Effect of High Intensity Storms on Soil Slippage on Mountainous Watersheds in Southern California

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Abstract. The conversion of brush areas to grassland increased soil slip erosion on mountainous watersheds in southern California during the intense winter storms of 1969. The incidence of soil slippage, site factors affecting slope stability, and amount of debris generated by slippage were investigated for sample brush and grass areas in the San Dimas Experimental Forest. Soil slippage occurred on 5.5% of the brush areas and 16.7% of the grass areas, the values for both areas being about twice those measured in 1966 for a less intense storm period. The effectiveness of linear discriminant analysis was below that of 1966. In all probability, the thresholds of several environmental factors are not linear, and the 1969 storms crossed the thresholds of several factors responsible for more widespread slippage.

Converting brush areas to grassland has long been accepted as a way of adding forage for livestock. More recently such conversions have been undertaken to increase water yields and to create fuel breaks for improved fire control. When increased grazing is the objective of conversion, then economics, the practicality of use, and the regulations of various management agencies dictate that only relatively gentle slopes (usually those less than 30%) be converted. Conversions for fuel breaks and water yield improvement lack the restrictions of conversions for increased grazing; consequently, a decision to convert to grass for the two less restricted purposes depends to a greater extent on the judgment of the land manager. So far, however, land managers seeking water yield improvement have generally applied the same slope criteria used for range improvement conversions. It is not difficult to imagine that the increasing demand for land resources may tempt some managers to attempt conversion on more rugged terrain. The present paper, which reports a recent experience on the San Dimas Experimental Forest in southern California, should help such managers to resist that temptation.

The winter of 1968–1969 was one of the most severe that southern California has experienced. Several large storms from late January to early March contributed 1346 mm of rain out of a season total of 1595 mm. These intense storms produced widespread flooding in many sections of the Los Angeles basin, particularly those immediately below the mountains. Unstable mountain slopes yielded large amounts of debris that aggravated flood problems. Many debris and flood control reservoirs were filled. A cursory investigation of the foothills of the San Gabriel Mountains revealed widespread soil slippage. It became evident that these shallow landslides contributed much of the debris produced during the storm period. Earlier reports [*Corbett and Rice*, 1966; *Rice et al.*, 1969; *Bailey and Rice*, 1969] had shown how less intense storms (1965–1966) had affected various parts of the San Dimas Experimental Forest in the San Gabriel Mountains about 35 miles northeast of Los Angeles. To determine the effects of the more intense storms of 1969, the present investigation sought to: (1) ascertain the distribution of soil slippage within the study area, (2) analyze some of the factors affecting slope stability, and (3) assess the role of soil slippage in debris production during the storm period. We hoped to improve our understanding of the processes operating within watersheds and thus to help land managers plan and work within their systems to lessen the impact of such natural hazards.

STUDY AREA

The San Dimas Experimental Forest is representative of much of the watershed land in

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southern California. It is underlain by a complex body of metamorphic and igneous rocks, mainly of precretaceous age, which are rapidly being uplifted. As a result of the uplift, drainage channels are steep and deeply incised into the terrain, average slopes of 30° being produced. The shallow soils (whose average depth is 63 cm) are loamy sands or sandy loams that transmit water readily (the saturated hydraulic conductivity being about 33 mm/hr [*Krammes*, 1969]).

The experimental forest was swept by fire in 1960. After the fire, portions of the forest were converted to grass. About one-quarter of the converted area included in our study supported a mixture of perennial grasses, and the remainder annual grasses [*Corbett and Green*, 1965]. At the time of our study both converted and brush areas had a ground cover of about 70%. In the grass areas nearly 18% of the ground cover was litter, and the rest grass plants. In the brush areas about 10% was litter, 40% brush canopy, and 20% herbaceous plants and brush seedlings or sprouts. For the present study, the proportion of live vegetation is probably the most meaningful vegetative parameter. Water use and anchoring by roots, rather than protection of the soil surface, are the most important effects of plant cover on soil slips.

Precipitation during the 1968–1969 storm season exceeded that during all other seasons since 1883–1884. The total precipitation in 1969 was 2.3 times the annual mean (Figure 1), the heaviest storms coming in January and February. About 90% of the annual rainfall fell in these months, compared with 41% for the mean precipitation curve. In the 1965–1966 season November and December were the wettest months with 81% of the total rainfall.

