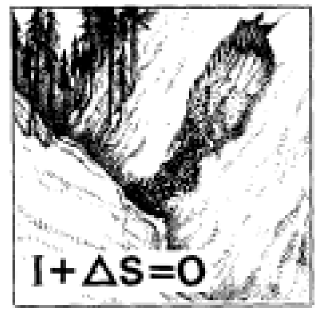

Sedimentation in the Chaparral: How Do You Handle Unusual Events?

Raymond M. Rice

ABSTRACT

Processes of erosion and sedimentation in steep chaparral drainage basins of southern California are described. The word "hyperschedastic" is coined to describe the sedimentation regime which is highly variable because of the interaction of marginally stable drainage basins, great variability in storm inputs, and the random occurrence of brush fires.

The difficulties and advantages of describing chaparral sedimentation using either empiric or process models are dicussed. Modeling based on Monte Carlo simulation is suggested as a way of capturing many of the benefits of empiric and process models.

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INTRODUCTION

Processes of erosion and sedimentation in steep chaparral drainage basins in southern California are described, as the basis of a wider discussion of sediment budgets, sediment routing, and drainage-basin modeling in general. A simulation approach to sediment budgets and sediment routing is proposed which incorporates some desirable features of process models and empiric models.

THE CHAPARRAL ENVIRONMENT

Chaparral occurs in a wide variety of environments. This discussion treats a narrower range of conditions occurring in the steep "front country" drainage basins of the San Gabriel and San Bernardino Mountains in the Transverse Range in southern California. These drainage basins present the greatest flood and management problems, and this limitation in scope permits a sharper definition of relationships than would be possible in a more general discussion.

Climate

Chaparral grows in a Mediterranean climate. In southern California, most chaparral stands receive between 400 and 700 mm of rain annually with about three-quarters of the precipitation falling during December through March. Rainfall varies greatly from year to year. In Glendora, rain in the wettest year of a 97-year record was over seven times that in the driest year (fig. 1).

Winter temperatures average 9^{o}C. The summer months average about 20^{o}C and are normally without rain. Fire is favored by severe heat waves, accompanied by humidities of 15 to 20 percent, which occur several times each season. Maximum temperatures during these heat waves are typically around 40^{o}C. Another fire-promoting element of the climate is the strong, desiccating, foehn winds that occur most frequently from mid-September through December. Chaparral vegetation has evolved in response to repeated fire and great annual and seasonal variations in moisture availability and evaporative stress.

Geology and Topography

The eastern portion of the Transverse Range is mainly underlain by Precambrian to Cretaceous igneous and metamorphic rocks; to the west, Cenozoic sedimentary formations predominate (California Division of Mines and Geology 1969). In both areas, poorly developed, coarse-textured, erodible soils are the rule. Soil depths average about 60 cm, but depth is of little hydrologic importance because the parent material is typically so weathered or fractured that for a depth of 1 to 3 m its ability to store and transmit water is little different from the overlying soil (Krammes 1967), As a consequence, chaparral drainage basins normally have a thick, hydrologically active mantle.

