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Geomorphic Analysis of Streamside Landslides in the Redwood Creek Basin, Northwestern California

By HARVEY M. KELSEY, MIKE COGHLAN, JOHN PITLICK, *and* DAVID BEST

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ABSTRACT

Debris slides and earthflows are the two main types of mass movement in the Redwood Creek basin. All the large, volumetrically significant landslides occur on steep slopes of the inner gorge adjacent to the main channel and major tributaries. We measured all landslide contributions for the period 1954 to 1980. Examination of aerial photographs showed that almost all these landslides occurred before 1966. The storm of December 1964 triggered the majority of the pre-1966 landslides. Along the 100-km length of the main channel, landslides are concentrated in two high-input reaches, one in the uppermost watershed from kilometers 0 to 29, and one in the uppermost lower watershed from kilometers 58 to 77. High-input reaches are also reaches of highest stream gradient and reaches where clastic sedimentary rocks (as opposed to schist) crop out in the channel. A cumulative volume-frequency analysis of all main-stem landslides shows that the smallest 50 percent of the landslides account for only 5 percent of the total volume and the largest 10 percent of the landslides account for 60 percent of the total volume. For tributaries, the volume-frequency relations are similar, although more of the landslides are smaller, and the few large landslides are volumetrically more significant. Both sets of landslide data are log-normally distributed, although constraints on geomorphic process cause a flattening at the extremes of the distribution curves. The most significant constraint is the upper limit to landslide size imposed by the slope length of the inner gorge, which limits landslide length.

Virtually all major landslides were triggered by storms. However, storms and logging together are the causes of widespread landslide activity. The degree to which logging increased slope failure is speculative because of a lack of data on physical slope conditions at failure and on the rainfall and runoff during large storms. On the basis of results of the investigation, we speculate on the long-term influence of landslide activity on the geomorphic evolution of the watershed.

[1] Department of Geology, Western Washington University, Bellingham, WA 98225.

[2] Stratigraphic Services Company, 1305 NE. 43 Street, Suite 406, Seattle, Wash.

[3] Department of Geography, University of Colorado, Boulder, CO 80309.

[4] Redwood National Park, Arcata, CA 95521.

INTRODUCTION

This paper presents results of a detailed investigation of streamside landslides in the 725-km^2 Redwood Creek basin (fig. 1). The investigation includes all major landslide activity during the period from 1954 to 1980. The major goals of the investigation are (1) to determine the volume of sediment produced by landslides, (2) to assess the temporal distribution of landslide contributions to the main channel of Redwood Creek relative to the occurrence of major storms, (3) to analyze the spatial distribution of landslide contributions along the 100-km length of the main channel of Redwood Creek, and (4) to evaluate the statistical distribution of landslide volumes along both the main stem and tributary channels of Redwood Creek. Landslide data presented in this paper include data for earthflows, which are discussed separately as appropriate.

ACKNOWLEDGMENTS

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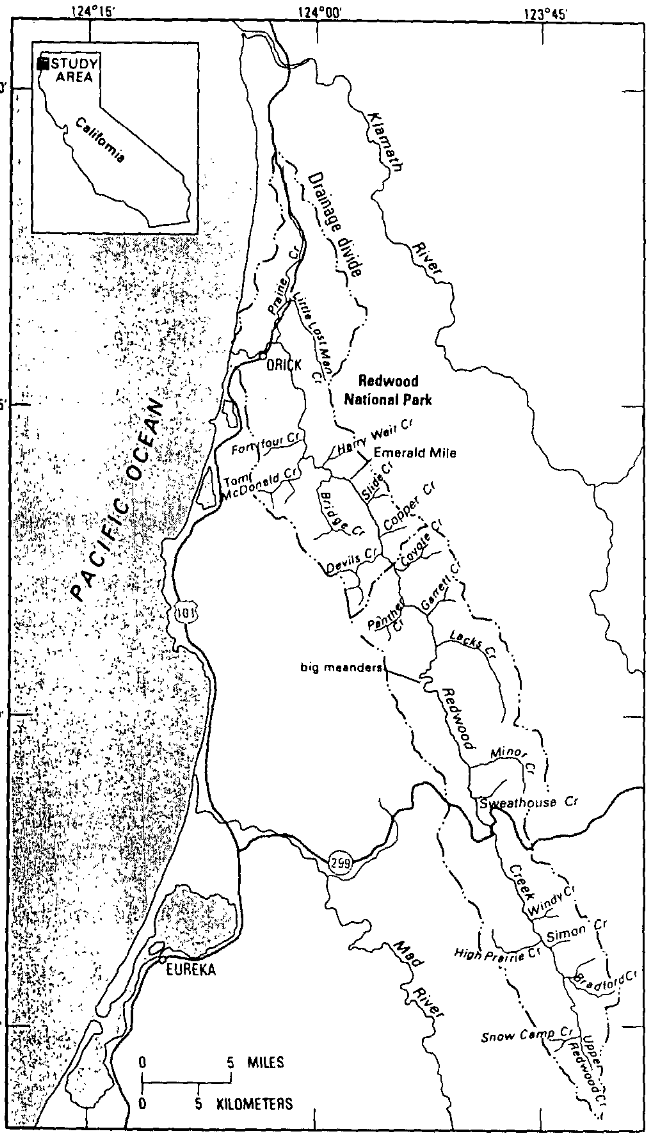

FIGURE 1.—Redwood Creek basin, showing major tributaries and reference locations.

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BACKGROUND

The Redwood Creek basin is underlain by the Franciscan assemblage, which is Late Jurassic to Cretaceous in age (Harden and others, 1982) and consists of mudstone, siltstone, schist, and scattered blocks of greenstone and chert. The basin is bisected by the Grogan fault. The main stem of Redwood Creek closely follows the trend of the fault zone for the upper 78 km of its 100-km length. Slopes west of the Grogan fault are underlain by schist, and slopes east of the fault are underlain by sandstone and mudstone (Harden and others, 1982). Both rock units are deformed by numerous fractures and shear zones, and the rock incompetence due to this deformation contributes to the high erodibility of the watershed.

The landscape of the Redwood Creek basin dramatically changed in the 28-year period between 1950 and 1978. An essentially unlogged watershed underwent extensive timber harvesting. Before 1950, only 8 percent of the coniferous forests in the basin had been logged, and by 1978, logging had eliminated 81 percent of these forests (chap. C, this volume). Two major storms occurred in northern California in 1955 and 1964, followed by later storms equally as intense in Redwood Creek, though not as regionally significant (Harden and others, 1978). The most obvious erosional change was the increase in incidences of streamside landsliding. Colman (1973) analyzed landslides in the Redwood Creek basin by individually documenting landslide history for 363 slides along the 100-km main channel. He showed that past mass-movement processes have sculpted many Redwood Creek hillslopes. He clearly documented an increase in mass-movement processes in the years between 1948 and 1973 and cited both timber harvesting and severe floods as causes of this increase. However, Colman stressed that the concentration of landslides adjacent to stream channels and the temporal distribution of landsliding suggest that storms had the most direct effect on the increased slide activity.