Ten storms occurred in January and February 1969. (A storm is considered terminated when a period of at least 24 hours elapses with no precipitation.) The two largest storms occurred during an 8-day period. They were separated by only 27 hours and deposited 802 mm of precipitation, 50% of the total for that year. Extensive soil slippage occurred in the San Gabriels during the 8 days. In the 1966 season storms causing slippage occurred during a 4-day period in late

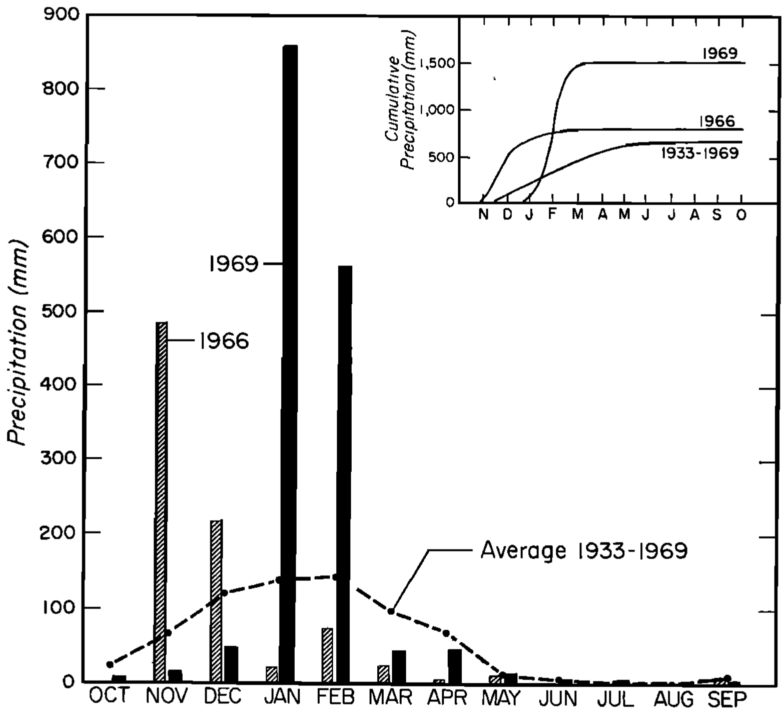

Fig. 1. Precipitation for specified years at Tanbark Flat climatic station, San Dimas Experimental Forest.

November (282 mm) and a 2-day period in late December (157 mm) 1965. These two storms accounted for 53% of the annual total.

It is difficult to say exactly which rainfall parameter is most related to the intensity of soil slippage. Any one of several mechanisms may trigger slips, and presumably each may be related to a different storm characteristic or set of antecedent conditions. *Bailey* [1967] picked the 12-day amount of precipitation as a good descriptor of the slip-producing capabilities of a storm. By that criterion, the 1966 and 1969 storms had return periods of about 11 and 43 years, respectively, for rainfall measured at Tanbark Flat on the San Dimas Experimental Forest.

Some authors have related the occurrence of slips to the 24-hour amount [*Rapp*, 1960; *Iwatsuka*, 1957]. *Simpson* [1969] has estimated the return period of the maximum 24-hour amount during January 1969 storms for several stations in the San Gabriel Mountains. For gages near the experimental forest he reported return periods of 5 to almost 50 years. We estimate the 24-hour return period of the 1969 storm at Tanbark Flat to be about 22 years and that of the 1966 storm to be about 7 years.

To the extent that such concepts are useful, we averaged the 24-hour and 12-day return periods at Tanbark Flat and concluded that the 1966 and 1969 storms have return periods of 9 and 32 years, respectively.

SOIL SLIPPAGE

Soil slips, sometimes referred to as debris slides or earth slips, are a form of shallow landslide involving only the material above the unweathered bedrock. More specifically, they are a downslope gravitational movement of weathered material released as the result of the accumulated stresses along a potential shear plane exceeding the inherent ability of the material to resist shear.

The resulting slip generally forms a spoon-shaped cavity on the slope. Debris moving downslope may spread out in a general fan shape or as a series of longitudinal trains, or it may be transported to a nearby channel to await removal by stream action. The exposed slip surface or slip plane, composed of either relatively unweathered bedrock or colluvial material, is subject to further erosion by raindrop impact, wind, sheet erosion, and rill and gully formation. Sometimes surface erosion induces the formation of a well-defined gully leading from the base of a slip downslope into a stream channel.

These three components (the slip cavity, the area of significant slope deposition, and the gully) constitute the unit area of slippage considered in this investigation. Other forms of mass movement, including several large slumps (large rotational blocks involving bedrock material) also occurred within the experimental forest, but they were not included in the study.

