

# Erosion and Sedimentation as Part of the Natural System<sup>1</sup>

Robert B. Howard<sup>2</sup>

Erosion and sedimentation are natural aspects of any environment regardless of geology or climate. The magnitude of erosion or sedimentation however differs from one environment to another. Various factors control the magnitude or rate of erosion in any given setting. To obtain a better understanding of contemporary erosion rates it is necessary to examine some of those geomorphic controls especially, in this paper, as they relate to the Mediterranean-type ecosystem. Concern with these present rates as well as attempts to estimate rates of these processes occurring in the geologically recent past fall within the province of geomorphology.

Geomorphology is that branch of the solid earth sciences concerned with the origin, development and morphology of the earth's myriad sub-aerial and submarine landforms and landscapes. There are two basic classes of processes responsible for earth surface morphology. These are the endogenic and exogenic processes. The endogenic forces derive their energy from the earth's internal heat. This group of processes is responsible for tectonism, igneous activity and metamorphism. Its global patterns and modes of operation are best understood in the light of the plate tectonic paradigm. The exogenic forces, on the other hand, are controlled largely by atmospheric agencies. These exogenic processes may be further subdivided into denudation and deposition.

## EXOGENIC PROCESSES

Denudation involves both weathering as well as erosion. Weathering, the *in situ* mechanical disintegration or chemical decomposition of rocks, may be thought of as the fundamental exogenic geomorphic process. Without weathering there is no sediment production and thus nothing available to be entrained, transported and ultimately deposited. In the absence of this most fundamental exogenic process, there would be no denudational or depositional environments and thus landforms and landscapes would remain unchanged with time. Erosion involves the entrainment as well as transport of rock waste by running water, gravity or mass

<sup>1</sup>Presented at the Symposium on Dynamics and Management of Mediterranean-type Ecosystems, June 22-26, 1981, San Diego, California.

<sup>2</sup>Associate Professor of Geomorphology, Department of Geography, California State University, Northridge.

---

Abstract: Dividing exogenic processes into constituents enables one to distinguish between denudational and depositional environments. This distinction leads to the recognition that the chaparral assemblage occupies a zone which is predominantly denudational. A qualitative assessment of some variables governing denudation rates is made. The factors associated with large sediment yields are all found in the chaparral watersheds of southern California.

---

movement, waves and currents, glacier ice and wind.

Deposition of materials in transport occurs either because of a change in the environment or a change in the strength of the transporting agent. Deposition, commonly occurring in the course of denudation, may be either temporary or relatively permanent. Temporary deposition merely involves the geologically short-term storage of sediment while in transit. In the fluvial context this would be as floodplain, alluvial fan or other form of valley fill. Ultimately most of this valley fill will be re-eroded and eventually deposited at some relatively permanent site where lithogenesis can occur. As lithogenesis takes place, the sediments are slowly buried under increasing thicknesses of younger overburden and are thus transformed from their original loose, unconsolidated condition into sedimentary rocks.

## EXOGENIC ENVIRONMENTS

From the foregoing, we may recognize two basic exogenic environments -- denudational and depositional. The denudational environments are those in which weathering and erosion dominate. In the fluvial context, these denudational environments tend to be found farthest upstream where slopes are steeper and relief tends to be greatest. In southern California the denudational environments coincide with the bedrock of the mountain fronts. This also tends to be the environment of the chaparral. These denudational environments may be either weathering or transport limited. In a weathering-limited environment, denudation depends on the rate of debris production by rock disintegration or decomposition. Where an environment is transport limited, denudation depends on the rate of accumulation of debris at slope bases and in stream channels, and by the frequency of events of sufficient magnitude to entrain and transport it. In most fluvial denudational systems, regardless of whether they are weathering or transport limited, there is a close association between the stream channel and its debris-contributing valley side slopes.

Environments in which deposition dominates tend to be found in the downstream direction where slopes are low and relief is small. In southern California, fluvial depositional environments are found along stream channels from their canyon mouths to the coast. Again, in southern California the depositional environment tends to be associated with the vegetation communities mapped

either as grassland or coastal sage. This is probably due to the rather high degree of ecological disturbance which occurs with each flood and subsequent depositional episode. In these depositional environments there tends to be a progressive divorcing of stream channels from their associated valley side slopes as one proceeds downstream.