Prompted by the relation of recent storms to the streamside landslides in Redwood Creek, Harden and others (1978) investigated historic major storms in the Redwood region and concluded that the location and timing of streamside landslides are influenced both by logging history and by variations in the localized intensity of storms. They further noted that in the late 19th century a series of severe storms occurred in the Redwood Creek watershed that appear to have been as intense as those of the period from 1950 to 1975. These storms, well prior to any timber harvesting, did not initiate extensive streamside landsliding (Harden and others, 1978).

Furbish and Rice (1983) studied the incidence of debris slides in steeplands of northern California in terrain similar to that of Redwood Creek by using discriminant analysis to distinguish slide sites from stable slopes. Their results indicated that areas most prone to failure are immediately downslope from major breaks in slope, adjacent to actively eroding channels, and within topographic depressions. Furbish and Rice also found that 95 percent of the debris slides in his study area occurred on streamside hillslopes that were 30° or steeper, in a slope

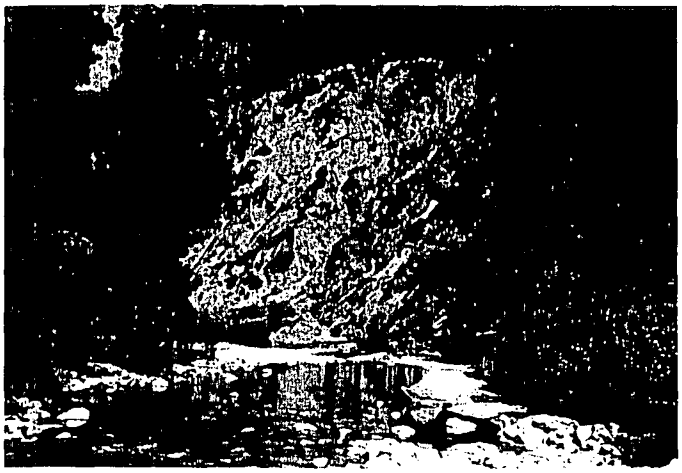

FIGURE 2.—Upstream view of a typical streamside debris slide along the main channel of Redwood Creek. This debris slide is at kilometer 16.9 on the main channel, 2.0 km downstream of Lake Prairie Creek, and is the 14th largest landslide of a total of 877.

zone known in northern California as the inner gorge. The inner gorge (Kelsey, 1988) is formed over time by coalescing debris slides that deliver sediment directly to the channel.

TYPES OF MASS MOVEMENT

Many types of mass movement occur on the steep slopes bordering the tributaries and the main stem of Redwood Creek. In this report, we treat three main categories of mass-movement features on the basis of morphology and process: debris slides, streambank failures, and earthflows. Debris slides, and the closely related debris avalanches, are almost exclusively confined to the steep slopes of the inner gorge. Streambank failures are not confined to the inner gorge but rather are distributed throughout the basin. Earthflows are located mainly in the midbasin area where incompetent rock units occur adjacent to Redwood Creek. Virtually all landslides in the Redwood Creek basin occur along streamsides and deliver sediment directly to perennial channels. Unlike other nearby watersheds where major debris avalanches occurred at headwaters between 1954 and 1980 (Buer and James, 1979; Kelsey, 1980), there was an insignificant amount of avalanching in the headwaters of Redwood Creek basin for the same period.

DEBRIS SLIDES AND STREAMBANK FAILURES

The most common streamside landslides in the Redwood Creek basin are debris slides (fig. 2). These slides are shallow (0.5–2.0 m) relative to their areal extent. Movement rates are rapid, and the slides expose a fresh sliding plane after failure. The long axis of the slide is most often perpendicular to slope contours. These slides generally occur in preexisting slope hollows that were probably sites of previous sliding.

Parent materials for debris slides are mainly fractured sandstones and metasandstones. The slide material consists of fractured rock with a thin veneer of poorly developed soil. The failure plane most often occurs within the fractured rock zone below the depth of tree root penetration; this location suggests that the effective shear strength provided by roots is mainly a tensile strength that prevents rupture at the surface.

Streambank failures, in contrast to the larger debris slides, seldom extend more than 50 m upslope from the channel edge. Streambank failures contribute sediment along the entire main stem of Redwood Creek, but they are most numerous in the lower part of the basin. Unlike other landslides, streambank failures tend to coalesce into a linear, basal-slope zone of streambank instability rather than being manifested as discrete landslides extending up the hillslope. They are more the product of streambank undercutting, whereas discrete landslides often result from saturation of a steep, inner-gorge slope by an intensive storm. Approximately 99 percent of the total volume of material eroded by mass-movement processes comes from debris slides and streambank failures. The transition from debris slides to streambank erosion is gradual, and because of the small volumes involved in streambank erosion, its sediment contribution is relatively minor.

EARTHFLOW LANDSLIDES

Earthflows are slowly moving landslides that move seasonally each winter after being thoroughly wetted by rainstorms. Seasonal movement ranges from a few centimeters to a few meters, and the raw, unvegetated toe slope is annually eroded by Redwood Creek as the earthflow moves toward the channel (fig. 3). These landslides have been described by Kelsey (1978), and both Harden and others (1978) and Nolan and Janda (chap. F, this volume) discuss rates of earthflow movement in the Redwood Creek basin.

Figure 4 shows the locations of earthflow activity in the Redwood Creek basin during the 1955 to 1980 study. Of the 16 active earthflows, all except 1 occur along the right bank of Redwood Creek along two distinct reaches of the creek. All earthflows except two occur on a west-facing slope exposure, and their distribution is strongly controlled by the geology. In both reaches, the Grogan fault zone coincides with the steep basal hillslopes next to the main channel, and the west-southwest slope exposures along the channel are underlain by sandstone of the Incoherent unit of Coyote Creek.

FIGURE 3.—The raw, unvegetated toe of the Sweathouse Creek earthflow, which is annually eroded by Redwood Creek as the earthflow toe moves in to the channel. Height of toe is approximately 20 m.