Distribution of slips, aerial photographic evidence. The study sites within the San Dimas Experimental Forest included areas of grass conversion paired with equal-sized areas of natural chaparral having similar soil type, soil depth, rockiness, and slope characteristics as determined from a soil map [*Crawford*, 1962]. A single soil type, the unnamed soil series A, covered 95.5% of the total study area.

The paired grass and brush areas had been tested for comparability by Hotelling's T^2 test, which uses nine variables [*Rice et al.*, 1969]. The test indicated that the mean conditions in the grass and brush sample areas were not significantly different with respect to slope, soil type, soil depth, parent material, aspect, and elevation. (The sample areas in the Rice et al. study were transferred from aerial photographs made in 1966 to a series of photographs (1:5000) from a flight on March 27, 1969.)

Each parcel of each soil class was evaluated separately by using a grid overlay to determine the areal extent of slippage. This procedure was comparable to that of *Corbett and Rice* [1966], but we did not determine the number of slips. So many slips had coalesced within the converted areas that attempts to reconstruct individual slips within these sites were futile. Furthermore, the wide variation in slip size (from small individual slips to large multiple slips) would have rendered a count of slips per hectare highly misleading.

In the 1969 storm season, 11.1% of the total study area was affected by soil slippage and in 1966 5.0% (Table 1). The data for 1969 include the whole slippage area (slip cavity, deposition, and gully); the data for 1966 pertain only to slip cavity. In 1966, however, slips were smaller, generated much less material, deposited much less material, and formed far fewer gullies. We

TABLE 1. Distribution of Soil Slippage for the San Dimas Experimental Forest during 1966 and 1969 Storm Seasons

Soil Type*	Type Area, ha		Relative Slip Areas, %			
	Converted	Control	1969 Converted	1969 Control	1966 Converted	1966 Control
B/3R1-1	1.8	2.3	0	0	0	0
A/1R1-2	3.5	3.7	0	0	0	0
A/3R0-2	1.7	1.8	2.2	0	1.3	0
A/3R1-2	10.6	10.8	4.6	1.0	0.3	0
A/2R1-3	32.8	31.2	9.8	5.1	6.0	1.1
A/3R1-3	28.7	29.7	33.4	6.6	9.0	1.7
B/3R1-3	4.4	4.5	7.6	0	2.4	0.1
Ac/4R1-3	13.5	12.5	36.2	2.2	8.6	0.3
A/1R1-4	23.2	22.2	12.3	8.0	13.0	5.1
Ac/1R1-4	9.7	9.9	17.1	5.2	13.4	1.8
Ac/2R1-4	13.4	16.0	22.1	13.6	13.5	2.6
Total	143.3	144.6	...	...	...	...
Average			16.7	5.5	8.2	1.7

* The soils were mapped according to standard soil series criteria [*Crawford*, 1962]. Each series has been tentatively designated by a capital letter. The small 'c' shows that the soil is colluvial. The first numeral in the denominator is the soil depth class: 1 (0–28 cm), 2 (29–58 cm), 3 (59–89 cm), and 4 (90–119 cm). The R1 is the rockiness class. The last numeral is the slope class: 1 (0–39%), 2 (40–54%), 3 (55–69%), and 4 (>70%).
Relative slip area percents are not corrected for slope.

believe that the 1966 data are not appreciably underestimated.

Within the converted areas, slippage amounted to 8.2% in 1966 and 16.7% in 1969. Control areas (with brush cover) showed a larger proportional increase: from 1.7 to 5.5%. In 1969 we may have overestimated the size of slips in converted areas because it was difficult to locate accurately the boundaries of thin areas of deposition in grass that were of a similar tone on the aerial photographs. We probably underestimated slips in brush areas because the canopy tends to obscure smaller slips, depositional areas, and gullies. Three years' additional brush growth probably

TABLE 2. Soil Slippage on Areas Converted from Brush to Grass and on Control Areas, San Dimas Experimental Forest, 1969

Soil Type*	Converted					Control				
	Area, ha	Affected Area, %	Slip, %	Deposition, %	Gully, %	Area, ha	Affected Area, %	Slip, %	Deposition, %	Gully, %
B/3R1-1	1.8	0	...	...	...	2.3	0	...	...	...
A/1R1-2	3.5	0	...	...	...	3.7	0	...	...	...
A/3R0-2	1.7	2.2	0	100	0	1.8	0	...	...	...
A/3R1-2	10.6	4.6	54	31	15	10.8	1	100	0	0
A/2R1-3	2.8	9.8	54	28	18	31.2	5.1	63	15	22
A/3R1-3	28.7	33.4	60	26	14	29.7	6.6	76	11	13
B/3R1-3	4.4	7.6	75	25	0	4.5	0	...	...	...
Ac/4R1-3	13.5	36.2	57	26	17	12.5	2.2	100	0	0
A/1R1-4	23.2	12.3	63	26	11	22.2	8.0	63	23	14
Ac/1R1-4	9.7	17.1	72	17	11	9.9	5.2	70	10	20
Ac/2R1-4	13.4	22.1	47	35	18	16.0	13.6	57	27	16
Total	143 3					144.6				
Average	...	16.7	58	27	15	...	5.5	66	18	16

