qal	32	.517	65	74	232	905
Gill Barranca	(24) 1.06	Qc, Pml, Qal	19	.572	61	67	188	693
Coyote Canyon	(25) 1.02	Pml, Mm, Ml, Mv, Qc, Qal	26	.509	55	60	209	1072
Mahan Barranca	(26) 1.54	Qc, Qt, Pml, Qal	6	.473	9	78	192	1035
Long Canyon	(27) 2.71	Qc, Qt, Pml, Qal	19	.603	0	81	205	1215
South Grimes Canyon	(28) 3.86	Qt, Qc, Qal	19	.495	0	99	192	1035
Gabbert Canyon	(29) 3.81	Qt, Qc, Qal	32	.482	3	98	192	830
Alamos Canyon	(30) 4.80	Ml, ϕc, Qal, Mm	32	.706	2	85	224	1035
Brea Canyon	(31) 1.92	Qal, ϕc	19	.575	10	77	150	712
Dry Canyon	(32) 1.20	ϕc, Qal	19	.647	62	58	159	712
Tapo Hill Diversion (West)	(33) .16	ϕc, Qal	13	.836	55	33	168	712
Tapo Hill Diversion (East)	(34) .22	ϕc, Qal	13	.630	55	35	168	712
Tapo Canyon	(35) 17.60	Qc, Mm, Qt, ϕc, Qal, Mm, Mu	6	.841	7	116	304	1325

[1] Values relatively less well defined.

$$\log S_y = 1.244 + 0.828 \log A + 1.382 \log ER + 0.375 \log SF + 0.251 \log FF + 0.840 \log K. \quad (2)$$

K is the storm-precipitation factor, and other variables are as defined for equation 1. The standard error of estimate is 0.324 log units (+111, −52 percent); the multiple correlation coefficient is 0.854.

$$\log S_y = -0.981 + 1.132 \log A - 1.059 \log TC + 1.322 \log ER + 0.363 \log SF + 0.250 \log FF + 4.847 \log MAP. \quad (3)$$

TC is total time of concentration, and other variables are as defined for equation 1. The standard error of estimate is 0.252 log units (+79, −44 percent); the multiple correlation coefficient is 0.918.

Although these equations achieve more of a reduction in standard error than similar previous analyses, the value of this analysis is its applicability to the more variable conditions in the western Transverse Ranges.

AREAL VARIATION IN EROSION RATES

The observed differences in erosion rates throughout the Transverse Ranges were confirmed by estimation of January 1969 and 50-year sediment yields using the predictive equations (table 7). Three distinct groups of watersheds delineated on the basis of erosion rates correspond closely with the three major drainages that reach the Pacific Ocean in Ventura County (fig. 3).

Area 1: High erosion rates.—The following study watersheds are in the drainage of the Ventura River:

Cozy Dell Canyon
Stewart Canyon
Fox Canyon near Ojai
Dron Canyon
Gridley Canyon
Senior Canyon

TABLE 7.—*Data for drainage basins above proposed and selected existing debris-basin sites in Ventura County. Only the watershed variables shown in this report to be significantly related to major-storm sediment yields are included*—Continued

Drainage basin (Number corresponds with location in fig. 3)	Mean annual precipitation *MAP* (in)	Calculated January 1969 sediment yield [2] per unit area (erosion rate) S_y'		Calculated 1969 sediment yield per unit area with *FF* of 20 S_y'		Total design-storm (1969) sediment yield S_y (yd ^{3})	Calculated sediment yield per unit area with 50-yr *K* factor and *FF* of 20 S_y'		Total design-storm (50-yr) sediment yield S_y (yd ^{3})
		(yd ^{3}/mi ^{2})	Source equation	(yd ^{3}/mi ^{2})	Source equation		(yd ^{3}/mi ^{2})	Source equation	
Area 1—Continued									
Cozy Dell Canyon	(1) 27.0	29,900	3	63,200	3	108,000	([3])		([3])
Stewart Canyon	(2) 28.0	47,500	3	84,300	3	167,000	([3])		([3])
Fox Canyon near Ojai	(3) 24.0	14,700	3	31,200	3	21,200	([3])		([3])
Dron Canyon	(4) 24.0	24,100	3	50,900	3	17,300	([3])		([3])
Gridley Canyon	(5) 27.0	30,700	3	65,200	3	264,000	([3])		([3])
Senior Canyon	(6) 27.0	39,000	3	82,500	3	462,000	([3])		([3])
Horn Canyon	(7) 27.0	38,100	3	80,700	3	264,000	([3])		([3])
Wilsie Canyon	(8) 26.0	23,800	3	50,600	3	134,000	([3])		([3])
Area 2—Continued									
Fresno Canyon	(9) 20.0	3,940	2	8,350	2	10,600	12,200	2	15,500
Sexton Canyon	(10) 21.0	2,990	2	4,490	2	12,000	11,200	2	29,900
Harmon Canyon	(11) 22.0	2,770	2	5,870	2	17,800	12,300	2	37,400
Peppertree Canyon	(12) 22.0	3,610	2	7,660	2	17,000	13,500	2	29,900
Aliso Canyon	(13) 22.0	4,010	2	8,500	2	96,500	16,600	2	189,000
Adams Canyon	(14) 21.0	5,630	2	11,900	2	99,800	18,400	2	154,000
Fagan Canyon	(15) 21.0	6,910	2	14,700	2	44,200	26,400	2	79,400
Mud Creek Canyon	(16) 21.0	[4]37,400	2	[4]27,900	2	[4]67,900	[4]54,700	2	[4]133,000
Orcutt Canyon	(17) 21.0	19,700	2	14,600	2	49,500	34,600	2	117,000
Keefe Ditch	(18) 22.0	11,800	2	25,100	2	15,300	41,800	2	25,500
Jepson Wash	(19) 22.0	17,900	2	19,300	2	25,300	32,100	2	42,000
Pole Creek Canyon	(20) 21.0	3,840	2	6,180	2	47,300	11,800	2	90,100
Real Canyon	(21) 19.0	18,300	2	18,100	2	4,530	34,000	2	8,490
Warring Canyon	(22) 20.0	23,800	2	19,100	2	20,600	35,900	2	38,800
Area 3—Continued									
Fox Canyon near Somis	(23) 18.0	6,180	2	4,560	2	11,000	14,400	2	34,600
Gill Barranca	(24) 17.0	5,550	2	4,180	2	4,430	12,500	2	13,200
Coyote Canyon	(25) 18.0	5,700	2	4,400	2	4,490	17,400	2	17,700
Mahan Barranca	(26) 17.0	1,630	2	1,990	2	3,070	8,200	2	12,600
Long Canyon	(27) 18.0	1,940	2	4,100	2	11,100	18,300	2	49,700
South Grimes Canyon	(28) 16.0	1,310	2	2,800	2	10,800	11,500	2	44,300
Gabbert Canyon	(29) 16.0	2,030	2	3,280	2	12,500	11,200	2	42,700
Alamos Canyon	(30) 16.0	3,400	2	6,060	2	29,100	21,900	2	105,000
Brea Canyon	(31) 14.0	2,640	2	3,140	2	6,030	11,600	2	22,300
Dry Canyon	(32) 15.0	5,620	2	4,210	2	5,050	14,800	2	17,800
Tapo Hill Diversion (West)	(33) 15.0	9,940	2	7,690	2	1,230	25,900	2	4,150
Tapo Hill Diversion (East)	(34) 15.0	6,360	2	4,950	2	1,090	16,600	2	3,650
Tapo Canyon	(35) 19.0	[5]3,280	2	[5]4,270	2	[5]75,100	[5]14,700	2	[5]259,000