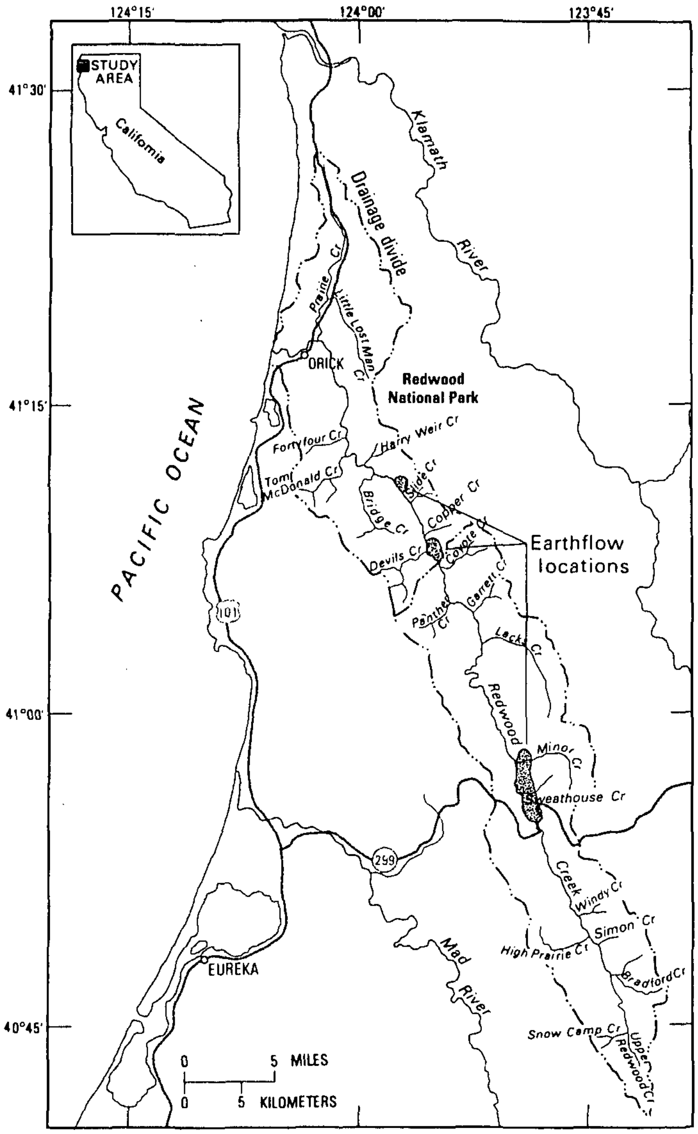

FIGURE 4.—Reaches where earthflows are abundant on the right bank of Redwood Creek (stippled areas). With one exception (the northernmost Counts Hill earthflow), the 16 earthflows occur along two distinct reaches of Redwood Creek.

Despite their high visibility and recognition as an erosion source, earthflows are not major contributors to sediment production compared to debris slides or streambank failures. Earthflows produced 1 percent of the total sediment contributed by streamside slope movements to the main channel during the study period.

VOLUMETRIC DATA

EXTENT OF COVERAGE

We measured all landslides and earthflows along the main channel of Redwood Creek. Those failures along the upper 34.4 km of the main channel were measured in the field, and the rest were measured from aerial photographs. Landslides and earthflows into major Redwood Creek tributaries were also investigated (chap. K, this volume), and the data for the tributaries were used in determining the total debris contribution to the main channel of Redwood Creek. On the main stem, we measured the volumes of 877 failures, 580 by field measurement and the remainder by measurement on photographs; on the tributaries we measured 975 failures, all except 7 by field measurement.

TECHNIQUES FOR MEASUREMENT OF DEBRIS SLIDES AND STREAMBANK FAILURES

In the field, we determined the volume of landslide-derived erosion by measuring the depressions left on the hillslopes after failure. Latest movement on most of the landslides postdates the early 1960's, and landslide scars measured during the 1980 field season were still recognizable both in the field and on 1978 aerial photographs. Extensive revegetation, however, made field measurement difficult in many instances. Both 1966 and 1978 photographs were used during fieldwork to ensure that revegetation did not obscure the full extent of the landslides. Depth of the landslide areas was measured with a tape and a rangefinder. Landslide depth was estimated by visually reconstructing the original hillslope shape prior to failure and estimating the average thickness of material lost. This procedure was usually straightforward. Only that material determined to have actually been delivered to the channel was counted, as there were numerous landslide sites where colluvial debris was still perched on the hillslope.

Estimating depth was the greatest potential source of error in field measurement. Individual slide volumes could be in error by as much as 100 percent on those hillslopes where outlines of the original topography were no longer apparent. Ambiguities of this sort were the exception rather than the rule, however, because head and sidewall scarps were clearly visible in most instances. In addition, we believe that, because of our tendency to be conservative when making depth estimates, our measurements may tend to underestimate rather than overestimate the actual slide volumes.

Landslide volumes along the lower two-thirds of the main channel were measured from aerial photographs having a scale of 1:6,000. Scales for the photographs were determined from measured ground distances transferred to each photograph. We used time-sequential aerial photographs taken in 1954, 1958, 1966, 1974, and 1978 to measure landslide volume and to separate landslide contribution by time interval. A series of 1948 aerial photographs that cover the entire length of Redwood Creek documents physical conditions there before major storms and the start of logging.

For analysis of the timing of sediment contribution by landslides, the two most important indicators were the landslides visible on the 1966 photographs, taken 18 months after the December 1964 storm, and the new or expanded landslides first visible on the 1974 and 1978 photographs. Pre-1966 landslides refer to all landslides that presumably occurred before, during, or shortly after the 1964 storm.

MEASUREMENT TECHNIQUE FOR EARTHFLOWS

The volume of material contributed by earthflows was computed by measuring the toe area of the earthflow along the streambank and the total movement of the toe into the channel during the study period. Total movement was either measured from aerial photographs or estimated from measurements of annual movement rates for selected earthflows in the Redwood Creek basin (Harden and others, 1978).

VOLUMES OF ERODED MATERIAL

Table 1 shows volumes of material eroded by landslides and earthflows for 1954 through 1980. The data show that, along the main stem, 84 percent of the total volume of material eroded landslides occurred in the period from 1954 to 1966. For both main-stem and tributary landslides, 82 percent of total volume of eroded material occurred in the period from 1954 to 1966.

TABLE 1.—*Volume of material eroded by landslides and earthflows, Redwood Creek basin*

Period of measurement	Main stem only[1] (m^3)	Main stem and tributaries[2] (m^3)
1954–66	3,343,700	5,246,700
1966–80	656,400	1,168,931
1954–80	4,000,100	6,415,600

[1] 877 sites.
[2] 1,952 sites.