* For explanation of symbols, see Table 1.
Percents are not corrected for slope.

increased this problem. For the 1969 storm season, the magnitude and complexity of the slippage areas required that we determine the relative area in slip cavity, deposition, and gully for the slippage areas within each soil class (Table 2). After the storm some slopes were patchworks of slip cavities, debris and gully areas, and grassy remnants of the original surface (Figure 2). The areas designated as 'slip' in Table 2 represent the cavities as they appeared on the aerial photographs and in the field. 'Deposition' areas include the areas downslope as well as those filling the lower portions of slips. Many of the larger slips also formed gullies leading downslope. 'Gully' areas include only those sites at which a new gully developed from a slip; they do not include sites representing the aggravation of a preexisting gully.

The pattern of erosion was similar in grass and brush areas. For both areas slips covered approximately 60% of the disturbed area. Gully development was nearly equal. The most noteworthy difference was that the area attributed to deposition was 27% in grass as opposed to 18% in brush. The smaller depositional area in brush is attributed to the arresting effect of the vegetation on the movement of debris downslope.

Field investigation. To obtain a representative sample of slips for field checking, 100 random points were selected in the converted and control areas and located on the aerial photographs. Each point was then paired with the nearest slip cavity within that soil class. The slips in each cover type were divided into six classes on the basis of their areas on the aerial photographs. A stratified random sample was then selected on the basis of the frequency of slip occurrence. The final sample included 20 grass and 20 brush slip sites. However, three very large slumps in the grass area were later deleted from the study because they were deep seated and resulted from mechanisms different from those of the other 37 sites. We felt that their inclusion might unduly bias the results obtained in the grass area.

The 37 slip and nonslip sites were further investigated in the field. Each slip cavity was measured to determine its area and volume (Table 3). Each slip and nonslip site was evaluated according to slope, aspect, distance to a channel, contact with a channel, contact with a contour trail, and contour curvature. Slope was measured from just above the slip scarp to the base or estimated base of the slip. The distance to the channel was measured from the slip scarp along the natural slope, as were all other distances. Contacts with the channel or trail were dichotomous variables. They applied to nonslip sites only if the length of the associated slip intersected either of the two features. The trail parameter was deleted from the brush comparison since none occurred within the brush sample areas. The contour parameter was also dichotomous and denoted whether the general land contour was convex or concave. Soil depth proved to be an elusive variable to measure in the field, especially in colluvial areas, and so depths were taken from Crawford's soil map.

Slips were always on slopes steeper than 60%, a lower threshold than the 80% found by *Rice et al.* [1969] in the 1966 storm. Hence the unweighted mean slope value was 93% in 1966 and 82% in 1969. That both the area and volume of the slips were dramatically affected was indicated by the difference in mean depth of new slips (computed by dividing the total volume by the total area): 39.6 cm in 1966 and 63.4 cm in 1969. Another important change was that the 1969 storms resulted in more slippage on side slopes and less on streamsides. This difference can be attributed to two factors: (1) a greater number of slippage areas in 1969 and (2) the failure of many less stable streamside sites in 1966. For analysis the slips extending from midslope to the channel were included in the midslope category since they were generally quite long and stretched considerable distances downslope to a channel. Usually the final few meters were choked with debris.

ANALYSIS

Discriminant analyses were performed in an attempt to estimate the contribution of various site parameters to slope instability (Table 4). The importance of slope, aspect (degrees from north), easterly aspect (dichotomous), and proximity to stream channel or trail (both dichotomous) was evaluated for the converted and control areas. These findings were then compared to the 1966 values obtained by *Rice et al.* [1969] (Table 4, analysis 1). Slope was again the leading factor and contributed at least two-thirds of the explained variability in both types of cover. Proximity to stream channels was not an important variable in the 1969 analysis. We