[2] Under conditions existing in January 1969.
[3] Preferable equation for these basins does not include *K* factor (see text).
[4] No useful estimate of sediment yield is possible (see text).
[5] Yields for basins where independent variables significantly exceed range of variables used to compute equations.

Horn Canyon
Wilsie Canyon

This group of watersheds forms the south slope of Nordhoff Ridge where bedrock is the Eocene sequence of the Matilija overturn, a deformed structural feature associated with recently active thrust faulting. Sediment yields are high relative to other parts of the Transverse Ranges. Erosion rates from the January 1969 storm ranged from an estimated 31,200 to 84,300 yd ^{3}/mi ^{2} (9,210 to 24,900 m ^{3}/km ^{2}) corrected for a uniform fire factor of 20 (table 7).

Area 2: Moderate erosion rates.—The following study watersheds are in the drainage of the Santa Clara River, with the exception of Fresno Canyon, which is in the Ventura River basin:

Fresno Canyon
Sexton Canyon
Harmon Canyon
Peppertree Canyon
Aliso Canyon
Adams Canyon
Fagan Canyon
Mud Creek Canyon
Orcutt Canyon
Keefe Ditch
Jepson Wash
Pole Creek Canyon
Real Canyon
Warring Canyon

The watersheds of this group are formed in the thick Miocene-Pliocene section of the Santa Clara River valley. The Fresno Canyon watershed is likewise underlain by this sequence where it strikes across the lower part of the Ventura River valley. Erosion rates from the January 1969 storm ranged from an estimated 4,490 to 27,900 yd ^{3}/mi ^{2} (1,330 to 8,240 m^3/km^2) corrected for a uniform fire factor of 20 (table 7).

Area 3: Low erosion rates.—The following watersheds are part of the Calleguas Creek drainage:

Fox Canyon near Somis
Gill Barranca
Long Canyon
South Grimes Canyon
Gabbert Canyon
Alamos Canyon
Brea Canyon
Dry Canyon
Tapo Hill Diversion (West)
Tapo Hill Diversion (East)
Tapo Canyon

Watersheds in this area are formed in sedimentary rocks which are similar to those exposed in area 2 but which are generally finer grained. Lower erosion rates in this area are also a function of lesser relief and less pronounced recent uplift. Erosion rates from the January 1969 storm ranged from an estimated 1,990 to 7,690 yd^3/mi^2 (587 to 2,270 m^3/km^2) corrected for a uniform fire factor of 20 (table 7).

EROSION RATES FOR PLANNING AND DESIGN

Two approaches to the selection of appropriate erosion rates for planning and for design of debris basins have been used in the Transverse Ranges.

The first approach is to recognize the difficulties in attaching any meaningful frequency to a sedimentation period and to select a major storm and designate it as the design storm. Design is then based on the erosion rates of that storm. This approach was used locally with the 1938 storm in southern California.

The second approach is to adjust a known or estimated erosion rate to a design frequency by using as an adjustment factor either rainfall or peak discharge of the selected frequency. Uncertainty introduced by extrapolation of events of design frequencies may be considerable, from both the standpoint of establishing meaningful frequencies for sedimentation periods of this magnitude and the statistics of the situation.

Both methods are used in this report, depending on the similarity of the 1969 storm to the desired design storm in a given area. The predictive equations indicate what the January 1969 sediment yield at a site would have been if a debris basin of standard design had existed. Where 1969 precipitation was significantly different from that of the design storm, substitution of 50-year rainfall variables in the equations can be made, assuming that the watershed response would be the same in both cases. Extension of the prediction equations is based on the general comments of Wallis (1967).

The January 1969 storm is locally an excellent design storm. Rainfall and discharge parameters were of the same general magnitude as those of a 50-year storm in many watersheds in the eastern Transverse Ranges of Los Angeles County. Westward in Ventura County the degree of similarity was more variable. In parts of the area the intensity factors were similar, but in other sections of the county there were marked differences. The following discussion notes these differences and suggests planning and design criteria.

Area 1 (watersheds north of Ojai in drainage of the Ventura River).—In this area, with as high an erosion potential as is known to exist in Ventura County, the January 1969 storm and a 50-year storm were similar (see table 3; K values of table 7 exaggerate differences). Rates from equation 3 were selected because that relation gave the value closest to the estimated actual January 1969 sediment yield in the existing Stewart Canyon debris basin (table 8). Suggested design yields for debris basins in this group of watersheds can be found in the column of table 7 entitled "Total design-storm (1969) sediment yield." Even though substitution of values of 50-year rainfall in equation 2 (equation 3 does not contain a storm-precipitation variable) may give higher rates, equation 3 best defines the erosion response of these watersheds. In light of the poorly defined distribution of storm precipitation in this area, planners may best rely on a relatively well-defined set of data—the rates that would have occurred in these basins in 1969 with a fire factor of 20, with the important check of an actual yield figure.