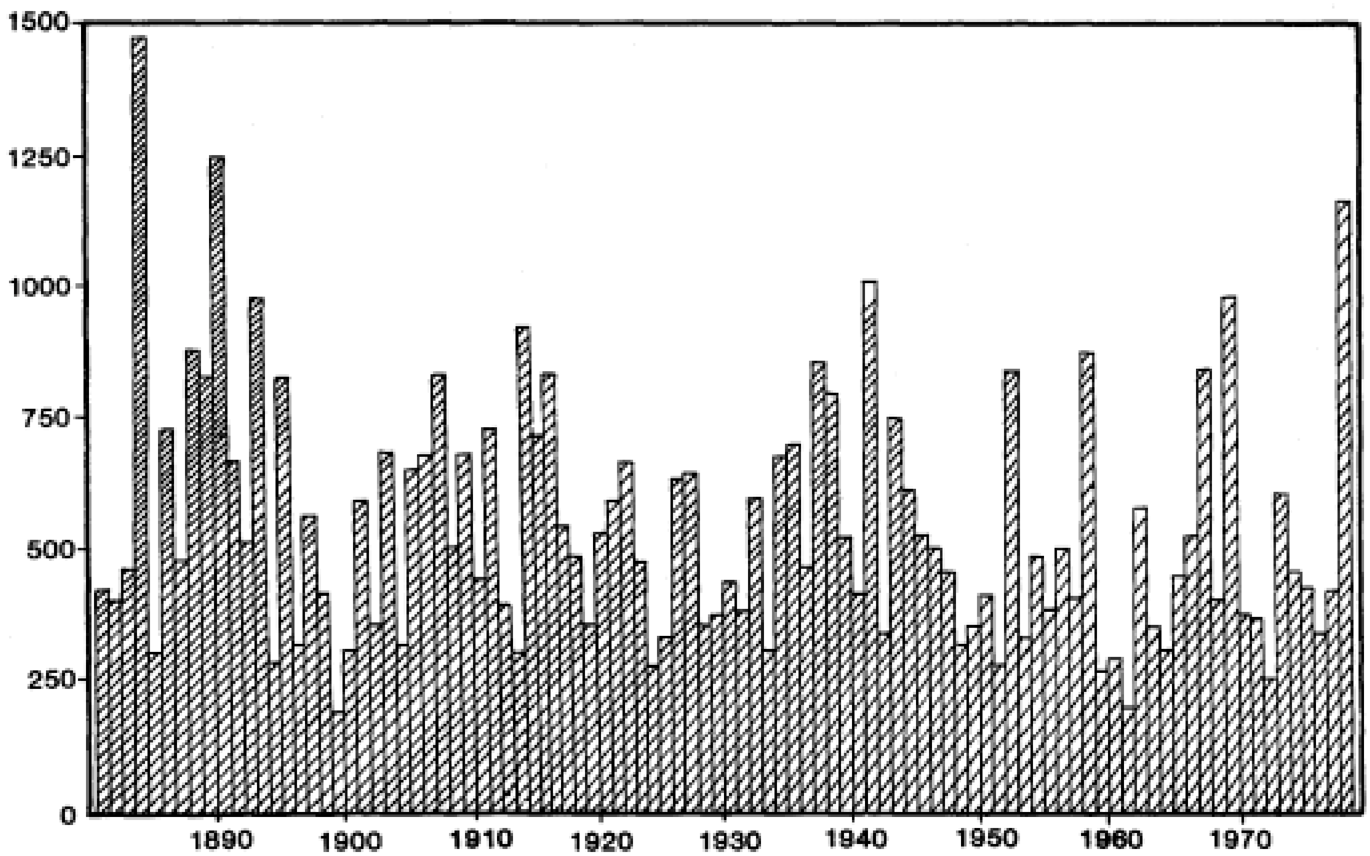

Figure 1.--Annual rainfall in the West rain gage. Glendora, California.

The mountains of the Transverse and Coast Ranges are currently being uplifted at a rate of about 60 cm a century (Scott and Williams 1974). This rapid uplift has rejuvenated the drainage system, producing average channel gradients of about 15 percent and average hillslope gradients of about 60 percent. The steep gradients cause the hillslopes to be very efficient at delivering soil to the stream channels, and the channels can also move large amounts of sediment if flows are high enough.

Vegetation

Chaparral plants are adapted to the Mediterranean climate and to the associated fires. Adaptations to drought, such as leaf morphology and the accumulation of extractive compounds in chaparral, contribute to high flammability. Because the plant community is specialized for postfire regeneration, the vegetative and hydrologic recovery of chaparral drainage basins is rapid after fire. As a result of rapid vegetative regrowth, Kittredge (1939) found that, 17 years after a fire, litter accumulation was 13 t/ha and, in an area not burned for over 50 years, the accumulation was 37 t/ha. This litter accumula tion protects the soil surface, increases its roughness, and temporarily stores rain falling at rates greater than the infiltration rate. These actions insure that surface erosion and overland flow rarely occur.

Fire

Ecological evidence suggests that fire has played a prominent role in chaparral communities for millions of years. Keeley (1977) proposes that the existence of the genera Arctostaphylos and Ceanothus, the majority of whose species do not sprout, indicates that the interfire interval formerly may have been longer than it is now. He calls this the "Stochastic-Fire Hypothesis." He argues that because lightning fires in southern California occur mainly in summer and mainly at high elevations in the interior portions of the mountain ranges, for most of the chaparral to be ignited by lightning would be difficult. He suggests that relatively few lightning fires would continue to burn long enough to be swept downslope and coastward by the autumn foehn winds. Aschmann (1977) believes that increased fire frequency resulted both from accidental and purposeful burning on the part of aborigines. Preliminary analyses of varved cores taken from the Santa Barbara basin support this idea (Byrne et al. 1977). That record indicated that very large fires may have occured every 20 to 40 years. A 150-year core taken from the 16th and 17th centuries showed considerably more variability in charcoal concentrations than one spanning the 40 years between 1931 and 1970. This suggests the hypothesis that the greater temporal and areal homogeneity of modern fire occurrence is a result of the population increase.

Figure 2.--Dry-ravel deposits which had been blocking channel of Monroe Canyon are eroded by storm of October 9-10, 1960.

EROSIONAL PROCESSES

Dry Ravel

Dry ravel is the most ubiquitous erosional process occurring in the chaparral. This process, sometimes termed "dry creep" (Krammes 1965), is the downslope movement by gravity of individual grains or aggregates of soil. The slope threshold for dry ravel is about 30 degrees. Kittredge (1939) estimated that dry ravel occurred on about 17 percent of his study area. My own inventory of the chaparral zone of southern California indicates that about 25 percent of the area is subject to dry ravel. The proportion of the front-country drainage basins that are steep enough for dry ravel is higher. In Englewild Canyon above Glendora, 40 percent of the slopes are steeper than 30 degrees. Englewild has gentler topography than the majority of the front-country drainage basins. Therefore, about two-thirds of the slopes of front-country drainage basins are probably steep enough for dry ravel.