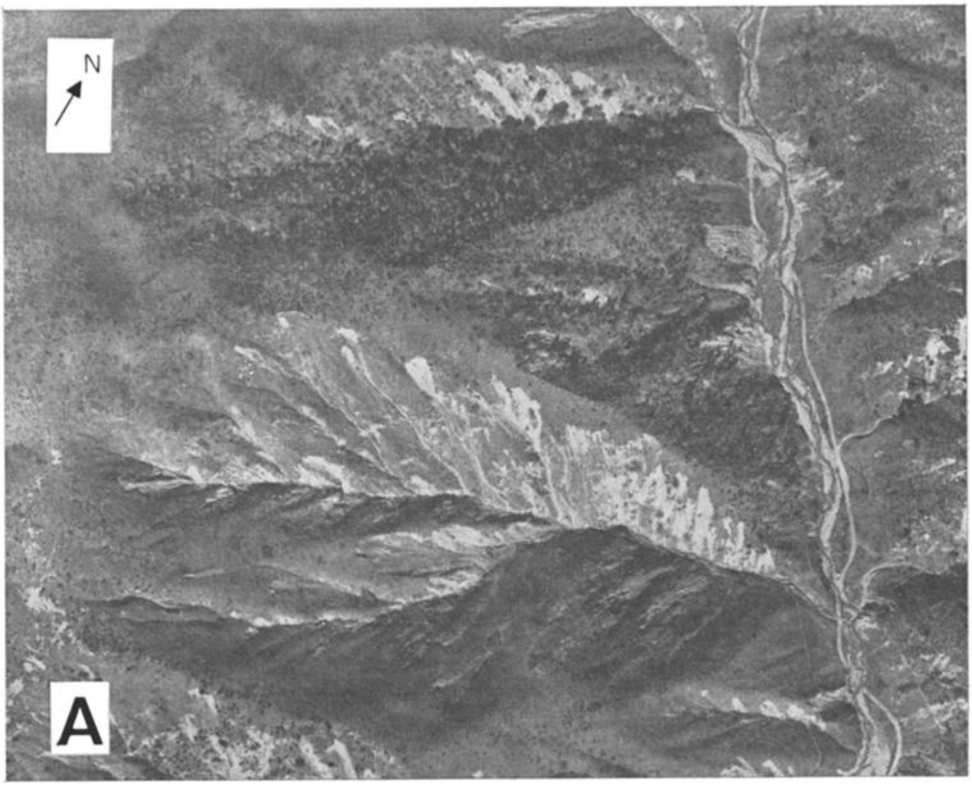

Fig. 2a. Portion of west side of Monroe Canyon, San Dimas Experimental Forest, California, after the 1966 storm. An unconverted drainage is in the upper part of the figure, and a converted drainage is in the lower part.

think that this change was due mainly to the vast increase in midslope instability. Aspect continued to play an important but reduced role in brush areas. Apparently the denser vegetation on more northerly exposures helped to stabilize slopes.

The analyses also revealed that aspect became a variable of some importance in the converted area in 1969. It carried a coefficient indicating that northerly aspects are less stable than southerly ones. Perhaps the roots of the former brush stand had been holding northerly aspects at steeper slopes than those possible with grass, and by 1969 the roots had decayed enough to permit more slippage. On southerly aspects, which had formerly supported a lighter brush cover, the change in strength that accompanied root decay was less and hence gave the negative correlation between slips and aspect. The hypothesis of root decay is supported by the work of *Bishop and Stevens* [1964] and by a study of slips on recently logged areas in Alaska [*Swanston*, 1969]. It seems plausible that the advent of root decay as an important destabilizing factor may require more time in the drier climate of southern California than in Alaska.

Two additional variables were then added to the analysis for evaluation: (1) distance to channel and (2) surface contour (Table 4, analysis 2). In both the grass and brush sample areas, the distance parameter had little effect. The contour variable, however, appreciably improved the total explained variance R^2. In both areas introduction of the contour variable decreased the amount of the explained variance attributed to slope. Aspect remained relatively unchanged, but soil depth became relatively more important in the converted areas.

In all analyses the proportion of the variance explained by the discriminant function R^2 was