PRE-1950 LANDSLIDES

In 1948, the timberlands within the Redwood Creek watershed were largely untouched, and the slopes adjacent to Redwood Creek were totally unlogged. The only road across the watershed was State Route 299, which split the upper one-third of the basin from the lower two-thirds (fig. 1). As shown on 1:12,000-scale aerial photographs taken in 1948, the slopes adjacent to the main channel above State Route 299 were completely unlogged, and the only watershed development consisted of two powerlines crossing from east to west and a few small roads. We surveyed the uppermost 17 km along the main stem of Redwood Creek by using the 1948 aerial photographs to determine the condition of hillslopes that would later be subject to major streamside landslides. Along this 17-km main-stem channel reach, 83 percent of the slopes that became landslides by 1966 were densely forested in 1948, while 6 percent showed evidence of a small landslide scar or a bare area at the toe of a slope, and 11 percent were already landslides of significant size. Several small landslide scars were contained within older, much larger revegetated scars. The survey of 1948 aerial photographs showed no scars from major landslide activity in the mid-19th century, despite well-documented evidence that major storms occurred in the latter part of the 19th century, especially in 1861 (Harden and others, 1978; Coghlan, 1984).

DISTRIBUTION OF LANDSLIDES

Analysis of the geographic distribution of slope failures along Redwood Creek shows two channel reaches of high landslide-derived input from kilometers 0 to 29 and from kilometers 58 to 77 (fig. 5*A*). Data for landslide-derived inputs include the inputs for earthflows, which contributed 1 percent of the total sediment volume contributed by streamside slope movements to the main channel during the study period. Reaches of low input extend from kilometers 29 to 58 (State Route 299 bridge to downstream end of big meanders; fig. 1) and from kilometers 77 to the mouth (from the Emerald Mile downstream to the mouth) (fig. 1). The amount of landslide input in the two high-volume reaches, 62,000

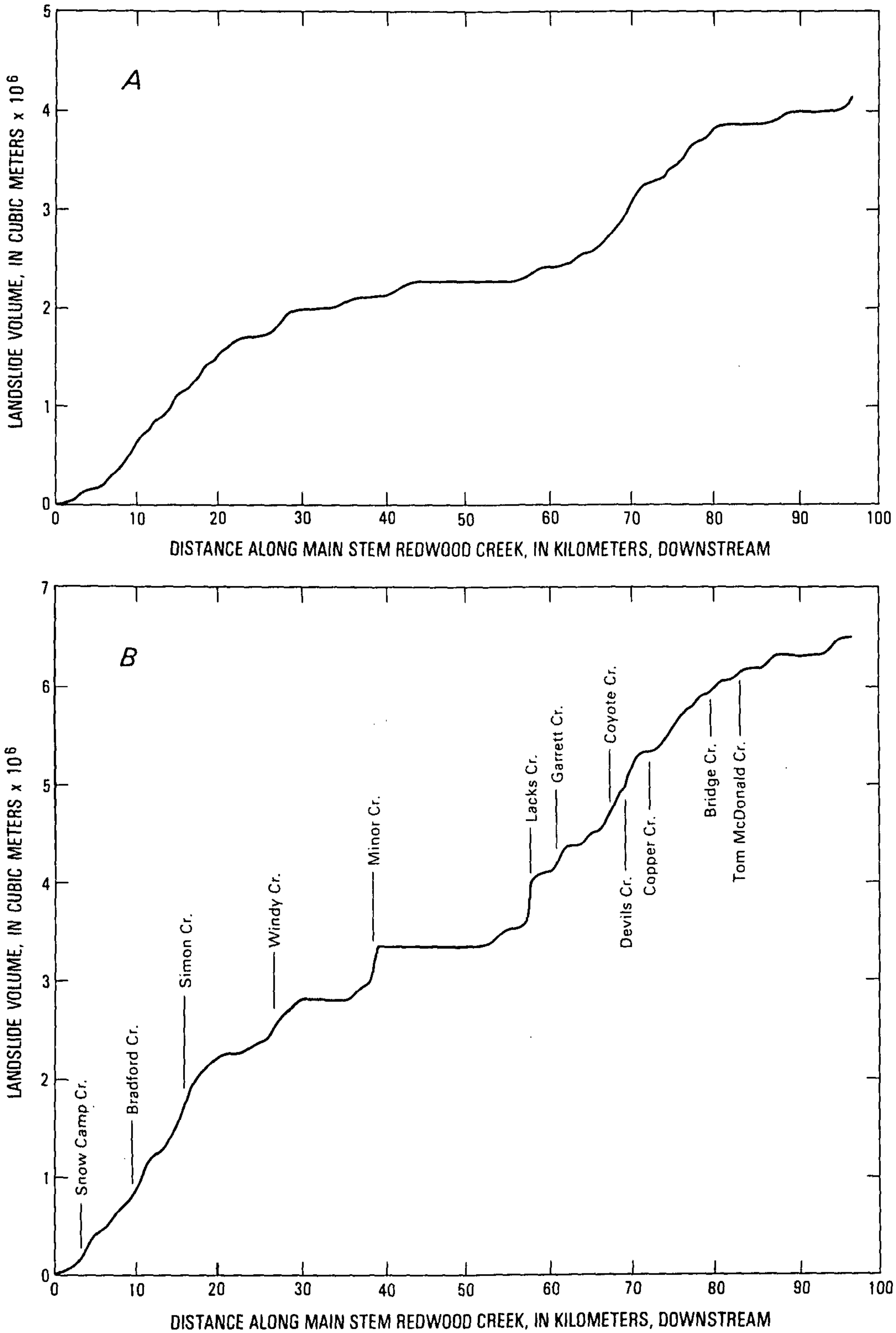

FIGURE 5.—Volume of sediment, cumulative through distance downstream along main-stem Redwood Creek, contributed by landslides for the period 1954–80. *A*, Volume contributed only by landslides along main stem, and *B*, Volume contributed by landslides along main stem and tributaries; location of tributary mouths is shown on graph. Note the two reaches of high input, kilometers 0 to 29 and kilometers 58 to 77.

m^3/km, is identical. Landslide input distribution is different when data from tributaries are included (fig. 5*B*). Tributaries rapidly transport approximately 80 percent of all landslide-derived material to the main stem (chap. K, this volume). Because little landslide debris is stored in tributary channels, tributary landslides are indicated as a single point-source contribution to the main stem at the tributary mouth (fig. 5*B*). Twenty-two tributaries are included in the cumulative volume totals, and these tributaries increased the landslide-derived sediment contribution to the main stem by 60 percent. Landslides along 12 of the tributaries (fig. 5*B*) contributed enough debris to noticeably influence the slope of the cumulative curve. Snow Camp Creek, Bradford Creek, Simon Creek, Windy Creek, Minor Creek, and especially Lacks Creek substantially increased the cumulative total of landslide-derived detritus delivered to the main stem.