The difference between the figure of 167,000 yd^3 (128,000 m^3) in table 7 and the actual maximum capacity of 300,000 yd^3 (230,000 m^3) in the Stewart Canyon debris basin may be considered as a safety factor or as volume that can be utilized for debris storage if there has been no burn in the preceding 4.5 years.

Area 2 (watersheds in the Santa Clara River valley, plus Fresno Canyon in the Ventura River drainage).—Southward within Ventura County, the intensity of the January 1969 storm decreased relative to the theoretical 50-year storm. In this area of variable but generally moderate sediment yields, the difference was enough to cause a difference in

TABLE 8.—*Data and comments on estimated January 1969 sediment yields per unit area (erosion rates) in selected existing debris basins in Ventura County*

Drainage basin (number corresponds with location in fig. 3)	Drainage area A (mi ^{2})	Fire factor FF (January 1969)	Estimated actual January 1969 sediment yield per unit area (erosion rate) S_y' (yd ^{3}/mi ^{2})	Calculated January 1969 sediment yield per unit area (erosion rate) S_y' (yd ^{3}/mi ^{2})	Calculated January 1969 sediment yield per unit area (erosion rate) Source equation	Comments
Stewart Canyon (2)	1.98	2	52,700	47,500	3	Maximum capacity was available at start of 1968–69 season. Berm of storm debris left at time of 1969 cleanout was approximately equaled in volume by amount of original bed material removed at time of 1969 cleanout.
Jepson Wash (19)	1.31	15	20,400	17,900	2	Cleanout in 1969 removed some original bed material; figure corrected by an approximation of this amount. Small amount of coarse debris passed spillway.

calculated rates by more than a factor of two. Equation 2 gave the best results when calculated 1969 values were compared with estimated actual 1969 yield in a debris basin in Jepson Wash (table 8). Design sediment yields for this group of watersheds may be found in the column of table 7 designated "Total design-storm (50-yr) sediment yield." The figures were calculated with equation 2 by substitution of the appropriate storm-period variables.

Area 3 (watersheds in the Calleguas Creek drainage).—The 1969 storm was inappropriate as a design storm in this area of low sediment yields because of proportionally lower rainfall intensities in the southern part of Ventura County. Equation 2 was used to calculate probable sediment yields resulting from 50-year precipitation in this area, and the results appear in table 7 under the column labeled "Total design-storm (50-yr) sediment yield." Unlike areas 1 and 2, there was no key watershed with a suitable existing debris basin from which to compare calculated and actual 1969 yields. This lack was not critical because there was little difference in yields determined with each of the three equations. In addition, because sediment yields in this area are less than elsewhere, sediment-retention structures may not be necessary in some watersheds of this group.

An additional factor suggests that actual yields in watersheds of area 3 will be substantially less than the volume indicated in table 7. This factor is the fine-grained nature of the bed material in the area. Fifteen field counts (50 points per locality) indicated an average silt- and clay-size content of 43 percent in the bed material of these watersheds. Catchments in areas with sediment this fine grained will have substantially lower trap efficiencies; that is, more sediment will pass the catchment and most should traverse a well-designed system of flood-control channels without excessive deposition. Because of this factor, less capacity will be needed but the reduction can only be estimated. A conservative approach might deduct 20–30 percent from the values of table 7.

This latter conclusion was confirmed during the reconnaissance of dry stock ponds, check dams, and small-scale debris basins in area 3 in 1970. Many structures, especially those with functioning outlet towers, retained little of the sediment inflow to the reservoirs during the 1969 storms. Much sediment clearly passed the structures by remaining in suspension.

ACCURACY OF EROSION-RATE ESTIMATES

It is important to realize the limitations to any indirect determinations of erosion rates—the practical uncertainty of the estimates. It is statistically impossible, even with the comprehensive data available to this study, to assess all the factors that control erosion rates. Side-by-side watersheds, identical in terms of the factors discussed in this report, may still show a difference of 50 to 100 percent in major-storm erosion rates. Past records of existing debris basins in southern California make this point abundantly clear. The chief reason for this lack of predictability is the extreme variability of the watersheds, which results in a situation where differences in a factor impossible to assess may cause significant differences in erosion rates. Examples of such unassessable factors include the many and differing mechanisms of landslide triggering, the intensity of grazing in the months immediately before a storm, or the efficacy of reseeding programs after a burn.

The calculation of individual sediment-yield volumes, based on the characteristics of that specific watershed, is a considerable advance over the use of the so-called debris-production curve. In the latter technique, a plot of sediment yield against size of drainage area is applied to all watersheds of a given area. The position of the curve is estimated according to degree of similarity with areas of known erosion rates. Application of the technique to the group of closely similar watersheds in area 1 north of Ojai is illustrated in figure 9. In this case, the curve is located from a control point—the value calculated for Stewart Canyon, site of a debris basin with an estimated actual January 1969 yield close to the corresponding calculated yield (see values in tables 7 and 8). The appropriate predictive equation 3 for Stewart Canyon was selected on the basis of the estimated actual yield in the Stewart Canyon basin. The shape of the curve was based on well-established relations between yields and size of drainage area, including many measurements in Los Angeles County (Ferrell, 1959). It is similar to the relation $S_y' \approx A^{-0.15}$, in which sediment yield per unit area is inversely proportional to basin area. Brune (1948, p. 15) and Langbein and Schumm (1958, p. 1079) developed this relation in the midwestern United States, and a similar relation has been shown to apply to watersheds with flood-control reservoirs in the Transverse Ranges (Scott, Ritter, and Knott, 1968, p. 29).

With a plot of the individual calculated yield values (fig. 9), it is clear that the figure for Stewart Canyon is a poor index for other watersheds in the group. The individual values based on equation 3 are plainly preferable. Because of an unusual distribution of basin characteristics, lower yield rates rather than larger are indicated in the smaller basins. The effect of basin size alone on sediment yield per unit area is, of course, to reduce yields per unit area from the larger basins.