Dry ravel is initiated by many types of small disturbances. Small sand runs can start when deer, small rodents, and even birds walk on a slope. One of the principal triggers, however, seems to be the movement of vegetation during periods of strong foehn winds. Five years of monitoring the Arroyo Seco drainage showed an average dry-season erosion rate of 0.96 m^3/ha, which was 55 percent of the total surface erosion measured (Anderson et al. 1959). Later studies of postfire erosion revealed that about half of the wet-season erosion was actually dry ravel occurring between winter rainstorms (Krammes and Osborne 1969). Consequently, I believe that, with unburned chaparral, the dry-ravel rate is about 1.4 m^3/ha per year. In the autumn of 1959, a wild fire swept over the Arroyo Seco study area resulting in about 39 m^3/ha of dry-ravel erosion during the next 3 months. The immediate effect of fire on dry ravel is to consume the forest litter that has been serving as temporary barriers to the downslope movement. Accelerated ravel occurs within minutes of the passage of the fire and can produce debris cones blocking stream channels within a few hours (fig. 2). Fire also accelerates dry ravel by the creation of a water-repellent layer (DeBano 1969). The waterrepellent layer traps precipitation in the surface soil where it is more easily evaporated. In addition to reducing percolation, it also prevents the capillary rise of water to the surface from deeper soil strata. By inhibiting the vertical movement of water, the water repellent layer causes the soil surface to dry more quickly between storms and, therefore, to be subject to dry ravel for a greater portion of the wet season. Although fire-related water repellency is detectable for a long time, it ceases to affect runoff or erosion significantly within 2 or 3 years after a fire.

Surface Erosion by Flowing Water

Surface erosion is a rarity in unburned chaparral drainage basins because litter usually protects the soil surface. Even without that protection, the thick, hydrologically active mantle can store and transmit large volumes of water. Furthermore, rainfall intensities rarely exceed infiltration rates. In none of the 300 largest storms during 24 years on the San Dimas Experimental Forest did the rainfall rate exceed the average hydraulic conductivity of the soil for 1 hour; in only 1 percent of the storms was it exceeded for 30 minutes (Reimann and Hamilton 1959). In all, only about 2.5 percent of the precipitation fell at a rate higher than the infiltration rate of the soil, and some of this rain was dispersed in time so that it had little effect on runoff. Both Colman (1953) and Troxell (1953) reported that almost no overland flow occurred during the flood of 1938. During that storm, less than 1 percent of the precipitation was measured as surface runoff from research plots, even though the streamflow from various drainage basins amounted to 16 to 38 percent of storm precipitation. Surface erosion remains almost nil without the transporting medium of overland flow, even though some minor erosion may result from drop impact of rainfall or throughfall.

The passage of a fire through chaparral usually greatly increases surface erosion by altering hillslope hydrology. A water-repellent layer is often created. This layer presents a relatively impervious barrier to deeper percolation. As a result, a drainage basin that might have a hydrologically active mantle 2 m thick when unburned may have its effective thickness reduced by fire to a few centimeters (Krammes and Osborne 1969). A recently burned slope can become "saturated" by just a few centimeters of precipitation.

Characteristically, dry ravel after fire accumulates during summer and fall on the flatter portions of burned slopes and in ephemeral channels. Overland flow the following winter scours most of its sediment load from these erodible deposits. The scenario may be repeated several winters after the fire as the rills formed during each runoff period are refilled by dry ravel between storms and during summers.

Landslides

Landslides were not considered as an important erosional process in the chaparral until the past decade when they were recognized as both an important erosional mechanism (Bailey and Rice 1969) and as a serious threat to life and property (Campbell 1975). They were probably ignored in earlier years because of their infrequency. Campbell (1975) placed the return period of the average landslide-producing storm in the Santa Monica Mountains at between 10 and 25 years. The return period seems to be less than 10 years for the front-country portions of the San Gabriel and San Bernardino Mountains. After being alerted to the significance of landslides by the storms of 1966 and 1969, I found records of soil slips (as they were called) on the San Dimas Experimental Forest in 1933, 1938, 1943, and 1965. These landslides occurred during storms producing about 500 mm of precipitation in a 5-day period, with 150 to 200 mm falling in 24 hours late in the storm. Campbell (1975) suggests that about 250 mm of antecedent precipitation followed by a period of rainfall in excess of 6 mm/hour constitute the conditions necessary for soil slips and debris flows in the Santa Monica Mountains. Bailey (1967) belives that the 12-day (before the end of the landslide-producing storm) precipitation amount is a good descriptor of the landslide-producing capabilities of a storm.

Data from 1966 and 1969 storms on the San Dimas Experimental Forest (Rice et al. 1969, Rice and Foggin 1971) give some appreciation for the effect of storm size on landslide erosion in the chaparral. These data may be affected, however, by the fact that the area burned in 1960. By Bailey's (1967) criterion, the 1966 and 1969 storms have return periods of about 11 and 43 years, respectively. Based on the 24-hour amount, the return periods would be 7 and 22 years. In the 1966 storm, 1.7 percent of the area produced landslides; in 1969, landslides were found on 5.5 percent of the area. In 1966, the erosion rate was 21.1 m^3/ha; in 1969, it was 298 m^3/ha. In 1966, the gentlest slope upon which a landslide was found was 40 degrees. In 1969, the threshold had lowered to 31 degrees. Campbell (1975) identified a range of 26 degrees to 45 degrees as the most common slope for the occurrence of soil slips. Slips on the San Dimas Experimental Forest were measured on slopes ranging from 31 to 48 degrees.