Landslide distribution varies systematically with the topography and geology of the Redwood Creek basin. The high-input reach from kilometers 0 to 29 parallels the Grogan fault, and the stream course is cut in sandstone just east of the fault. The valley is narrow and has a well-defined inner gorge. The reach of low input, from kilometers 29 to 58 begins where the Grogan fault trace obliquely crosses the creek and the stream channel is cut in schist (Harden and others, 1982). In this low-impact reach, valley width increases and an inner gorge is absent or poorly developed. In the lower basin, along the high-input reach (kilometers 58–77), the inner gorge becomes more obvious again and valley width narrows. Farther downstream, in the low-input reach from kilometer 77 to the mouth, the stream course diverges west, away from the Grogan fault trace and into the schist. In this lower reach, the valley continually widens, and an inner gorge is absent or poorly developed.

According to this distribution, high-input reaches are generally in the steeper, inner gorge reaches composed of sandstone, and low-input reaches are generally in schist. Though schist bounds the main stem of Redwood Creek for 63 percent of its length above Orick, only 41 percent of the volume of landslide-derived contributions to the main stem comes from schist slopes. For tributaries, only 23 percent of the landslide-derived contributions originate in schist basins.

Landslide distribution has a systematic relationship to the distribution of channel-stored sediment. Landslides are one of the significant sources of the coarse sediment stored in the channel. Figure 6 shows the spatial relation between reaches of high landslide-derived sediment input and reaches of marked net increase in channel sediment storage. Channel storage data are from Madej (chap. O, this volume). Figure 6 shows that the boundaries of segments A through D separate reaches of high and low input of landslide-derived material. Reaches of high input are those where storage is relatively low, and reaches of low input are those where sediment storage increases most rapidly. Madej (chap. O, this volume) shows that channel storage is best correlated with valley width and stream gradient, the wider, lower gradient reaches being the areas of maximum increases in storage. Therefore, low-input reaches are generally the wide, low-gradient reaches, and the high-input reaches are the narrow, higher gradient reaches having less tendency to store sediment.

CUMULATIVE VOLUME-PERCENT RELATIONS FOR LANDSLIDES

How large must an individual landslide be to contribute significantly to the total volume of landslide-erosed material? Cumulative volume-frequency analyses for 877 landslides along the main stem of Redwood Creek (fig. 7*A*) and for 975 tributary landslides (fig. 7*B*) indicate the relative importance of the smallest and the largest landslides. Along the main stem, landslides having volumes of less than 1,280 m^3 accounted for 53 percent of the landslides measured but for only 5 percent of the total measured volume. The main stem frequency curve (fig. 7*A*) also indicates that the largest 10 percent of the landslides measured account for 60 percent of total landslide volume (4×10^6 m^3, see table 1).

For tributaries, the volume frequency relations are similar to those for the main stem, though there are more small landslides, and the few large landslides are volumetrically more significant. Landslides of less than 708 m^3 account for 61 percent of total volume (fig. 7*B*).

In the main stem and the tributaries, 95 percent of the volume of landslide-derived material is contributed by well less than half the total number of landslides. Therefore, all erosionally significant landslides are large enough to be visible on 1:6,000- and 1:12,000-scale aerial photographs, and landslides hidden by tree cover are volumetrically insignificant.

TEST FOR LOG-NORMAL DISTRIBUTION OF MAIN-STEM LANDSLIDES

Normal probability plots of the logarithm of volumes for 877 main-stem landslides (fig. 8*A*) and 975 tributary landslides (fig. 8*B*) show that in both cases the plotted points approximate a straight line, though the upper and lower ends of each curve are deflected to give a subtle S curve. Because the data plot in a straight trend, both sets of landslide volumes appear to be log-normally distributed. We performed both a chi square test and a Kolmogorov-Smirnov test on both data sets to test the