The inconsistency illustrated in figure 9 occurs in as uniform a set of basins as exists in areas of high erosion rates in the Transverse Ranges. Although the curve is based on a good control—a major-storm yield from a basin of intermediate size—it indicates the poor results that would be obtained from in-

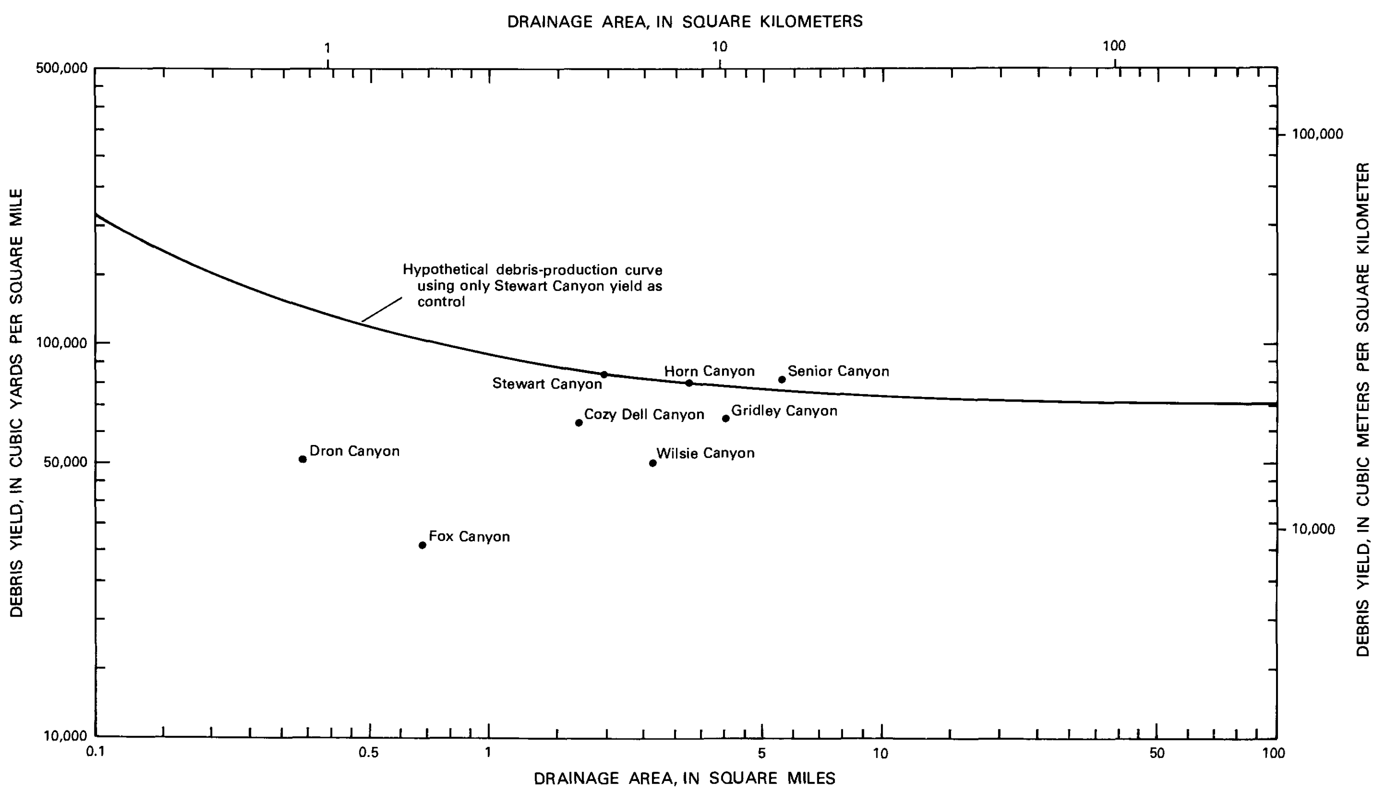

FIGURE 9.—Sediment yields for watersheds near Ojai (area I) compared with debris-production curve based on estimated actual yield in Stewart Canyon.

discriminate use of debris-production curves in the area.

The reasons for the general inapplicability of debris-production curves in the area are, first, the high magnitude of erosion rates and the consequent sensitivity to minor variations in basin and storm characteristics, and second, the variability of the watersheds. This general situation has been the curse of designers of debris basins and flood-control reservoirs throughout the Transverse Ranges. There are a number of impoundment structures, constructed by many different agencies, which overestimate the yield by as much as 500 percent or underestimate the yield by as much as 80 percent. This variation is a function of the complexity of the problem, not of incorrect approaches, and was only readily apparent for the first time after the storms of 1969. In fact, estimates of major-storm yields within 50 percent of the ideal value verge upon extrasensory perception. Studies that indicate an accurate predictive technique for historical annual sediment yields over an extended period in a single watershed do not necessarily define major-storm yields there or elsewhere with remotely similar accuracy.

Most design has proved to be overdesign, because of the natural designer's bias in this direction, but also because true underdesign is not always apparent. Debris basins filling to near capacity show a remarkable ability to retain coarse material owing to loss of flow competence with reduction in gradient caused by the wedge of sediment deposited behind the impoundment. The coarse sediment displaces eroded finer grades of sediment, some of which may be transported through the flood-control system without causing serious problems. In the case of overdesign, the large trap efficiencies of the debris basins will cause retention of nearly all detritus, including fine sediment that could traverse the system without difficulty. Thus, the apparent degree of overdesign is lessened. In short, there is a natural apparent fit of sediment yields to the capacity of debris basins, regardless of overdesign or underdesign.

Overdesign is, of course, not the serious problem it first may appear to be. Excess capacity serves as debris-storage space which, in a time of disappearing disposal sites and escalating haulage costs, is of considerable value. It also allows greater flexibility in cleanout schedules after a major storm or a large burn. At some sites where excess capacity can be added at little additional cost it may be economically justifiable to add excess capacity as a safety factor. Additional capacity in cases of underdesign can normally be added by excavation below natural stream gradient, provided a stabilized inlet structure is included to prevent upstream scour.