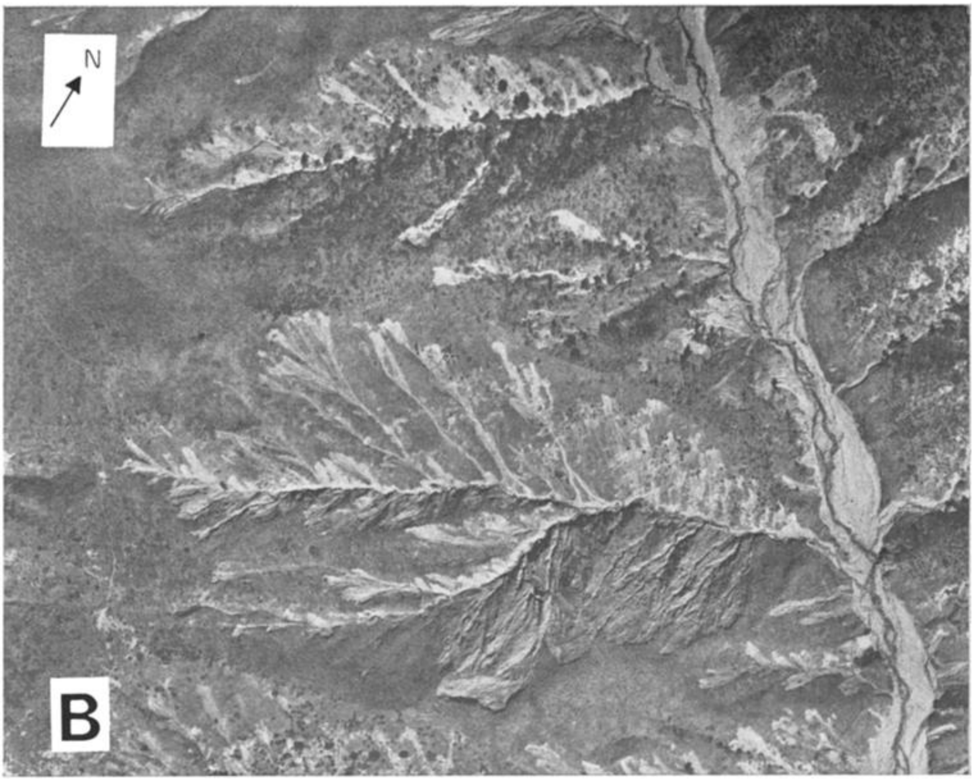

Fig. 2*b*. The same area after the 1969 storm. Intense storm activity caused greater slippage, especially in the converted area.

much lower than that in the 1966 study. Hence the interpretation that we attach to our analyses is much more tenuous than that of *Rice et al.* [1969]. We think that the lower R^2 results from the larger size of the 1969 storm. In 1966 the joint occurrence of several destabilizing site conditions may have been required before slippage could occur, whereas in 1969 any one of the site conditions could have triggered a slip. In such a case the correlation between site variables and the occurrence of slips would be less in 1969 than in 1966.

DEBRIS PRODUCTION

The extensive slippage in mountainous watersheds contributed considerably to the total debris produced during the 1969 season. Aerial photographic analysis determined the percent of debris for slip cavity, deposition, and gully in the slippage areas of the individual soil types, and the soil types were subsequently grouped into land classes by combining soil depth and slope and deleting rockiness (Table 5). The mean depths of cavities, gullies, and depositional areas were used to estimate the total amount of debris generated by each land class. Mean values for the cavities were obtained from the field data. Values for debris deposition and gully cross sections were obtained by a walking inspection of about 8 km of contour trails in grass and brush watersheds in the experimental forest. Mean gully cross sections for brush and grass areas were approximately equal at 2360 and 2146 cm^2, respectively. Debris deposition was deeper in the brush, owing to the arresting effect of the brush stems: 17.9 versus 11.4 cm.

From these data the total amount of debris moved downslope by slippage and subsequent erosional processes was estimated for each land type. The total erosion from the 288-ha study

TABLE 3. Field Data on Soil Slips Surveyed in the San Dimas Experimental Forest, Southern California, 1969