Channel Processes

Stream channels constituted a buffer in the routing of sediment from chaparral drainage basins. Virtually all dry-ravel deposits stop there (fig. 2). They serve as magazines of sediment which insure that most high flows occurring will transport sediment from the drainage basin at near their capacity. A good proportion of the landslide deposits will also come to rest in the stream channel because much of the material they transport is not readily carried by the stream. Consequently, sediment tends to accumulate in the stream channel and is flushed out infrequently by high flows, often in the first

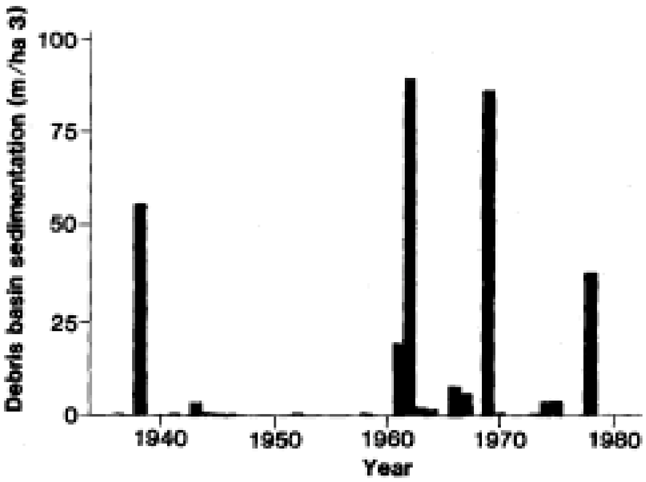

Figure 3.--Annual accumulate in Bell IV debris basin. (Hydrologic Year 1961 and 1962 record combined, sediment distributed between them based on records from nearby basins. Hydrologic Year 1978 is occular estimate, survey data not yet available.)

postfire years. Observed postfire erosion rates depend on the particular sequence of fire and winter rains. For example, in the Bell IV drainage basin on the San Dimas Experimental Forest, about 108 m^3/ha of sediment were discharged in the first 2 postfire years (fig. 3). The first year was very dry and the second had normal rainfall. In contrast, nearby Harrow Canyon--which burned in 1968--produced 438 m^3/ha of sediment as the result of a storm having a return period of about 35 years occurring the following winter. These interactions between fires and storms tend to cause erratic sediment delivery. Ninety-two percent of the sediment yielded by Bell IV during its 41-year record occurred in 5 years (fig. 3). The dependence on high flows for sediment transport makes fire and soil-water repellency important in chaparral drainage basins.

Sources of Sediment

Identifying the sources of sediment in the chaparral drainage basins is often difficult. During large storms, when most of the sediment is produced, events that take place late in the storm tend to obscure evidences of earlier erosion. The sources of sediment from Harrow Canyon durng the 1969 flood are an exception. As part of a study after the 1968 burn in Harrow Canyon and Englewild Canyon (Rice and Osborne 1970), I had extensively reconnoitered all of the canyons in the vicinity a few weeks after they had burned. Most of the channels were deeply filled with old alluvial and colluvial sediments. Channel-stabilizing check dams had been constructed on these deposits in some of the canyons. In Englewild Canyon, the pipeline of a private water development ran 600 m up one of the main forks lying on the bank of the creek. After the flood, practically all the channels were scoured to bedrock, the check dams had vanished, and remnants of the pipeline were found, in places, nearly 5 m above the new stream channel. Identifying sediment sources after the flood would have been difficult had it not been for the early reconnaissance and measurements of other erosional mechanisms (column 1, table 1).

Table 1--Sources of postfire sediment

Erosional processes	Harrow Canyon 1969 1/ Observed erosion	Harrow Canyon 1969 1/ Adjusted erosion	Estimated typical pattern
	Percent		
Wind	2/1	1	1
Dry ravel	3/1	20	40
Landslides	4/2	2	1
Surface erosion	3/22	27	18
Channel scour	5/74	50	40

1/Measurements and estimates cover the period from the fire (8/23/68) until the end of the rainy season (5/9/69).

2/Estimate .3 mm (based on deposits collected in Glendora).

3/Measured by 10 erosion plots (each .004 ha, Rice and Osborne 1970).

4/Mapped from a helicopter and converted to volume using equation in Rice et al. (1969).

5/Residual obtained by subtracting above estimates from the 438 m^3/ha measured in debris basin.

The Harrow Canyon measurements, however, probably underestimated dry ravel because most of it would have occurred before the installation of the plots. Surface erosion is also probably underestimated because of the length of the plots (14.4 m). Allowing for these assumed errors, half of the sediment produced in 1969 came from channel deposits (column 2, table 1). Prefire conditions in Harrow Canyon were unusual. Climatic and vegetative evidence indicated that the winters after the previous fire (more than 70 years earlier) were mild, permitting vegetation to become established on postfire alluvial and colluvial deposits. This vegetation was robust enough to stabilize the channel during the large floods of 1938 and 1943 when many southern-California channels were cleaned out. Apparently, Harrow Canyon channels were scoured in 1969 only because an exceptionally large flood occurred on a freshly burned drainage basin. More typically, erosion after a fire would come about 40 percent from the channel and an equal amount from dry ravel. (column 3, table 1).