As debris basins are constructed throughout the Transverse Ranges, the additional sediment data collected will require the modification of the erosion rates in this report. It is certainly true that any study of erosion rates is immediately outdated by the next significant storm.

LONG-TERM EROSION RATES

ESTIMATION OF RATES

The average annual rate at which sediment is eroded from a watershed is the sum of the large contributions from major storms like those of 1938 and 1969 plus the individual contributions of lesser storms and periods of low flow, all divided by the number of years of record. It is, with a correction for trap efficiency, a good measure of the rate at which the land surface of the Transverse Ranges is undergoing denudation. Long-term erosion rates are of practical value in the planning of cleanout costs over a long period, the selection of debris-disposal areas, and related problems of sediment management. Long-term rates that reflect natural conditions will be a useful index for assessment of possible future increases in erosion related to environmental changes.

Figure 10 is a plot of average annual sediment-yield rates for a group of watersheds in Los Angeles County for periods of 25 to 42 years. Watersheds that are the sites of channel-stabilization programs, involving the construction of check dams, were excluded from this group. Fire conditions for the watersheds plotted were typical of the Transverse Ranges; nearly all the watersheds had been burned at least once during the period of record. The unexpected feature of this plot is that the apparent decline in erosion rate with increase in basin size is substantially greater than is empirically the case in single-storm yields, as shown by the trend of a typical design curve (fig. 9). Although part of this anomaly is caused by sluicing of some sediment from the largest basins, it is likely that long-term curves are actually steeper than single-storm curves, reflecting a relation between impoundment trap efficiency and watershed size. Trap efficiencies are less over the long term because the finer grained erosional products of lesser storms more readily pass the outlet structures. And, predominantly be-

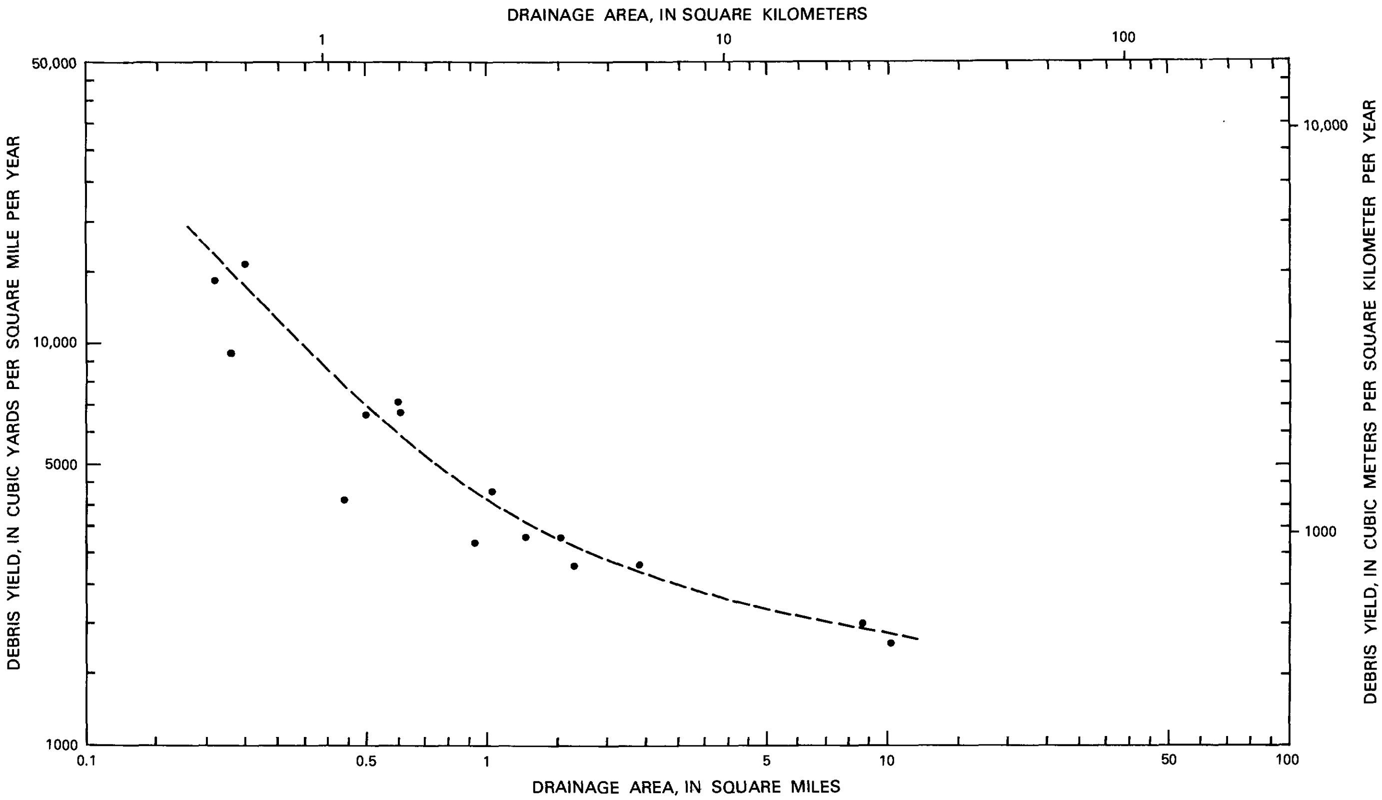

FIGURE 10.—Long-term sediment yields at selected sites in Los Angeles County.

cause of selective sorting (Scott, 1967, p. 315), grain size is finer at the outlets of larger watersheds, thereby increasing the effect of reduced trap efficiency on the sediment yields of larger basins.