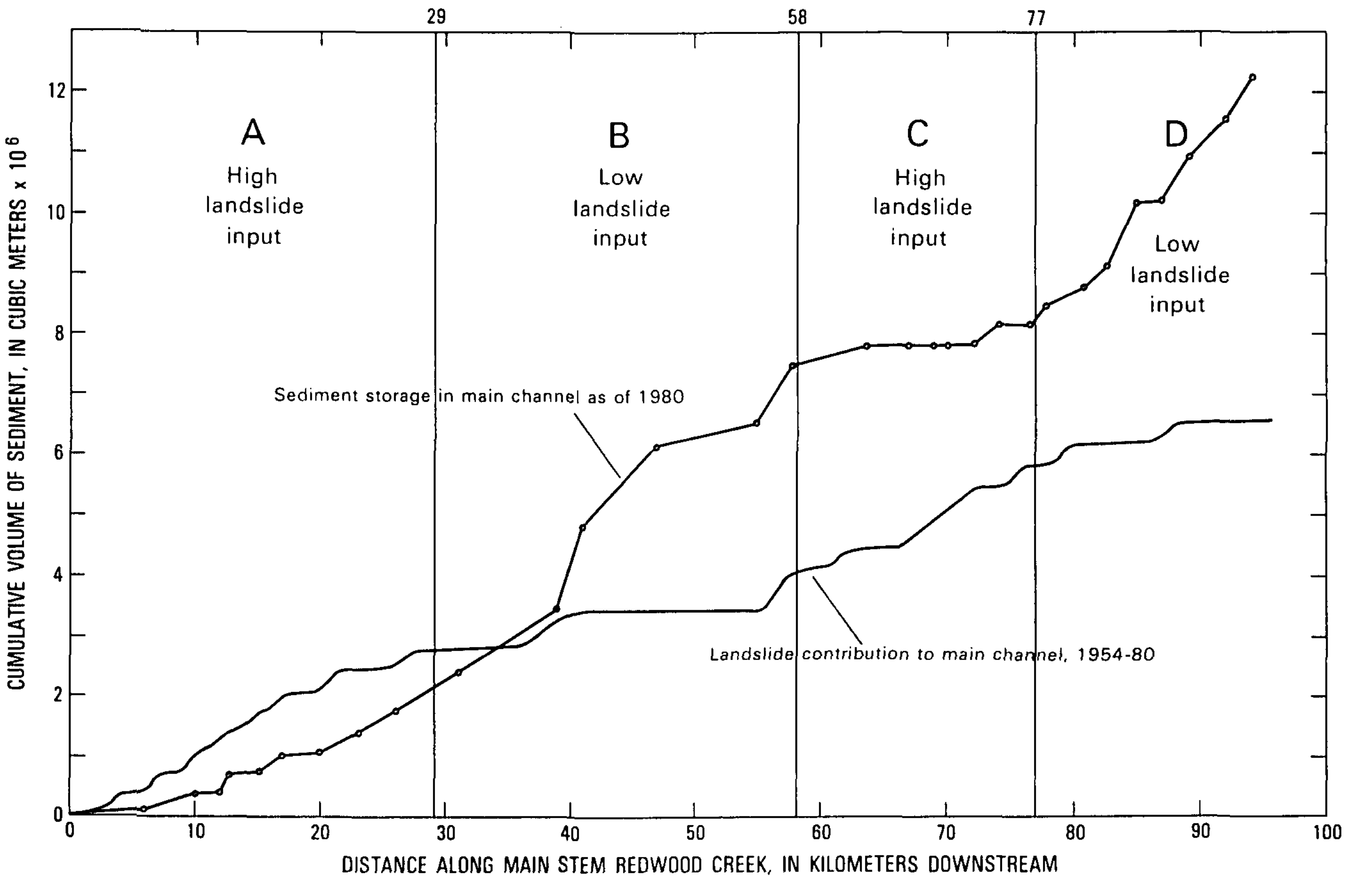

FIGURE 6.—Comparison of volume of sediment stored in main channel and volume of sediment contributed by landslides to main channel, both cumulative through distance downstream along the main channel of Redwood Creek. Reaches from kilometers 0 to 29 and 58 to 77 are high-input reaches but reaches of low sediment storage. Reaches from kilometers 20 to 58 and from kilometer 77 to the mouth are reaches of low input where sediment storage increases most rapidly.

null hypothesis that landslide volumes approximate a log-normal distribution. For both tests we could not reject the null hypothesis.

GEOMORPHIC IMPLICATIONS OF THE LOG-NORMAL DISTRIBUTION OF LANDSLIDE VOLUMES IN THE REDWOOD CREEK BASIN

The geomorphic significance of the apparent log-normal distribution of landslide volumes lies in the poor fit at the upper and lower ends of the distribution curve (fig. 8). These extremes probably represent constraints on landslide size due to geomorphic process. At the lower end, the volumes of streamside landslides do not reach zero, but rather there are many small landslide and bank erosion events. These small slope failures are more numerous than in a log-normal distribution. However, the very small failures are absent from the distribution curve because steep streambank slopes impose a lower limit of 10 m^3 on the size of most failures. However, all sizes of failures do occur, down to volumes less than 1 m^3 of bank erosion.

The flat upper ends of the curves in figure 8 indicate an upper limit to landslide size due to the constraint of inner-gorge slope length. Above the break in slope of the inner gorge, landslide scarps advance headward much more slowly, effectively imposing an upper limit on landslide size. The flat upper end of the log-normal distribution emphasizes the importance of the break in slope transition at the top of the inner gorge.

FACTORS INFLUENCING THE TIMING OF LANDSLIDES

Virtually all landslides occur during large storms. We measured the volume of landslides that occurred from 1954 to 1966 and the total landslide volume contributed to the main channel from 1954 to 1980 (fig. 9). Most of the pre-June 1966 landslide volume entered the channel during the 1964 storm. About half the 1964 landslides existed before December 1964, but they were greatly enlarged that December. Approximately 18 percent of

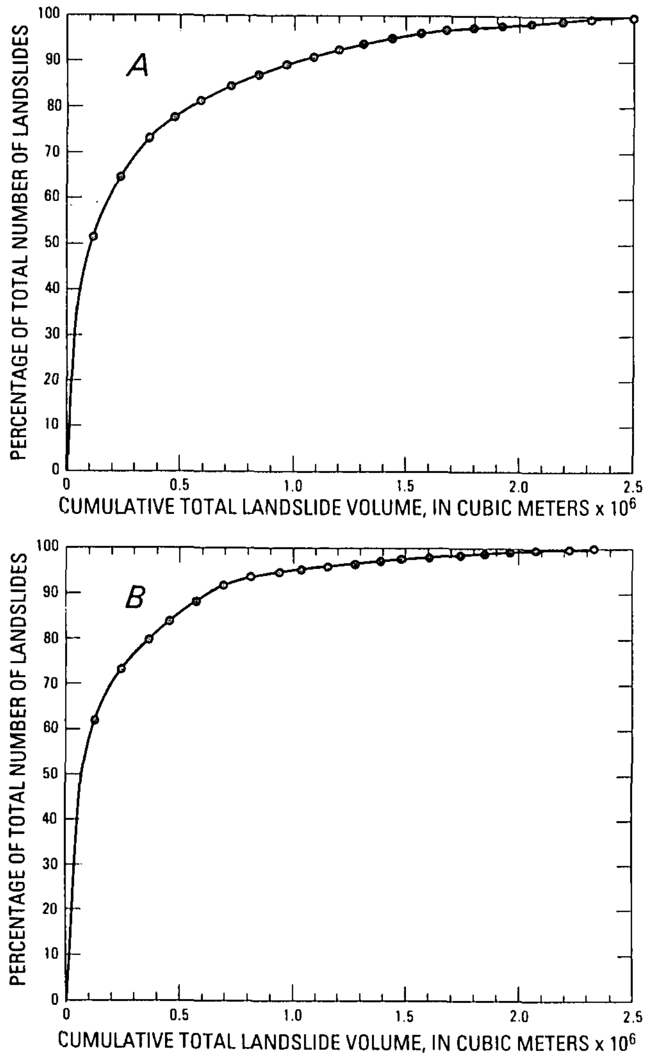

FIGURE 7.—Cumulative volume-frequency relations for streamside landslides. *A*, Landslides along the main stem of Redwood Creek, n=877. *B*, Landslides along tributary channels, n=975.

the total landslides occurred from 1966 to 1980 (fig. 9), and most all the 1966–80 slope failures occurred downstream from kilometer 12 and were concentrated in the 13-km reach starting just below Lacks Creek (km 58) and continuing to 3 km upstream of Bridge Creek (km 76) (fig. 1).

For the 1964 storm, it is not possible to analyze the relative importance of the storm and of land use because the exact physical factors causing the failures are not known. However, for landslides along the upper 35 km of the main stem where the 1964 landslide damage was especially severe, logging and (or) logging roads were present on a vast majority of the sites (table 2). Pitlick (chap. K, this volume) also shows that, for Redwood Creek tributaries, 80 percent of the total landslide volume came from slopes logged prior to failure.