The previous discussion related to immediate origin of sediment in postfire runoff, not the original source of the sediment. Data on the relative magnitude of various sources of erosion on hillslopes is virtually nonexistent. I believe that about 80 percent of the sediment leaving chaparral drainage basins is initially eroded by gravitational processes of dry ravel and landslides. Channel scour of bedrock (as contrasted to remobilization of deposits) is a minor source of new sediment.

THE STOCHASTIC PROPERTIES OF SEDIMENT TRANSPORT IN CHAPARRAL DRAINAGE BASINS

Fire Occurrence

Wind and humidity are importance determinants of fire occurrence. Humidity determines whether ignition takes place, and wind is the primary meteorological control of the rate of spread and ultimate size of the fire.

Topography plays a role in determining the ultimate consequences of a fire. Fires starting low on the slopes usually have a better chance of spreading and inflicting drainage basin damage than those starting on ridges.

Another determinant of effects of fire is the condition of the vegetation (Rothermal and Philpot 1973). The age of vegetation affects both the fuel loading and the proportion of the stand that is dead. Age also affects seasonal changes in green-fuel moisture. These factors, in turn, interact with wind velocities to change the rate of spread. As the result of the interaction of these functions in a manner that is partially random, partially deterministic, a source of ignition may result in nothing--or in a conflagration. The chance of a conflagration increases markedly about 20 years after a fire because of accumulation of enough fuel to carry fire readily (Rothermal and Philpot 1973).

The Impact of Fire

What a fire does to the soil and vegetation depends both on the characteristics of the fire and the conditions of the vegetation and soil. Impact on soil centers mainly on whether or not a water-repellent layer is created. The degree of water repellency is determined by the temperature and duration of the fire and by the texture and water content of the surface soil (DeBano et al. 1970). A coarse-textured soil with a low moisture content which is subject to a hot (700^{o}C) surface temperature for a relativey short period (10 to 15 minutes) is most likely to develop severe water repellency. The effect of a fire on vegetation depends on its age and vigor (older or weaker plants are less able to regenerate after fire). Less seed survives fires in older stands which tend to burn hotter than younger stands. Plant vigor depends both on the general health and the physiologial stress to which the plant is subject before the fire. Because of opposing seasonal trends of burning condition and plant vigor, the likelihood of a fire is positively correlated with the likelihood of damaging the chaparral and creating soil-water repellency.

The responses of several front-country drainage basins to the storms of 1969 indicate the magnitude of the effects of fire. Average peak discharge from 11 burned drainage basins was seven times greater than the average peak discharge from four drainage basins which had not burned for 9 years or more. Sediment yield from five unburned drainage basins increased by a factor of 14 and for two burned drainage basins by a factor of 120.

Storms

A storm, whatever its intensity, interacts with drainage basin vulnerability. Vulnerability of a drainage basin to excessive erosion and sedimentation is determined by its soil-water status, density of its vegetation and litter, the degree of soil-water repellancy, and recent storm history. The same storm can have quite a different effect on different drainage basins. For example, during the 1969 storm, a drainage basin that had not burned for 50 years produced landslide erosion at a rate of 16 m^3/ha. A similar drainage basin burned the previous summer produced 10 m^3(ha, and one burned 9 years before produced 298 m^3/ha. In the first drainage basin, good infiltration, and perhaps some decadence in the vegetation, may have led to reduced slope strength. The root system of the former vegetation in the freshly burned drainage basin had not decayed significantly, and the water-repellent layer created by the fire minimized percolation of water to potential failure surfaces. Most of the slides were associated with stream channels and probably triggered by undercutting. Although storm variability might account for the differences in landsliding in these two drainage basins, it is unlikely to be the explanation for the high erosion in the 9-year-old drainage basin. More likely, enough time had elapsed since its fire that infiltration had been restored sufficiently to allow saturation above potential failure surfaces. The regrowing vegetation, however, was not large enough for its root system to restore slope strength. It also could not transpire at a rate that depleted soil water to the same extent as mature chaparral.

Hyperscedasticity

I would like to propose the term "hyperscedasticity" to describe the sedimentation regime of chaparral drainage basins. It is a regime in which a sensitive terrane reacts to highly variable disturbances producing erratic outputs of sediment. The climate is highly variable, with extremes of rainfall and drought. Many slopes are steep and composed of deeply weathered parent material. Consequently, they are very sensitive to disturbances. Fire is a largely random component playing a prominent role in the environment. So prominent, in fact, that definition of the hydrologic and sedimentologic processes of chaparral drainage basins hinges on an understanding of the role of fire. In addition to the major random components, many minor ones are related to fire behavior, fire effects, vegetative recovery, seismic activity, and channel stability. The sediment regime is further complicated by the existence of thresholds in many important processes, most notably fire and mass wasting. The conditional and independent probabilities associated with these processes and their linkages have resulted in a sediment regime dominated by a few very large events, many insignificant ones, and low predictability.