No method of computing trap efficiency (see Brune, 1953) is entirely satisfactory when applied to debris basins. Plotting of debris-basin capacities against drainage areas and a quantitative consideration of the difference in grain size of deposited and discharged sediment indicates that approximately 40 percent of the total silt and clay, 94 percent of the sand, and 99 percent of the grades coarser than sand are retained in a properly designed debris basin with a watershed 1–2 mi ^{2} (2.6–5.2 km ^{2}) in area and a functioning outlet tower. If the average size distribution is likewise estimated, an average estimated trap efficiency of 85–90 percent is probable over the long term, with the lower figure applicable to larger watersheds (2–10 mi ^{2}, 5.2–26 km ^{2}) and the higher figure more likely for smaller basins ($<$2 mi ^{2}, $<$5.2 km ^{2}).

With a correlation for trap efficiency of the above amount, the rates in figure 10 can be applied with confidence as average long-term erosion rates, based on the 25–40 year period prior to 1970. The rates shown would apply to watersheds under 10 mi ^{2} (26 km ^{2}) in size in areas of high erosion rates like that near Ojai (area 3) and in the frontal watersheds of the San Gabriel Mountains. Lower rates in other areas would be scaled down proportional to the reduced size of major-storm rates in such areas.

An additional means of estimating long-term rates is the comparison of January 1969 storm yields, where they were similar to 50-year design yields, with long-term rates in the same basins. The same factor, percent of design yield equivalent to average annual rate, could logically be applied to other watersheds in the same general area. For watersheds with records exceeding 25 years, the average annual rate was 2 to 17 percent of the January 1969 yields modified to the design burn condition. Closer inspection of the data and elimination of basins where sluicing of sediment was a factor or where burns were unusually common during the period of record indicated that a more probable range was 8 to 13 percent, with the lower range of 8 to 10 percent applicable to watersheds of 1 to 5 mi ^{2} (2.6 to 13 km ^{2}) in size, and the range of 10 to 13 percent useful for watersheds from 5 to 10 mi ^{2} (13 to 26 km ^{2}) in size.

IMPLICATIONS OF LONG-TERM EROSION RATES

Figure 10 indicates that a watershed in an area of high erosion rates with a drainage area of 0.5

mi^2 ($1.3\ km^2$) has been eroded at an approximate rate of 7,700 yd^3/yr (5,900 m^3/yr) for the last 40 years. This rate is equivalent to a net denudation rate of 7.5 ft (2.3 m) per 1,000 years, or nearly 1 in (25.4 mm) each 11 years. Although high, this rate is less than maximum rates elsewhere that reflect gullying of deposits such as loess. The above rates in the Transverse Ranges probably approach the maximum for areas in which consolidated bedrock is being eroded directly. It should be emphasized that such a rate does not reflect uniform denudation over the surface of a watershed.

As indicated by Schumm (1963, p. 3), rates like the above tell us that considerably less time is required for erosion of an uplifted area than was formerly thought. The above rate of 7.5 ft (23 m) per 1,000 years indicates that Gilluly's estimate (1949, p. 570–571) of 5,000 ft (1,520 m) of erosion from the Ventura anticline in a period of 1 million years (5 ft, or 1.5 m, per 1,000 years) is possible.

Modern rates of uplift in tectonically active areas of California are as much as 25 ft (7.6 m) per 1,000 years (Gilluly, 1949 and Schumm, 1963). A rate of 17 ft (5.2 m) per 1,000 years has been recorded for Mount San Antonio, the highest peak in the San Gabriel Mountains (Stone, 1961). Stone also found that level-line data indicated that the south flank of the San Gabriel Mountains was undergoing uplift at a rate of 20 ft (6.1 m) per 1,000 years. Both the Holocene and the historical uplift along active faults described earlier clearly define rates on the order of 25 ft (7.6 m) per 1,000 years and locally suggest rates that are even higher. The measured rate of erosion, scaled down as necessary if applicable to such large areas, still is no more than a fraction of the rate of uplift.

The importance of this comparison is that it is indeed probable that major landforms and watershed characteristics in the Transverse Ranges are influenced by both tectonism and erosion. A measure of reaction to uplift more sensitive than any physiographic factor yet proposed is the key to accurate correlation of erosion rates in the Transverse Ranges. Whether the use of the extent of slope failures as described above is an answer or not, future studies of erosion and sedimentation in the study area and similar parts of California should treat this problem as a prime consideration.

PRESENT STAGE IN CYCLE OF ALLUVIATION AND CHANNEL ENTRENCHMENT

The latest period of widespread alluviation in the Transverse Ranges has been at least temporarily reversed during historical time. The deposits of many headwater areas in area 3 have been deeply entrenched within valley floors. At least a few channels are now incised in bedrock. Elsewhere, fill surfaces and alluviated hillslopes have not suffered localized erosion such as gullying. Vegetation is intact except where heavily grazed or recently burned.

Whether erosion is now increasing or decreasing in intensity is of practical interest. Decisions based on present trends must be qualified with the consideration that such trends may be only short-term perturbations about a long-term trend or equilibrium condition and, as such, may be broken at any time. To determine the trend of alluviation or channel entrenchment, parts of Tapo Canyon (fig. 3), the most widely alluviated of the 72 study watersheds, were studied in detail.

Evidence from exposed root structures of perennial plants showed that hillslopes in Tapo Canyon are undergoing sheet erosion of moderate and areally uniform intensity. Rates of erosion appeared to vary expectably according to topographic position and soil erodibility; however, several episodes of channel cutting have occurred in historical time in Tapo Canyon, and the latest is apparently increasing in intensity at present. Entrenchment of the channels is similar to that described by Bull (1964, p. 117–125) from channels on fans along the eastern Coast Ranges in Fresno County.

Present stream channels in Tapo Canyon are confined to steep-walled trenches in the silt-rich valley fills (fig. 11). The trenches range from 8 to 35 ft (2.9 to 10.7 m) in depth and, as in Fresno County, contain well-developed remnants of paired terraces 5 to 14 ft (1.5 to 4.3 m) above the present channel. Bull (1964, p. 121–122) was able to make a clear correlation between the two periods of trenching in Fresno County and periods of high annual rainfall and high frequency of large daily rainfall in 1875–95 and 1935–45.