Vegetation plays a very large role in fluvial environmental systems. Initially it acts as a biological barrier to erosion by intercepting precipitation and causing it to dissipate its kinetic energy on leaves and other aerial portions of the plant. Organic matter incorporated into the soil greatly influences soil structure and subsequently the hydraulic properties of the land surface. Vegetation's influence does not end with its effect on hydraulic properties of soils but continues through weathering and hence debris production. Vegetal-biochemical reactions termed pedochemical weathering aid in the formation of various alteration compounds as well as in the actual breakdown of bedrock.

#### CONTEMPORARY DENUDATION RATES

Contemporary denudation rates are based on measurements of sediment yielded from an entire drainage basin. This is usually accomplished by measuring the sediment (dissolved, suspended and bedload) departing the basin through its outlet. This total sediment yield provides an average basin-wide denudation value. Although a significant indicator of gross denudation, this type of measure does not provide information on actual source areas of sediment within the basin. Because sediment yields fluctuate widely (often by as much as a factor of five from year to year) calculations with the greatest validity are those made from considerable periods of record (Ahnert 1970). Holeman (1968) using a wide variety of sources projected sediment yield of the various continents. His study puts denudation into a global or spatial context. It also permits an initial understanding of some of those variables which exert controls on the rates of denudation. The results of Holeman's study show Asia and North America as the continents yielding the greatest average amounts of sediment to the oceans, North America yields an average of 245 tons/mi<sup>2</sup>/yr as determined from humid streams of the eastern and southeastern United States. This results in a surface lowering of approximately 3.2cm/1,000yrs (1.25in/1,000yrs). Asian sediment yields, as determined from several streams draining highly mountainous monsoonal regions, approach 1530 tons/mi<sup>2</sup>/yr for an average surface lowering of 20 cm/1,000yrs (7.87in/1,000yrs). Judson and Ritter (1964) examined regional denudational rates in the United States. Their study reveals that the Colorado river basin has the highest sediment yield with some 1255 tons/mi<sup>2</sup>/yr or a surface lowering of 16.5cm/1,000yrs (6.5in/1,000yrs). The Pacific slope basins showed the second highest yields with values slightly more than half those of the Colorado (700 tons/mi<sup>2</sup>/yr or 9cm/1,000yrs).

#### FACTORS CONTROLLING DENUDATION RATES

Coupling information from the aforementioned studies with studies by Ahnert (1970) on functional relationships between slope, relief and denudation and with that by Langbein and Schumm (1958) on the sediment yield-climate relationship, it is possible to delimit qualitatively those variables which exert a strong influence on denudation rates. Denudation rate is strongly dependent on scale, with smallest basins having the highest rates. This is probably a function of the steepness of slopes and, hence, greater relief of smaller basins of lower order (Ahnert 1970). Additionally, smaller basins would tend to be at higher elevations and, thus, receive more precipitation than neighboring, higher-order basins. Being primarily denudational these smaller basins would also be flushed by storm runoff more readily. Larger basins on the other hand tend to have lower sediment yields because an increasing percentage of the basin's area becomes depositional causing sediment storage to increase with basin size. With basin size held constant Langbein and Schumm (1958) demonstrated a relationship between denudation rate and effective annual precipitation. Maximum clastic denudation seems to occur at about 30.5cm/yr (12in/yr) or at the approximate boundary between desert and grassland. Reduced clastic denudation occurs at precipitation amounts above and below this 30.5cm/yr value because of increased vegetal coverage of the surface in wetter environments and reduced precipitation in the drier ones. At the high annual precipitation amounts typical of humid tropical regions denudation rates probably increase, however the denudation is probably chemical and not clastic. A final factor influencing denudation that should be mentioned here is revealed by Holeman's (1968) study which shows monsoon Asia with enormous sediment yields. Apparently strong seasonality in precipitation is associated with large sediment yields.