MODELING, SEDIMENT BUDGETS, AND SEDIMENT ROUTING

Process Models

Process models, to even a greater extent than statistical models, are creatures of the computer age. As computers became larger and more economical to use, approximating erosional processes in the memory of a machine became possible. A three-dimensional array could describe the physiography of the drainage basin to whatever detail was deemed necessary. Based on physical laws or empiric data, rules could be incorporated governing how water or sediment moved from node to node within the array. Such models have proved useful, especially in well-behaved cases. They have the intuitive appeal of being similar in form to the prototype system.

Just how strong is the similarity between actual conditions and process modeling of erosion and sedimentation? From a practical point of view, processes must be approximated by lumping various components in time, space, and function. After these comparisons are made, the model is then usually "tuned" until it will reproduce a set of empiric data. Such a procedure invalidates the claim of generality. Proponents argue that process models are extrapolatable to different areas because they are based on physical relationships, and physics does not change with time and distance. This claim of robustness has been compromised by the approximations and by incorporating calibration procedures into process-model building.

The calibration of process models carries another risk. Because their data requirements are exacting, the available suitable data sets tend to be small. When a small sample is drawn from a time series that produces significant effects only infrequently, the sample is likely not to include such an event. This attribute of the calibration of process models tends to cause underestimation of the variance of the dependent variable, which is particularly undesirable because accurate reproduction of large events is critical to model utility. If, on the other hand, the sample happens to include a large event, the large variance computed may be misinterpreted as "typical."

Empiric Models

Multiple regression is the principal empiric model used. Certainly, it has the longest history as a predictive tool in hydrology and sedimentation. This discussion will, in the main, be relevant to other statistical procedures as well. When using such models, the hydrologist breathes a prayer: "Dear Lord, let the world be linear and Gaussian." He desires linearity so that the structural form of the analysis is correct and normality so that he can estimate the precision of coefficients. The prayer is rarely answered. Nonetheless, empiricists are forced to jam the world into the regression straightjacket and hope that--even if their prayer is not answered--the central-limit theorem will come to their rescue. To make that rescue more likely, they are tempted to include more and more observations of poorer and poorer quality in their analyses so that n may more closely approach infinity. Most modern computer utilities offer programs that assist the analyst in selecting an optimum set of independent variables. But, no resort to "heroic statistics ... offers a real substitute for solid data" (Philip 1975).

Assuming that the previously mentioned problems have been more or less satisfactorily resolved, the empiricist still has only what could be charitably termed a pseudophysical model. His partial-regression coefficients express the relation between each independent and the dependent variable. The "independent" variables, however, are rarely independent. Some are correlated (perhaps an artifact of the data base), and others have functional relationships (such as soil with slope, aspect, and elevation). This means that the regression coefficients are only hinting at a functional relationship. To their credit, regression analyses facilitate the consideration of a much larger set of casual variables than would be practical for most process models. They also may have a slight advantage over process models in that if extreme events are included in the data set, the least-squares analysis will tend to cause them to dominate the form of the resulting regression equation. They share the same sampling problems that cause process models to be unlikely to include important events, however.

Monte Carlo Models

Models based on Monte Carlo simulation may incorporate desirable features of both process models and empiric models. Similar to process models, a Monte Carlo model would form a chain of conditions or processes that feed one another. The chain would begin with meteorological inputs and terminate with the delivery of sediment. Unlike in a process model, the nodes in the model would not have a spatial relation to one another and would not form a grid in two or three dimensions. Rather, the nodes would define a series of relations linking inputs to the output of sediment. Both the mean and variance of a function would be defined at most nodes. In this fashion, both the estimate of the presumed relation and the uncertainty associated with that estimate enter into the simulation. Although conceiving these nodes as bivariate relations is easiest, no inherent reason prevents nodes representing multivariate relations.

Each time the flow of the program reaches one of the nodes, it branches to a subroutine that generates random numbers. The number so acquired is then applied to the probability distribution of that function to determine the value of the function to be used in that simulation. The uncertainty related to various functional relationships is thus retained explicitly in a model, which is otherwise deterministic. The model could be cycled many times in the analysis of any particular set of circumstances so as to yield a spectrum of possible outputs. The analyst would have an estimate both of the expected response to a particular situation and of the probability of very beneficial or very disastrous consequences. Management decisions might hinge more on the extreme outcomes than upon the expected outcomes.

A much-simplified case will be used to give a little further appreciation for the functioning of a Monte Carlo model. It treats mass wasting as a function of storm size and fire history. Sedimentation is handled by a delivery ratio, and none of the interactions among sediment processes is considered. The greatest simplification, however, is in treating the process as an annual series rather than considering within-year temporal variation in many of the functions.

In the example, the objective is to estimate mean long-term production of sediment from mass movements. A further assumption is that the functions shown in figure 4 have a sound basis in theory and also in empiric data. The first step in the simulation is to estimate the size of the largest storm of the season by sampling from the probability distribution of maximum annual storm precipitation (fig. 4a). If the storm size obtained from the samping is less than some critical value (x), the remainder of the simulation is irrelevant and can be bypassed because the storm is so Fvall that the probability of landslides is essentially zero regardless of vegetative condition. In this case, the occurrence of the trial would be recorded and a new drawing made from the storm size distribution.