At least the younger period of trenching in Tapo Canyon is a probable equivalent to that in Fresno County. Preservation of a debris-retention structure set with lengths of oil-well casing on the paired-terrace remnants dates the second episode of entrenchment as post 1928–33. The now-suspended base of the structure is 10 ft (3 m) above the present channel bottom (fig. 12). The same 1935–45 period of high annual rainfall seen in Fresno County is evident in many local records. No correlation can be established for the older of the two historical periods of channel cutting, but the possibility of correlation is clear.

FIGURE 11.—Typical silt-rich valley fill in tributary of Tapo Canyon. Individual points to in-place stump of fossil California coastal live oak *(Quercus agrifolia)*.

FIGURE 12.—Undercut debris-retention structure in tributary of Tapo Canyon. Individual standing in bottom of wash provides scale.

The latest period of trenching is being continued or renewed by the latest post-1965 wet period. As much as 1.5 ft (0.5 m) of net scour occurred during 1969 storm runoff alone.

TIME VARIATION OF EROSION RATES

The recency and severity of the channel cutting in Tapo Canyon is testimony to the sudden changes in erosional factors that can take place in the study watersheds. It emphasizes the sensitivity of the watersheds to change. An indirect cause of this sensitivity is the presence of easily erodible fills adjacent to active stream channels. These fills create a future potential for erosion rates higher than those measured, with relatively minor changes in climate or land-use factors. No such fills exist in the watersheds of area 1; few of any consequence are found in area 2; however, they are widely developed and constitute a significant unknown in the erosional regime of area 3.

Over the short term, it is unlikely that the rates of table 7 will be markedly affected by the activities of man, because of the rugged, nearly inaccessible nature of the watersheds with moderate and high erosion rates—those of areas 1 and 2. One exception to this generality is a change in wildfire rate. The resultant trend of more common but more effectively controlled burns is not yet clear.

Grazing intensity will be a chief cause of change in the relatively low rates of area 3. Watersheds of area 3 will also be those most susceptible to minor changes in hydrologic or land-use factors because of the widespread alluvial fills in those watersheds.

With the assumption that the climate of the past 40 years will be typical of the future climate, erosion rates based on the existing historical records can be extended. Estimates of annual precipitation back to 1769, 100 years before measurements began, were made for the Los Angeles area by Lynch (1931) on the basis of notes by Spanish missionaries. His graph, combined with subsequent data, reveals a downward trend from what was probably the peak of a wet period in 1769 to a major trend reversal in 1884. Since then a pronounced series of wet and dry periods has occurred, of roughly equal magnitude and duration. During the period of sediment records a dry period extended from 1923 through 1934, a wet period from 1935 through 1944, a dry period from 1944 through 1964, and a wet period from 1964 through at least 1970. The period of record is therefore representative of several wet and dry intervals.

Extrapolation of past rates, either those based on long-term records or the assumed frequencies of single events, should be done with caution. There is no guarantee that future data will be similar to those of the past, especially when considerable changes in erosion rates can be produced by minor variations in a number of factors.

REFERENCES CITED

Anderson, H. W., 1949a, Discussion of "Flood frequencies and sedimentation from forest watersheds:" Am. Geophys. Union Trans., v. 30, p. 621–623.

——— 1949b, Flood frequencies and sedimentation from forest watersheds: Am. Geophys. Union Trans., v. 30, p. 567–584.

——— 1954, Suspended sediment discharge as related to streamflow, topography, soil, and land use: Am. Geophys. Union Trans., v. 35, p. 268–281.

——— 1957, Relating sediment yield to watershed variables: Am. Geophys. Union Trans., v. 38, p. 921–924.

Anderson, H. W., Coleman, G. B., and Zinke, P. J., 1959, Summer slides and winter scour—dry-wet erosion in southern California mountains: Pacific Southwest Forest and Range Expt. Sta. Tech. Paper 36, 12 p.

Anderson, H. W., and Wallis, J. R., 1965, Some interpretations of sediment sources and causes, Pacific Coast basins in Oregon and California: Federal Inter-Agency Sedimentation Conf. Proc., U.S. Dept. Agriculture Misc. Pub. 970, p. 22–30.

André, J. E., and Anderson, H. W., 1961, Variation of soil erodibility with geology, geographic zone, elevation, and vegetation type in northern California wildlands: Jour. Geophys. Research, v. 66, p. 3351–3358.

Bailey, R. G., and Rice, R. M., 1969, Soil slippage: An indicator of slope instability on chaparral watersheds of southern California: Prof. Geographer, v. 21, p. 172–177.

Benson, M. A., 1964, Factors affecting the occurrence of floods in the Southwest: U.S. Geol. Survey Water-Supply Paper 1580–D, 72 p.

Bouyoucos, G. J., 1936, Directions for making mechanical analyses of soils by the hydrometer method: Soil Sci., v. 42, p. 225–229.

Brune, G. M., 1948, Rates of sediment production in midwestern United States: U.S. Dept. Agriculture Soil Conserv. Service SCB–TP–65, 40 p.

——— 1953, Trap efficiency of reservoirs: Am. Geophys. Union Trans., v. 34, p. 407–418.

Bull, W. B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U.S. Geol. Survey Prof. Paper 352–E, p. 89–129.

Crippen, J. R., and Beall, R. M., 1970, A proposed streamflow data program for California: U.S. Geol. Survey open-file rept., 46 p., and app.

Dixon, W. J., 1968, Biomedical computer programs: Univ. California Pubs. in Automatic Computation, n. 2, 600 p.

Espey, W. H., Jr., Morgan, C. W., and Masch, F. D., 1966, Study of some effects of urbanization on storm runoff from a small watershed: Texas Water Devel. Board, rept. 23, Univ. of Texas, 110 p.

Ferrell, W. R., 1959, Debris reduction studies for mountain watersheds: Los Angeles County Flood Control District, rept. 164 p.

Gilluly, James, 1949, Distribution of mountain building in geologic time: Geol. Soc. America Bull., v. 60, p. 561–590.

Krammes, J. S., 1960, Erosion from mountain side slopes after fire in southern California: Pacific Southwest Forest and Range Expt. Sta. Research Note 171, 7 p.

Kundert, C. J., 1955, Los Angeles sheet *of* Geologic map of California: California Div. Mines and Geology Map Sheet.