TABLE 2.—*Logging and logging roads on landslide sites along the upper 35 km of main-stem Redwood Creek, 1954–66*

Reach (km downstream from headwaters)	No. of slides	Landslide volume (m^3)	No. of slides with no roads or logging	No. of slides with no roads	No. of slides with one or more roads
0–8.35	98	115,700	4	24	50
8.35–10.55	50	133,100	30	34	16
10.55–11.65	23	78,800	4	5	18
11.65–13.25	39	193,900	0	9	30
13.25–14.25	25	42,200	7	7	16
14.65–16.70	45	271,600	20	21	24
16.70–18.35	23	146,800	6	11	12
18.35–20.15	26	195,000	0	3	23
20.15–21.65	25	119,400	12	16	9
21.65–25.25	64	265,800	11	24	9
25.25–27.60	46	81,900	10	20	7
27.60–30.60	60	103,700	14	23	15
30.60–33.40	39	184,600	3	10	22
33.40–35.75	23	58,400	0	2	5

The 1972 and 1975 storms caused more hillslope erosion in the mid-to-lower basin than in the headwater reaches. The post-1966 landslides in the lower basin are most likely a combined result of these storms (Harden and others, 1978). By the late 1960's, most of the timber harvest activity was concentrated in the lower watershed (chap. C, this volume), and logging-related road construction near the main channel and tributary channels increased the incidence of landslides during the 1972 and 1975 storms.

LANDSLIDE CAUSES AND GEOMORPHIC THRESHOLDS

Recent research has suggested that geomorphic processes change due to the crossing of thresholds (Schumm, 1979). The threshold for landslides occurs when slope shear strength decreases to the magnitude of the downslope driving forces. The most important factors influencing slope shear strength are normal stress, angle of internal friction, soil cohesion, and the height of the water table (Carson, 1971). The height of the water table determines the pore water pressure, which acts in opposition to the normal stress. Cohesion is the soil strength that remains when the effective stress (normal stress minus pore water effects) is zero. In forested soils, cohesion is highly dependent on reinforcement by the root network (Burroughs and Thomas, 1977). The height of the water table is directly related to precipitation and storm size; it is the most transient of these factors and acts as a trigger in most north coast landslides. In addition, over longer periods of time, average soil shear strength gradually decreases due to weathering.

The number and spatial distribution of places where landslide threshold conditions occur determine the severity of landsliding. The 1964 storm in the upper watershed pushed physical conditions on many lower hillslopes past this threshold, causing extensive slope failures. In the

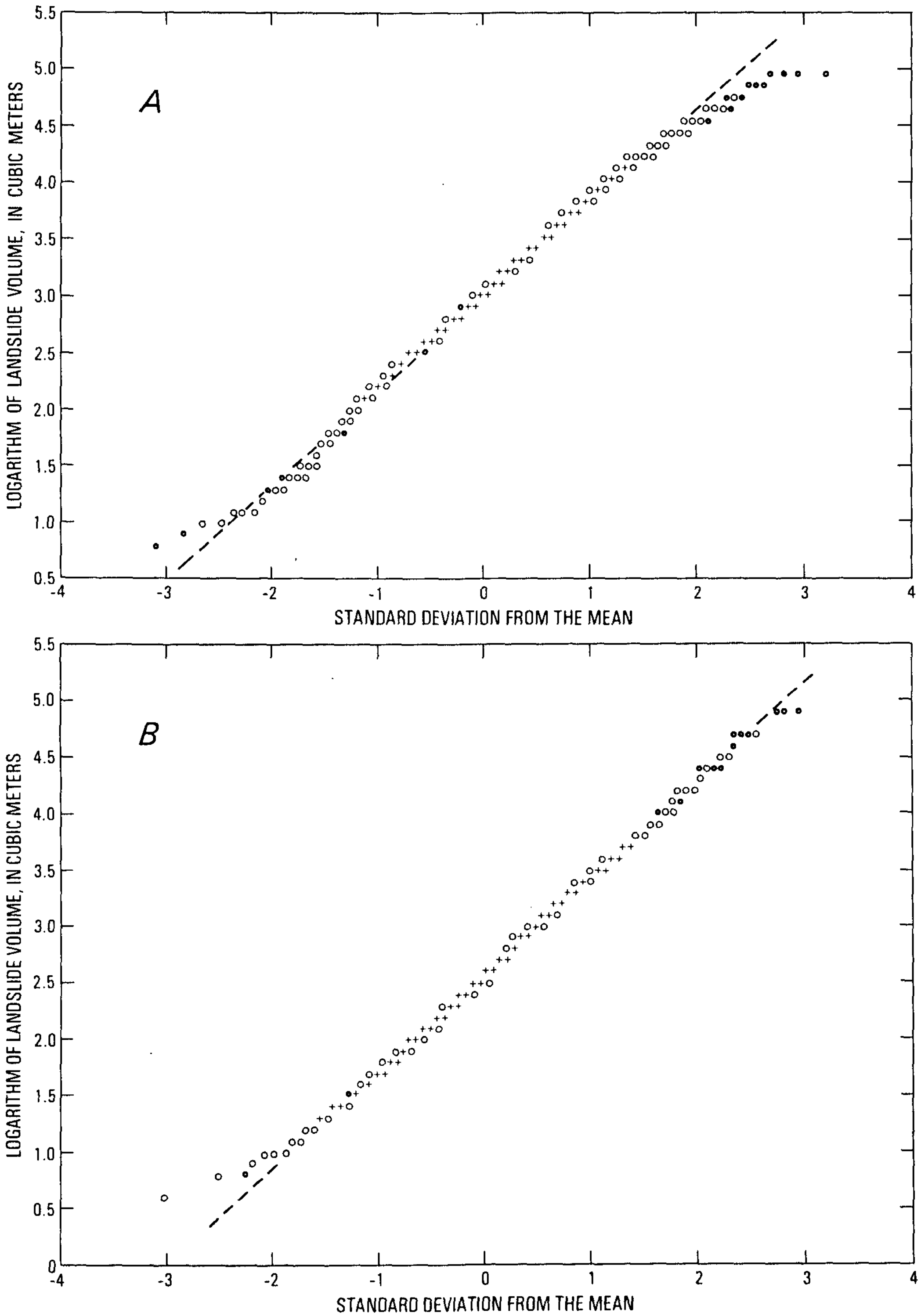

FIGURE 8.—Normal probability plot of the logarithm of landslide volume (m^3). *A*, Landslides along the main stem of Redwood Creek, n=877. *B*, Landslides along tributary channels, n=975. Solid dots=1 landslide; open dots=2–9 landslides; crosses=≥10 landslides.