If the drawing from the storm size distribution results in the storm larger than the threshold size, the remainder of the simulation comes into play. The next random drawing is from the population distribution of possible ages of chaparral (fig. 4b). Vegetation age--more correctly, its size and vigor--largely determines drainage-basin response to the storm.

The age is related to resistance to landslides in figure 4c. Resistance is highest immediately after a fire because the root system is still intact and reduced infiltration is likely because of water repellency. Resistance declines in the next few years as infiltration is restored and root decay sets in. Then, after about 8 years, the slope becomes more resistant as roots develop on sprouting plants and new seedlings. Between 25 and 30 years, a slight decline takes place as the pioneer species such as *Ceanothus* are crowded out by more long-lived species. The decline soon levels out as the stand enters senescence, with a gradual turnover of plants as individuals die and are replaced. The curve in figure 4c is patterned after root biomass of redwood (*Sequoia sempervirens* (D. Don) Endl.) in northwestern California (Ziemer, R. R., 1700 Bayview Drive, Arcata, California, personal communication). It is also similar to curves developed for the uprooting resistance of trees in Japan (Kitamura and Namba 1966). I have assumed that the variance of this trend in landslide resistance would increase markedly after a fire and then decline. The basis of that assumption is that, in the early years, recovery would be dependent on postfire weather, the age of vegetation at the time of the previous burn, and the severity of the previous burn. As the stand gets older, it comes to express the ecological potential of the site, regardless of the point at which it began its recovery. Consequently, the variance in very old stands becomes rather small.

From the resistance obtained from the relationship of figure 4c, the expected volume of erosion from an average landslide-producing storm is computed using a function relating landslide volume to resistance (fig. 4d). This mean response is then increased or decreased according to storm size, using the relationships in figure 4e. In this case, the variance results from the fact that storms that are nominally identical, in terms of figure 4a, actually have different capacity to produce landslides because of the distribution of rainfall intensity within the storm. Between storm variability in erosion is assumed to decline for larger storms.

The last step in this model is to estimate sedimentation using a delivery ratio (fig. 4f). The mean response assumes debris resulting from the landslides during small storms will have low fluidity and, consequently, low delivery ratios. As the debris increases, the delivery ratio increases to a maximum and then declines as landslide debris becomes so prevalent that it greatly exceeds the ability of the stream to carry it from the drainage basin. The variance responds to those same factors. In small storms, the delivery ratio depends on the location of slides throughout the drainage basin and is, therefore, highly variable. As storm size increases, delivery to the stream increases and the variance declines. With large amounts of debris, the system becomes stream-power dependent and the variance is correspondingly reduced.

The model could be run for a specified number of cycles or halted when estimates of the mean and variance of sediment production had stabilized. In addition to generating information about the distribution of possible sediment outputs, a Monte Carlo model could yield data concerning the stochastic properties of the time series of sediment outputs. These possibilities make the application of Monte Carlo simulations to sediment outputs worthy of investigation. Bear in mind, however, that although sampling from probability distributions is frequent in the use of Monte Carlo models, the accuracy and precision of the estimates of sediment production are unknown. Even if all the variates used in their development were normally distributed, no general or exact way exists for computing the parameters of the output distribution based on the estimates of the various inputs. Usually a Monte Carlo model will rest on a more uncertain foundation. Some functions will be well defined by empiric data (figs. 4a, 4b), others will be built of sketchy information and extrapolation (fig. 4c), and still others will reflect only theory or hypothesis (figs. 4d, 4e, 4f). Therefore, in spite of the intuitive appeal of Monte Carlo models, their results have to be accepted on faith or calibrated with empiric data.

Some statistical problems are relevant to all types of models: process, empiric, or Monte Carlo. Paramount among them is the hyperscedastic