Site	Slope, %	Aspect, °	Volume, m^3	Area, m^2	Length, m	Width, m	Mean Depth, cm	Class	Soil Depth, cm
				Site Converted from Brush to Grass					
064	65	020	5.94	13.94	5.2	3.4	42.6	Midslope	46
048	90	235	9.24	11.43	4.0	4.0	80.8	Channel	15
055	82	075	10.13	22.03	7.3	4.0	46.0	Trail	46
002	79	015	11.40	19.98	6.4	4.0	57.1	Midslope	76
097	68	005	17.18	47.30	12.2	5.5	36.3	Midslope	76
099	81	155	16.91	44.14	9.5	5.8	38.3	Midslope	46
058	78	130	21.47	40.78	14.3	4.0	52.6	Midslope	15
045	99	105	22.01	37.64	7.6	9.1	58.5	Channel	15
041	72	100	43.60	96.38	13.4	12.5	45.2	Midslope	76
020	103	070	56.71	141.73	27.7	8.8	40.0	Channel	107
005	86	010	68.00	163.20	15.5	12.5	41.7	Trail	76
088	78	130	73.50	113.94	17.4	9.1	64.5	Midslope	15
006	77	000	100.00	150.93	17.1	10.1	66.3	Channel	76
040	84	015	170.74	356.51	31.1	22.9	47.9	Channel	76
017	86	085	192.21	284.29	27.1	16.8	67.6	Midslope	76
101	83	320	638.86	611.52	27.4	43.3	104.5	Channel	107
032	85	020	847.85	1456.60	79.6	25.0	58.2	Midslope channel	107
Mean	84*		135.63	212.49	19.0	11.8	55.8		61.8
				Site Not Converted from Brush to Grass					
543	80	095	4.69	15.61	4.6	4.3	30.0	Midslope	46
503	67	085	11.46	31.13	12.2	3.4	36.8	Midslope	46
544	78	110	13.64	33.55	9.8	4.3	40.7	Midslope	76
545	63	220	15.79	27.51	13.1	2.7	57.4	Midslope	76
528	107	245	16.95	48.88	10.1	5.8	34.7	Channel	46
515	60	190	24.38	45.07	10.1	5.5	54.1	Midslope	46
560	97	175	27.33	73.23	17.4	6.4	37.3	Midslope	76
537	69	000	35.57	61.43	14.9	5.2	57.9	Midslope	46
518	62	190	45.10	76.58	15.5	6.7	58.9	Midslope	46
587	98	000	62.55	90.61	16.5	7.3	69.0	Midslope	107
527	101	250	73.37	193.49	29.9	10.1	37.9	Midslope channel	46

TABLE 3. (Continued)

Site	Slope, %	Aspect, °	Volume, m³	Area, m²	Length, m	Width, m	Mean Depth, cm	Class	Soil Depth, cm
546	64	320	73.88	152.51	21.3	11.3	48.4	Midslope	76
538	81	010	79.20	194.33	17.7	15.9	40.8	Midslope	46
579	102	330	86.54	156.60	23.2	7.9	55.3	Midslope	76
508	82	044	129.66	180.39	17.1	13.7	71.9	Midslope	46
534	93	350	131.57	226.58	17.7	16.2	58.1	Midslope	46
520	76	135	160.78	232.62	20.1	11.6	69.1	Midslope	46
551	104	285	337.20	500.00	45.7	13.7	67.4	Midslope channel	46
509	85	005	379.13	414.87	24.1	22.6	91.4	Midslope	46
574	91	045	391.91	580.95	53.4	21.3	67.5	Midslope channel	76
Mean	89*		105.04	166.80	19.7	9.8	54.2		58

* Weighted mean by slip volume.
Length and width values are maximums.

area, as estimated from slip cavity and gully data, was 163,853 m³, of which 73% was generated from grass areas (Table 5). The material averaged 844 m³/ha for converted grass areas and 298 m³/ha for brush areas. The eroded debris was deposited downslope, deposited in stream channels, or removed by fluvial action. The amount of deposition downslope was probably underestimated, since only the coarser deposits were discernible in the field. Finer deposits had become vegetated and incorporated into the former soil surface. The amounts of deposition recorded were 5–10% of the total amount of debris generated for the various land classes. Therefore the total amount removed from the slopes was estimated at 112,698 m³ for grass areas and 40,516 m³ for brush areas.

The study area was divided into land classes on the basis of soil depth and slope to show how debris production was related to these two important variables (Figure 3). The contributions by grass areas exceeded those by their paired brush areas in all classes. The largest single contributor was the class 3-3 grass area.

Converted areas 4-3 and 1-4 contributed approximately equal amounts of debris. Converted area 4-3, however, generated the largest amount relative to its size, almost 3.35 times its areal contribution. Class 2-4 was the only brush area to generate debris in a proportion greater than its relative size.

A detailed interpretation of the data presented in Figure 3 and Table 5 is not warranted because of the relatively low total explained variance of the discriminant analysis. Nevertheless some observations are in order. As expected, relative debris production shows an overall increase with slope class although slope class 3 contributed more than slope class 4. This reversal may have occurred because steeper slopes, thinner soils, and higher proportions of bare rock outcrop in slope class 4 tended to reduce the amount of material available for slippage. Differences within land classes may be attributed to differences in such parameters as aspect, amount of rock outcrop, stream density and size, and vegetation type (annual or perennial grass; sage or oak, broad leaf, or chamise chaparral) *Rice et al.*, 1969]. For example, the very low contribution from the class 4-3 brush area is attributed to a single northerly aspect having a well-established cover of oak chaparral, oak