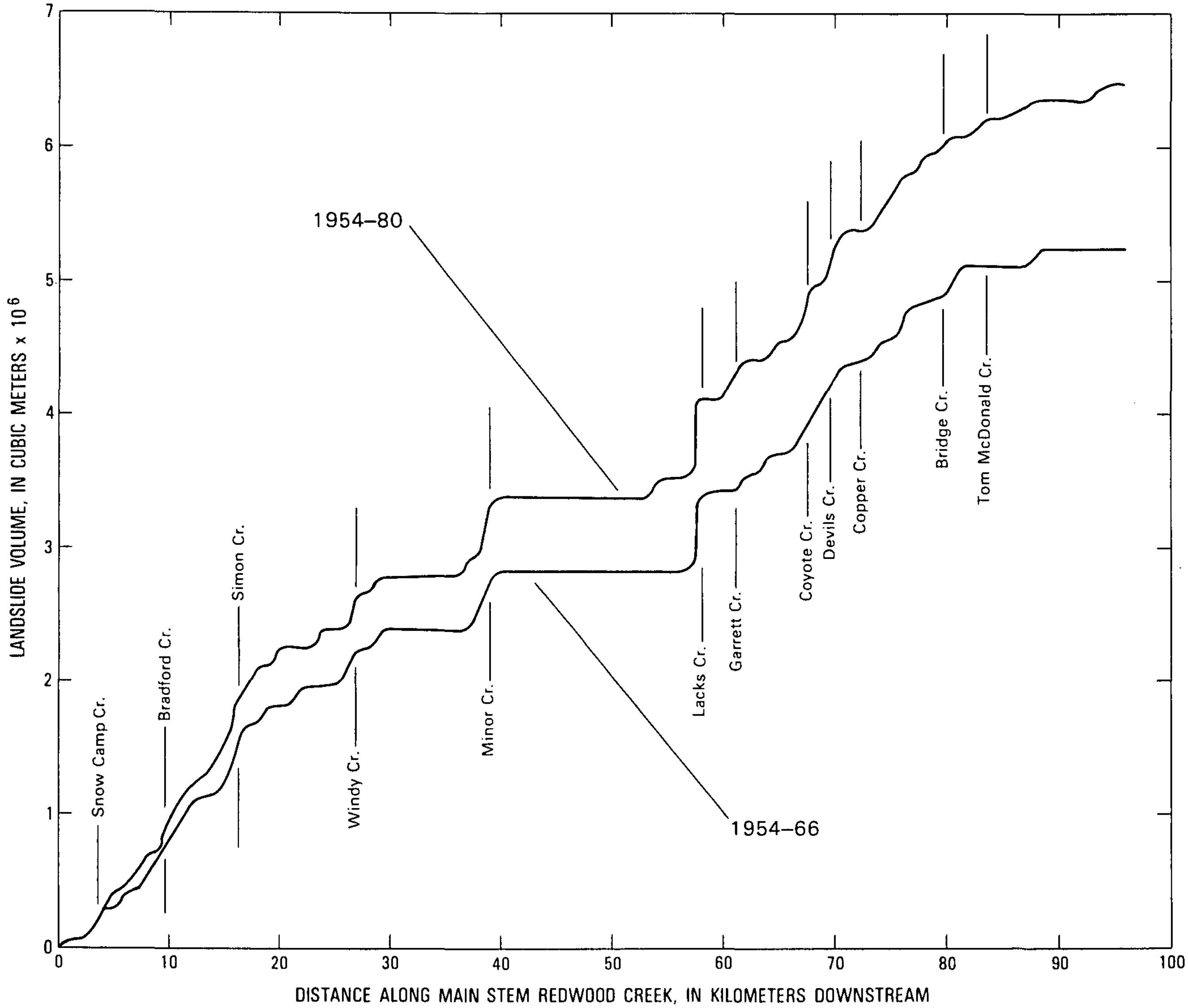

FIGURE 9.—Volume of landslide contributions for 1954–66 and for 1954–80 as accumulated in a downstream direction, including contributions from tributaries.

upper watershed, extensive logging during the 1950's had resulted in the loss of root-related cohesion on many hillslopes. Additionally, road construction both increased slope angles on road cuts and rerouted surface drainage. Shortly thereafter, the 1964 storm occurred and brought prolonged and, at times, high-intensity rainfall.

We speculate that it was the combination of individual, high-intensity storms and the widespread slope-weakening effects of logging that was responsible for the severe landslides of 1964. Precipitation totals in the upper watershed appear to have been very high during this storm (Harden and others, 1978). Though detailed storm data for December 1964 are not available, the internal structure of a large storm in mountainous mid-latitude areas is highly variable. These storms contain short-lived high intensity precipitation pulses that appear as rain bands or even more localized precipitation cells (Houze and others, 1976; Amorocho and Wu, 1977). During a large storm, the size of a single cell may determine the spatial limit of streamside slope failures. The concentration of debris slides along reaches of Redwood Creek suggests the existence of such cells during the 1965 storm.

In sum, road-building activities and logging both reduce slope shear strength. These activities alone are not sufficient to cause failure in most cases, but major storms are the events that push physical conditions past a stability threshold. It is likely that the level of that threshold is significantly lower on slopes that have roads or have been recently logged. Storms also may cause widespread failure in areas not subjected to human activity, but the intimate association of logging and landsliding suggests that, in Redwood Creek, timber harvest played a decided role in many failures.

LONG-TERM PERSPECTIVE: LANDSLIDE FREQUENCY CHANGES AND SOIL DENUDATION

The geomorphic significance of the 1954 to 1980 episode of landsliding on Redwood Creek can best be appreciated in a long-term perspective. Major floods occurred in approximately 1590 and 1750 on the East Fork of Willow Creek (Helley and LaMarche, 1973), which is 10 km east of the midpoint of the Redwood Creek drainage. Deposits in the East Fork suggest that flood peaks in both 1590 and 1735 were at least as high as those of 1964 in that drainage. Given the proximity of upper Redwood Creek, high storm intensities for the earlier dates must have occurred there too. However, evidence of large landslides in upper Redwood Creek appears to be at least 200–300 years old, and no major deposition related to the storm of 1861 is recorded in the channel. The 1964 landslides in Redwood Creek demonstrate a different geomorphic response to the more recent storm compared to similar, earlier storms.

Both land-management and climatic variables presently determine landslide frequency. On mountainous slopes managed for timber production, slope shear strength can be kept at a reduced level by periodic but repeated logging and by permanently maintained roads that locally increase slope angle. Without proper land management, failure frequency will increase even if storm frequency does not fundamentally change, resulting in higher rates of landslide erosion.

Higher rates of erosion can alter the conditions of soil denudation. The development and preservation of regolith on top of bedrock depend on weathering rates that proceed faster than, or equal to, the rate of denudation. On forested slopes in Redwood Creek having a regolith that supports vegetation, denudation rates are presently limited by regolith-transporting processes, which include debris slides. Were rates of erosion to increase, more regolith would be stripped away until the surface consisted of resistant, unweathered bedrock. We believe that rates of erosion will increase if poor land management practices continue, in which case, bare hillslopes will become more prevalent locally. Once established, these bare hillslopes will likely persist because of the transition from a transport-limited to a weathering-limited condition of denudation.

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