Langbein, W. B., and others, 1947, Topographic characteristics of drainage basins: U.S. Geol. Survey Water-Supply Paper 968–C, p. 125–157.

Langbein, W. B., and Schumm, S. A., 1958, Yield of sediment in relation to mean annual precipitation: Am. Geophys. Union Trans., v. 39, p. 1076–1084.

Liang, Ta, and Belcher, D. J., 1958, Airphoto interpretation, *in* Landslides and engineering practice: Highway Research Board Spec. Rept. 29, Natl. Resources Council Pub. 544, p. 69–92.

Lustig, L. K., 1965, Sediment yield of the Castaic watershed, western Los Angeles County, California—a quantitative geomorphic approach: U.S. Geol. Survey Prof. Paper 422–F, 23 p.

Lynch, H. B., 1931, Rainfall and stream runoff in southern California since 1769: Metropolitan Water Dist., southern California, Los Angeles.

Matalas, N. C., and Reiher, B. J., 1967, Some comments on the use of factor analysis: Water Resources Research, v. 3, p. 213–223.

Middleton, H. E., 1930, Properties of soil which influence soil erosion: U.S. Dept. Agriculture Tech. Bull. 178, 16 p.

Morisawa, Marie, 1957, Accuracy of determination of stream lengths from topographic maps: Am. Geophys. Union Trans., v. 38, p. 86–88.

Morton, D. M., and Streitz, R., 1969, Preliminary reconnaissance map of major landslides, San Gabriel Mountains, California: California Div. Mines and Geology Map Sheet 15.

Nelson, L. M., 1970, A method of estimating annual suspended-sediment discharge: U.S. Geol. Survey Prof. Paper 700–C, p. 233–236.

Proctor, R. J., and Payne, C. M., 1972, Evidence for, and engineering consequences of, recent activity along the Sierra Madre fault zone, southern California [abs]: Abs., Cordilleran Sec., Geol. Soc. America, mtg. at Honolulu, Hawaii, p. 220–221.

Putnam, W. C., 1942, Geomorphology of the Ventura region, California: Geol. Soc. America Bull., v. 53, p. 691–754.

Rice, R. M., and Foggin, G. T., III, 1971, Effect of high intensity storms on soil slippage on mountainous watersheds in southern California: Water Resources Research, v. 7, p. 1485–1496.

Ritchie, A. M., 1958, Recognition and identification of landslides, *in* Landslides and engineering practice: Highway Research Board Spec. Rept. 29, Natl. Resources Council Pub. 544, p. 48–68.

Rowe, P. B., Countryman, C. M., and Storey, H. C., 1949, Probable peak discharges and erosion rates from southern California watersheds as influenced by fire: U.S. Forest Service unpublished rept., 270 p.

——— 1954, Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds: California Forest and Range Expt. Sta., 49 p.

Schumm, S. A., 1954, The relation of drainage basin relief to sediment loss: Internat. Union Geodesy and Geophysics, Assoc. Sci. Hydrology, Gen. Assembly, Rome, v. 1, p. 216–219 [1955]; also available as Internat. Assoc. Sci. Hydrology Pub., no. 36 [1955].

——— 1956, Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey: Geol. Soc. America Bull., v. 67, p. 597–646.

——— 1963, The disparity between present rates of denudation and orogeny: U.S. Geol. Survey Prof. Paper 454–H, 13 p.

Scott, K. M., 1967, Downstream changes in sedimentological parameters illustrated by particle distribution from a breached rockfill dam: Symposium on River Morphology, General Assembly of Bern, Internat. Assoc. Sci. Hydrology, Internat. Union Geodesy and Geophysics, Pub. n. 75, p. 309–318.

——— 1971, Origin and sedimentology of debris flows near Glendora, California: U.S. Geol. Survey Prof. Paper 750–C, p. 242–247.

——— 1973, Scour and fill in Tujunga Wash—a fanhead valley in urban southern California—1969: U.S. Geol. Survey Prof. Paper 732–B, 35 p.

Scott, K. M., and Gravlee, G. C., 1968, Flood surge on the Rubicon River, California—hydrology, hydraulics, and boulder transport: U.S. Geol. Survey Prof. Paper 422–M, 40 p.

Scott, K. M., Ritter, J. R., and Knott, J. M., 1968, Sedimentation in the Piru Creek watershed, southern California: U.S. Geol. Survey Water-Supply Paper 1798–E, 48 p.

Sharp, R. P., 1954, Physiographic features of faulting in southern California: California Div. Mines Bull. 170, chap. 5, p. 21–28.

Shen, H. W., 1972, Watershed sediment yields: Paper presented to Inst. on Application of Stochastic Methods in Civil Eng., Colorado State Univ., Fort Collins, 11 p.

Snedecor, G. W., and Cochran, W. G., 1967, Statistical methods [6th ed.]: Iowa State Univ. Press, p. 394–395.

Stone, Robert, 1961, Geologic and engineering significance of changes in elevation revealed by precise leveling, Los Angles area, California [abs.]: Geol. Soc. America Spec. Paper 68, p. 57–58.

Strahler, A. N., 1957, Quantitative analysis of watershed geomorphology: Am. Geophys. Union Trans., v. 38, p. 913–920.

Tatum, F. E., 1965, A new method of estimating debris-storage requirements for debris basins: Federal Inter-Agency Sedimentation Conf. Proc., U.S. Dept. Agriculture Misc. Pub. 970, p. 886–897.

U.S. Forest Service, 1953, Santa Clara-Ventura Rivers and Calleguas Creek watersheds: Rept. of Survey, 34 p., 5 app.

Varnes, D. J., 1958, Landslide types and processes, *in* Landslides and engineering practice: Highway Research Board Spec. Rept. 29, Natl. Resources Council Pub. 544, p. 20–47.

Wallis, J. R., 1965, A factor analysis of soil erosion and stream sedimentation in northern California: Univ. California unpub. Ph.D. thesis, 141 p.

——— 1967, When is it safe to extend a prediction equation? —an answer based upon factor and discriminant function analysis: Water Resources Research, v. 3, p. 375–384.

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