#### EVENT FREQUENCY, THRESHOLDS AND SEDIMENT YIELD

Before focusing on denudation and deposition in the chaparral system one last topic deserves to be mentioned. More and more frequently geomorphologists are being made aware of event frequency and thresholds in relation to sediment yield. In their classic study Wolman and Miller (1960) demonstrated that the greatest amount of work done on the landscape over the long run is accomplished by the frequently occurring moderate events. On this basis fluvial geomorphologists have concentrated on bankfull discharge as the most probable flood event and the flow to which the channel's geometry is adjusted. Statistically, this bankfull discharge can be expected to occur as the annual maximum every 1.58 years. On the other hand it can be expected to occur as a less than annual maximum every 0.9 year or 11 times in a 10-year period. In recent years, with the increasing publication of research on subhumid and dry region processes, the notion of the extreme

event in these erosional systems is once again gaining credence (see especially Thornes 1976). While the general proposition put forth by Wolman and Miller concerning the magnitude and frequency of events is not in serious doubt for humid regions with perennial streams, the situation in arid, semiarid and subhumid environments appears to be different. Several arguments can be advanced to support the contention that in these drier environments total work on the landscape over the long run is biased toward the higher magnitude, lower frequency geomorphic events. First, detrital materials tend to be of larger size and greater volume in most dry regions and, thus, require higher critical stresses for their entrainment and transport. Moderate to low magnitude events, occurring however frequently, will generally be insufficient to reinitiate bedload movement, save for the smallest particles. Second, in most dry regions, alluvial surfaces consist of poorly sorted, highly permeable materials so extensive transmission losses can be expected when flows do occur. These excessive losses decrease the likelihood that any sediment transport will occur with low to moderate events. Third, detachment of soil particles from hillslopes followed by their entrainment is an intensity related phenomenon (Mutchler and Young, 1975). Fourth, mass movement in the form of soil slips, debris flows, slumps or landslides are triggered by high magnitude events (Campbell 1975; Rice and Foggin 1971; Scott and Williams 1978). If slope failure were related to more frequent, moderate events then they would present more of a problem than is the case at present. A last argument is based on the statistics of precipitation distribution. As the total annual precipitation decreases its variability increases (Goudie and Wilkinson 1977). A corollary to this statement is that as precipitation totals decrease then the likelihood of the total annual amount occurring as one or two storms increases. This argument implies that because the subhumid and drier regions experience low, highly variable amounts of precipitation then the idea of a single moderately frequent event to which the landscape or stream channels are adjusted is tenuous at best.

Coupled with rethinking of the magnitude and frequency concept there has been, especially in the last few years, recognition of the metastable condition of most landforms (Schumm 1973). From this recognition the notion of thresholds or potential morphological instability has been, and continues to be, developed (see especially Coates and Vitek 1980). There are two classes of thresholds, extrinsic and intrinsic. Extrinsic thresholds are external to the system. Examples are a storm induced flood event or an earthquake which triggers slope failure. Intrinsic thresholds, on the other hand, are internal to the system. An example of an intrinsic threshold might be the slow continuous weathering of slope materials until their shear strength is reduced to the minimal value for continued stability. The idea of thresholds means that slow changes in landforms or landscapes continue to occur through erosion

or deposition. This slow change in morphology leads up to the threshold--that metastable condition or point of potential morphological instability. A subsequent event, not necessarily a major event either, can then occur and push the apparently stable morphological system over this particular threshold resulting in erosion, deposition and a sudden shift in form. A corollary to this threshold concept is that neighboring systems do not necessarily reach thresholds simultaneously. Thus, one area may be undergoing rapid change while adjacent areas are still approaching their metastable condition. This complex response of geomorphic systems can lead to considerable confusion in interpretation of a landscape's geomorphic history.