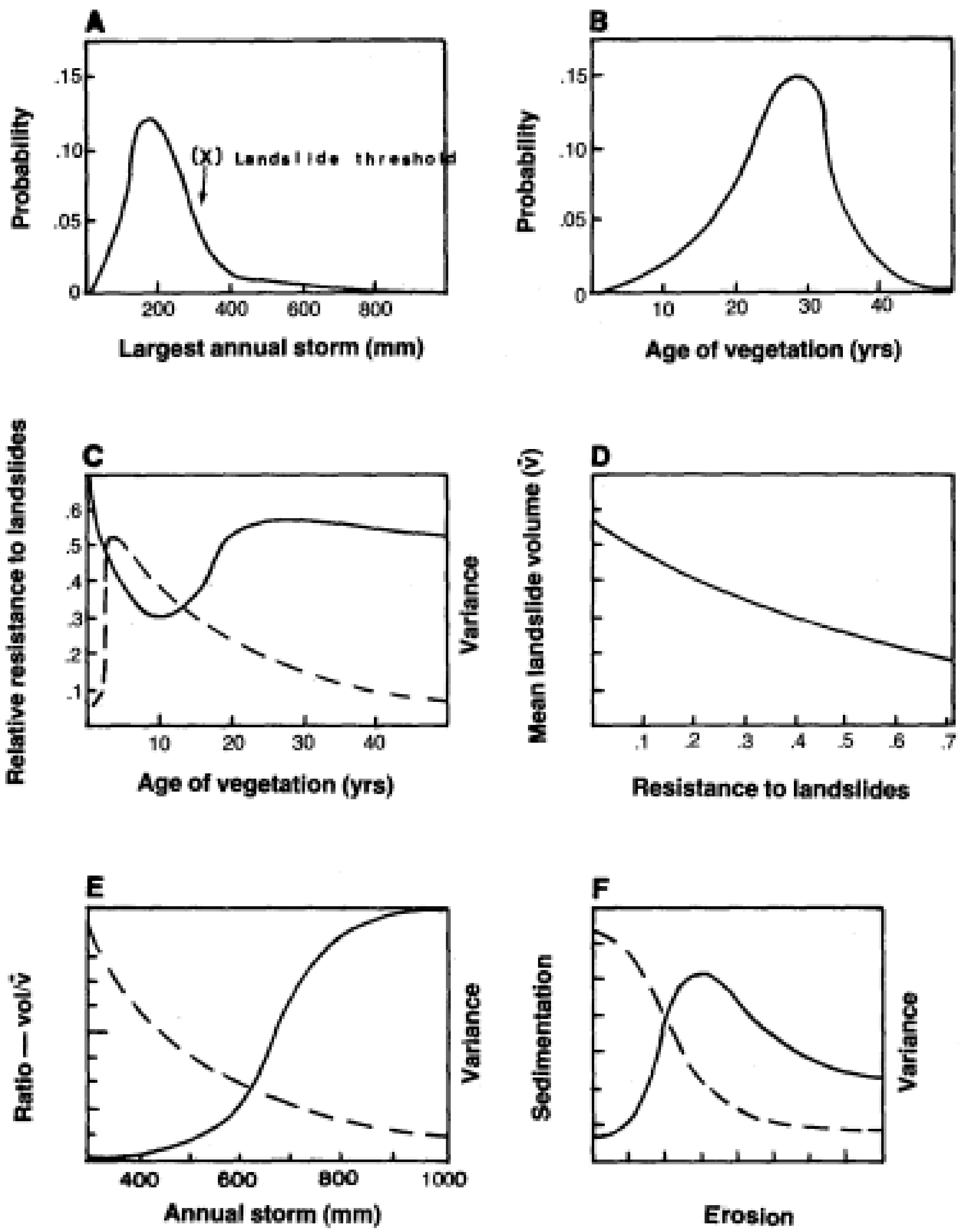

Figure 4.--Functions (solid lines) and their variances (broken lines) used to sketch the structure of a simulation of landslide erosion in Chamise chaparral.

nature of most of the phenomena, especially the outputs. This has the effect of making the relevant data base extremely small. The information from the Bell IV drainage basin probably represents something like 4.5 "years" of record for use in building a sedimentation model--even though it took 41 years to collect. This small, relevant data base places a heavy burden on modelers; they have been able to observe very few of the possible interactions of a complex process.

Because of the hyperscedasticity of the phenomena and the way data are collected, the robustness of the coefficients should be doubted: To what extent do they estimate their parametric values, and to what extent are they the result of spurious correlations in the developmental data? And what about the developmental data; are they from a stationary time series? Are current estimates of parameters (even if accurate) valid estimates of their future values? Models are often constructed because changes are planned for a drainage basin. Normally, we had no *a priori* way of knowing how well models will hold up under changed conditions. Are the processes defined in sufficient detail? These questions, too, will have to be resolved on faith. Each model builder must wield Occam's razor, attempting to include all the complexity necessary for accurate prediction, but nothing more.

The small, relevant data base for modeling hyperscedastic processes presents a paradox: Good models require a large amount of good data for their development, but the lack of a long and abundant data stream is just what makes necessary the development of models of erosion, sediment transport, and other hydrologic phenomena. Clearly we are in a "trans-scientific" environment. Weinburg (1972) has introduced this adjective "trans-scientific" to describe "questions which can be asked of science and yet cannot be answered by science." Although posing such questions as rigorously testable hypotheses is possible, conducting the research necessary to answer them is impractical (if not impossible). In response to this dilemma, "It remains our obligation to insure that our methods are as scientific and objective as possible. Let us at least work towards a situation where the trans-scientific judgements which practical hydrologists are forced to make are informed and sustained by a truly scientific hydrology: a skeptical science with a coherent intellectual content firmly based on real phenomena (Philip 1975)."

Process models, because of their data requirements, will ususally have applicability only to the management of drainage basins where high values are at stake--values which can justify the expenditure of the resources required for their use. In most circumstances, to quote from Philip (1975), "The task of performing an accurate detailed physical characterization and using this in a reliable predictive calculation is scientifically feasible; but would almost always demand for its proper performance, the expenditure of resources out of all proportion to the benefits." Empiric models are at the other extreme. Although requiring only a modest expenditure of resources, their rigid structure dictates that they lack a firm basis in real phenomena.

Monte Carlo models may offer a feasible solution to some trans-scientific hydrologic problems. Their resource requirements are intermediate between process models and empiric models. Like empiric models, they consider random variation explicitly. In common with processed models, they permit an amalgam of empiric information, theory, and (if necessary) conjecture. Hopefully, the result can satisfy Philip's (1975) desire for "a coherent intellectual content firmly based on real phenomenon."

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