#### THE CHAPARRAL ENVIRONMENT AND SEDIMENT YIELDS

With these concepts in mind we can now attempt to characterize the geomorphic processes and responses of the chaparral environment. The physical environment of southern California's chaparral ecosystem exerts a strong control over rates and total amounts of denudation. The region is tectonically active with mountain masses being uplifted at rates between 3.96m/1,000yrs (13ft/1,000 yrs) in the Santa Monica mountains and 5.2m to 6.1m/1,000yrs (17ft to 20ft/1,000yrs) in the San Gabriel mountains (Gilluly, 1949). These tectonically active denudational environments (mountain masses) rise very abruptly from their associated depositional aprons of sediment (alluvial fans and alluvial plains). Because of tectonism the mountain masses possess very steep slopes, high relief and relatively small drainage basins especially along the mountain fronts. Lithologically the eastern Transverse ranges along with the Peninsular ranges are composed of crystalline igneous rocks largely of Mesozoic age coupled with some Precambrian metamorphic rocks. Most of these rocks are highly altered because of age, emplacement, weathering or faulting. The western Transverse ranges consist mainly of Cenozoic sedimentary rocks which have been uplifted and deformed into east-west trending folds and reverse faults by a predominant north-south compression. Climatically the chaparral environment displays a strongly seasonal precipitation pattern which is characteristic of the Mediterranean climate. This November to March rainy season quite obviously affects the distribution of runoff events. Superimposed onto this seasonal regime is the orographic influence on the spatial distribution of precipitation. The range of average precipitation is from 38cm (15in) near sea level to over 66cm (26in) at about 817m (2680ft). With this geological setting and climate, fairly high normal sediment yields should be expected from southern California's chaparral watersheds. This should be self-evident by comparing the nature of the physical environment with those variables which seem associated with high sediment yield, namely, seasonality of rainfall, small size of drainage basins, steep slopes and high relief, and precipitation amounts on the order of 38cm to 50.8cm (15in to 20in). Given these facts it is really

quite surprising that the chaparral watersheds do not yield an even greater amount of sediment under normal conditions. This might be due to litter accumulations on the watershed's surface which promote infiltration and impede overland flow. Additionally, litter would absorb some of the raindrop impact and reduce the dislodging of soil particles. From time to time sediment yields increase dramatically due to the interplay between the factors of fire, highly variable annual precipitation totals and effects associated with approaching thresholds. The greatest sediment yields occur when all three of these factors combine as in wet years after a fire in an area where channels and slopes are near threshold conditions.

One cannot talk of the chaparral of southern California without mentioning fire. It appears that fire is a major environmental agent in shaping California's chaparral (Hanes 1977). Temporally, fire shows a distinct seasonality occurring in the late summer and early fall, just prior to the rainy season. Anywhere from four to six months of drought precede this fire season. The dryness can be further enhanced by the development of Santa Ana winds which occur most frequently during this time of the year (McCutchan 1977). The recurrence interval for fire is extremely variable but under natural conditions it ranges from 10 to 40 years (Muller et al. 1968). After fire, runoff and sediment yield increase well above normal. This is probably due in part to the development or enhancement of a hydrophobic layer below the soil's surface (DeBano 1966, 1971).

Mean annual precipitation in the Los Angeles basin as determined from the period 1960-1979 is 38cm and shows a strong winter maximum. For this mean precipitation value, the variability should exceed 30 percent (Goudie and Wilkinson 1977). The extremely variable precipitation and its potential effects are illustrated by the 12 year period 1968-69 to 1979-80. The water year 1968-69 was an extremely wet one with some 66cm (26in) of rainfall in the lowland areas of the Los Angeles basin. High daily totals imply that there were many high intensity episodes in the various storm events. During the drought year 1975-76 only about 20cm (8in) of rainfall was recorded in the basin. The wettest year in the previous 80 years occurred in the water year 1977-78 when approximately 80cm (31.5in) of rainfall were recorded in the lowlands. The daily totals of precipitation during the 1977-78 year were lower than for the 1968-69 year implying lower intensity storm events. Because major mass movements are related to large magnitude hydrologic events, dry years produce no debris flows, landslides and few soil slips. Tan (1980) has demonstrated that storm intensities in wet years influence the timing and types of mass movements. In very wet years with high intensity storms debris flows tend to be the dominant mass movement type. This was noted especially in January 1969 storms (Campbell 1975; Scott and Williams 1978). In the very wet year 1977-78, although higher total precipitation was recorded, the daily totals

were less, implying lower storm intensities. Lower precipitation intensities allow for greater infiltration and subsequent percolation. This resulted in deep seated landslides occurring with delay periods of between 2 and 6 months after storms ended.

Thresholds may be slowly approached or attained even during the dry season. Studies have revealed that between one-third and almost one-half (45 percent) of the erosion in unburned chaparral watersheds occurs as dry ravel during the dry season (Krammes 1965; Rice 1974). Anderson et al. (1959) measured dry ravel yields of between 224kg/ha (200lbs/acre) to 4300kg/ha (3800lbs/acre) from small watersheds in the San Gabriel mountains. Subsequent studies by Krammes and Osborn (1969) have determined that between one-third and three-quarters of the wet season erosion was also occurring as dry ravel. This would mean that a maximum of from 63 to 86 percent of the total surface erosion in unburned watersheds is occurring as dry ravel. Some of this dry ravel material may accumulate behind stems and trunks or under litter. However, most of it finds its way into the steep low order stream channels where it builds up awaiting a storm of sufficient magnitude to transport it.

The greatest sediment yields from southern California chaparral watersheds occur when fire, a large magnitude event and an approaching threshold combine. The stage is generally set by events during the fire season. Fire consumes the aerial portions of most plants and, thus, the support for much material entrapped by vegetation is lost. Dry ravel may show as much as a 9-fold increase after fire (Krammes 1965). This increased volume of slope debris is added to the growing volume of fill existing in the stream channel. A very important effect of fire in the chaparral is the production or enhancement of a water-repellent layer caused by burning the litter. This water-repellent layer develops at depths of between 2 and 5 centimeters below the surface. The layer is most intense or best developed in soils with a large amount of sand because sandy soils have less specific surface to be coated with hydrophobic substances than a silty or clayey soil. Sandy soils also have higher permeabilities and thus greater penetration of the hydrophobic vapors occurs. This water-repellent layer reduces the effective moisture storage capacity of the chaparral regolith from a meter or so to less than a few centimeters.

During the rainy season the effects of water repellency are far-reaching. The immediate effect is to reduce moisture storage capacity. Subsequently, this reduced storage capacity influences infiltration rates, overland flow, raindrop impact, rill formation and debris flow initiation. Saturation of the upper few centimeters of the watershed's regolith results in positive pore water pressures and reduces the shear strength of the regolith. The reduction in moisture storage capacity forces overland flow to occur under pre-

precipitation amounts or intensities that would normally infiltrate completely. With most of a hill-slope bare after fire, raindrop impact entrainment is increased. When coupled with saturation-induced overland flow, this maximizes surface erosion.

Rills tend to be a ubiquitous feature on rapidly eroding, burned, chaparral watersheds. Wells and Brown (in press) have proposed a mechanism for formation of these features which involves water repellency. Saturation of the upper few centimeters of soil above the hydrophobic layer results in the development of positive pore water pressure and significantly reduces the effective normal stress. A narrow linear failure occurs in the near surface wettable layer above the hydrophobic zone producing the rill. Fluvial erosion in the newly formed rill scours out the water repellent materials by developed turbulence. Once the hydrophobic layer has been scoured out of the rill's bottom infiltration may once again occur and the full thickness of the regolith is available for moisture storage. At this point flow in the rill may cease. In the formation of these rills a significant amount of sediment may be yielded to stream channels.

Debris flows also contribute very large amounts of sediment to stream channels. These flows frequently begin as soil slips, shallow surface failures that are often noticeable on the grassy hillslopes of southern California. Soil slip frequencies are maximized under post-fire conditions with high intensity storms (Campbell 1975). Even under moderate storms pore fluid pressures may attain significant positive values. Sediment yield potentials from soil slips can be considerable. Conservatively, soil slip scars may frequently cover 2 to 3 percent of a watershed's surface after a rainy season. Each scar often has a surface area of 50 to 60mm<sup>2</sup> (59 to 72yd<sup>2</sup>) with average depths of material removed of about 40cm (15.7in). The volume of debris yielded from one of these small slips would be on the order of 20 to 24m<sup>3</sup> (26 to 31yd<sup>3</sup>). In a 1 hectare (2.47acre) watershed with 2 to 3 percent of the surface scarred by soil slips having the above conservative dimensions the sediment yield would be on the order of 80 to 120 m<sup>3</sup> (104 to 156yd<sup>3</sup>). Actual sediment yields from any watershed in any year would depend on surface conditions and storm magnitudes. Rice and Foggin (1971), for example, report brush area sediment yields in southern California of only 21.1m<sup>3</sup>/ha for 1966, a year of moderate precipitation whose storm return period was about 9 years. In the wet year 1969 these brush area sediment yields increased to 298m<sup>3</sup>/ha however this was for a storm season with a 32-year recurrence interval.

The hydrophobic layer also influences debris yields due to sheet erosion. For example, if 1mm (0.04in) is removed from the surface of a 1 ha basin, sediment yield will be some 10m<sup>3</sup> (13yd<sup>3</sup>). From a 100ha (247acre) basin with a hydrophobic layer just 2cm (0.8in) below the surface there can be a potential loss of 18,800m<sup>3</sup> (24,400yd<sup>3</sup>)

of sediment. Scott (1971) reports that in January 1969 one small watershed on the south flank of the San Gabriel mountains near Glendora, California yielded the equivalent of approximately 60,000 m<sup>3</sup>/ha (200,000yd<sup>3</sup>/mi<sup>2</sup>).

Dry ravel debris of considerable volume builds up in stream channels during the dry seasons between fires. Little erosion of this debris occurs during normal rainy seasons in the absence of fire. Post-fire increases in dry ravel are amplified during extremely wet years. Given a large magnitude flood event such as any of those that occurred in 1968-69, 1977-78, or 1979-80, slope debris is mobilized as soil slips are converted into debris flows. The large volume of sediment stored in the stream channels is also mobilized and flushed out and this reinforces the notion of the higher magnitude less frequent flood event being the principal fluvial geomorphic agent in dry and subhumid environments. The available research information would seem to imply that channel processes and sediment yields are time evolutionary. That is, several large storms of similar magnitudes will show decreasing sediment yields and channel scour because the first storm or two removes most of the available sediment and exposes the bedrock.

Rice (1974) and Rowe, *et al.* (1954) have discussed the pattern of sediment yield from chaparral watersheds after fires. Post-fire conditions usually last for about 8 to 10 years. In the first year after fire, sediment yields show anywhere from a 5-to 35-fold increase over normal. In subsequent years the reduction in sediment yields approaching normal becomes apparent. The second year after fire shows a 2-to 12-fold increase, third year increases over normal are reduced to, 0.7-to 7-fold. This increased sediment yield drops to zero after the 8-to 10-year recovery period. The percentage of total sediment increase also shows a decrease with time. In the first year about 55 percent of the total 8-to 10-year increase in sediment yield has occurred. This drops off to about 18 percent in the second year followed by 11 percent in the third year and 7 percent in the fourth. By the end of the first 4 years about 91 percent of the total sediment yield increase has occurred.

#### CONCLUSIONS

From the foregoing it can be seen that erosion and sedimentation are normal and must, therefore, receive consideration in any environment. In the chaparral environment of southern California with its tectonically active mountain masses, high relief, steep slopes and strongly seasonal precipitation large normal sediment yields are to be expected. Increased sediment yields of up to 30 times normal are also natural in this environment because of fire, approaching thresholds and the variable, seasonal precipitation.

Acknowledgements: I thank Wade Wells II, Pacific Southwest Forest and Range Experiment Station,

and Robert Brumbaugh, Department of Geography, California State University, Northridge for their critical comments on the initial drafts of this review paper.

#### LITERATURE CITED

- Ahnert, F., 1970, Functional relationship between denudation, relief, and uplift in large mid-latitude drainage basins: *American Journal of Science*, v. 268: 243-263.
- Anderson, H.W., G.B. Coleman and P.J. Zinke, 1959, Summer slides and winter scour...dry wet erosion in southern California mountains: U.S. Department of Agriculture, U.S. Forest Serv. Tech. Paper PSW-36
- Campbell, R.H., 1975, Soil slips, debris flows, and rain storms in the Santa Monica mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851.
- Coates, D.R. and J.D. Vitek, 1980, Thresholds in Geomorphology: Winchester, Allen and Unwin.
- DeBano, L.F., 1971, The effect of hydrophobic substances on water movement during infiltration: *Soil Science Society of America, Proceedings*, v. 35: 340-343.
- DeBano, L.F., 1966, Formation of nonwetable soils ...involves heat transfer mechanism: U.S. Department of Agriculture, U.S. Forest Serv. Res. Note PSW-132.
- DeBano, L.F., R.M. Rice and C.E. Conrad, 1979, Soil heating in chaparral fires: Effects on soil properties, plant nutrients, erosion, and runoff: U.S. Department of Agriculture, U.S. Forest Serv. Res. Paper PSW-145,
- Gilluly, J., 1949, Distribution of mountain building in geologic time: *Geological Society of America, Bulletin*, v.60: 561-590.
- Goudie, A. and J. Wilkinson, 1977, *The Warm Desert Environment*: Cambridge, Cambridge University Press.
- Hanes, T.L., 1977, California chaparral, in M.G. Barbour and J. Major, eds. *Terrestrial Vegetation of California*: New York, Wiley Interscience: 417-469.
- Holeman, J.N., 1968, The sediment yield of major rivers of the world: *Water Resources Research*, v. 4: 737-747.
- Judson, S. and D.F. Ritter, 1964, Rates of regional denudation in the United States: *Journal of Geophysical Research*, v. 69: 3395-3401.
- Krammes, J.S., 1965, Seasonal debris movement from steep mountain side slopes in southern California, in *Federal Interagency Sediment Conference, Proceedings*: Washington, D.C., U.S. Department of Agriculture Miscellaneous Publication 970: 85-88.
- Krammes, J.S. and J. Osborn, 1969, Water-repellent soils and wetting agents as factors influencing erosion, in L.F. DeBano and J. Letey, eds. *Symposium on Water Repellent Soils, Proceedings*: Riverside, University of California: 177-187.
- Langbein, W.B. and S.A. Schumm, 1958, Yield of sediment in relation to mean annual precipitation: *American Geophysical Union, Transactions*, v, 39: 1076-1084.
- McCutchan, M.H., 1977, Climatic features as a fire determinant, in U.S. Forest Service, *Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems*: U.S. Department of Agriculture, U.S. Forest Service General Tech. Rep. WO-3.
- Muller, C.H., R.P. Hanawalt and J.K. McPherson, 1968, Allelopathic control of herb growth in the fire cycle of California chaparral: *Torrey Botany Club, Bulletin*, v. 95: 225-231.
- Mutchler, C.K. and R.A. Young, 1975, Soil detachment by raindrops, in *Present and Prospective Techniques for Predicting Sediment Yields and Sources*: U.S. Department of Agriculture, ARS-S-40: 113-117.
- Rice, R.M., 1974, The hydrology of chaparral soils in *Symposium On Living With The Chaparral, Proceedings*: Riverside, California, Sierra Club: 27-34.
- Rice, R.M. and G.T. Foggin, 1971, Effect of high intensity storms on soil slippage on mountainous watersheds in southern California: *Water Resources Research*, v. 7: 1485-1496.
- Rowe, P.B., C.M. Countryman and H.C. Storey, 1954, Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds: U.S. Department of Agriculture, Pacific Southwest Forest and Range Experiment Station Report.
- Schumm, S.A., 1973, Geomorphic thresholds and complex response of drainage systems, in M.E. Morisawa, ed. *Fluvial Geomorphology*: Winchester, Allen and Unwin.
- Scott, K.M., 1971, Origin and sedimentology of 1969 debris flows near Glendora, California: U.S. Geological Survey Professional Paper 750-C: 242-247.
- Scott, K.M. and R.P. Williams, 1978, Erosion and sediment yields in the Transverse Ranges, southern California: U.S. Geological Survey Professional Paper 1030.
- Tan, S.S., 1980, Slope failures in Orange County due to 1978 rain: *California Geology*, v. 33: 202-205.
- Thorns, J., 1976, *Semi-Arid Erosional Systems*: London School of Economics, Geographical Papers Number 7.
- Wells, W.G. and W.M. Brown, in press, Effects of fire on sedimentation processes, in *Sediment Management for Southern California Mountains, Coastal Plains and Shoreline*: Pasadena, California Institute of Technology, Environmental Quality Laboratory Report: Appendix D-4.
- Wolman, N.G. and J.P. Miller, 1960, Magnitude and frequency of forces in geomorphic processes: *Journal of Geology*, v. 68: 54--74.