TABLE 4. Discriminant Analyses of the Occurrence of Soil Slips on Converted and Unconverted Brush Sites, San Dimas Experimental Forest

	Analysis 1				Analysis 2	
	1969 Grass	1969 Brush	1966 Grass	1966 Brush	1969 Grass	1969 Brush
Slope	68	77	72	56	44	53
Aspect	7	17	0	28	6	19
East	3	3	2	0	4	4
Soil depth	8	1	6	4	12	0
Channel	4	2	19	11	6	2
Trail	10	...	1	...	9	...
Distance					1	1
Contour					18	22
Total	100	100	100	100	100	100
Coefficient of determination R^2	0.31	0.17	0.57	0.57	0.37	0.25

All values are in percent expressed as the ratio of the sum of squares due to the coefficient of the variable to the total sums of squares for all variables.

TABLE 5. Types of Debris by Land Class Produced during 1969 Storm, San Dimas Experimental Forest

	Total Area, ha	Slipped Area, ha	Debris, m^3				
			Slip	Gully	Deposited	Removed	Total
Class 3–1*							
Grass	1.82	...	...	...	...	...	...
Brush	2.31	...	...	...	...	...	...
Class 1–2							
Grass	3.52	...	...	...	...	...	...
Brush	3.72	...	...	...	...	...	...
Class 3–2							
Grass	12.30	0.53	1,709	549	214	2,043	2,257
Brush	12.63	0.11	701	...	...	701	701
Class 2–3							
Grass	32.78	3.21	9,624	4,318	1,023	12,919	13,942
Brush	31.24	1.59	5,569	2,468	427	7,610	8,037
Class 3–3							
Grass	33.06	9.92	33,100	10,020	2,298	40,192	43,120
Brush	34.28	1.96	8,232	1,797	386	9,643	10,029
Class 4–3							
Grass	13.52	4.89	19,469	6,212	1,447	24,234	25,681
Brush	12.51	0.28	1,920	...	...	1,920	1,920
Class 1–4							
Grass	32.90	4.51	18,508	3,706	1,164	21,050	22,214
Brush	32.05	2.29	9,141	2,472	821	10,792	11,613
Class 2–4							
Grass	13.40	2.96	9,458	3,980	1,478	12,260	13,438
Brush	16.03	2.18	8,445	2,456	1,051	9,850	10,901
Total†	288.07	34.43	125,875	37,978	10,639	153,214	163,853
Grass	143.30	26.02	91,867	28,785	7,954	112,698	120,652
Brush	144.77	8.41	34,008	9,193	2,685	40,516	43,201

* For explanation of symbols, see Table 1.

† Discrepancy in total figures due to rounding in Tables 1 and 2.

woodland, and big cone Douglas fir. With this one exception, there was a definite trend of increasing debris production with increasing soil depth, perhaps simply because there was more debris to erode.

MANAGEMENT IMPLICATIONS

In the drier parts of the West, where there is much type conversion, land managers may fail to give adequate consideration to erosion from gravitational mass movements. Particularly in a region of sandy soils, managers may be more aware of soil losses caused by sheet erosion, rilling, and gully erosion, which occur to some extent every year. Soil slips, though less frequent, produce substantial amounts of erosion, and conversion may increase the amount. Consequently, to arrive at more accurate appraisals of the desirability of conversion projects, managers should consider the indirect cost of erosion as well as the direct cost of establishing and maintaining conversion.

It may be argued that the soil slip problem can be avoided merely by sticking to the present guidelines that dictate converting only terrain with slopes gentler than those on which no slippage has been observed. In practice it may be difficult to adhere strictly to such guidelines. In many cases small steeper facets are inevitably included in the gentler terrain of a conversion area. If herbicides are used, as is the case in about half of the conversions in California, these atypical areas will probably be converted. Even if it were possible to avoid spraying these areas directly, over time, drift and revolatilization of the herbicides would likely reduce the brush cover on these steep areas.

Conversions for water yield improvement usually place first priority on sites adjacent to stream channels. In geologically young mountains like the San Gabriels, the steepest slopes tend to be adjacent to the channels. These slopes are the type in which slips are most likely to occur.

Fire control considerations necessarily dictate fuel break locations. They will usually be on ridge tops, which are somewhat more resistant to erosion than most of the terrain. Nonetheless, in comparing 2.1 km of grass-covered fuel breaks on the San Dimas Experimental Forest with an equal length of unconverted ridge tops of similar slope, aspect, and soil depth, we found 8.2% of the area on the fuel breaks and 4.6

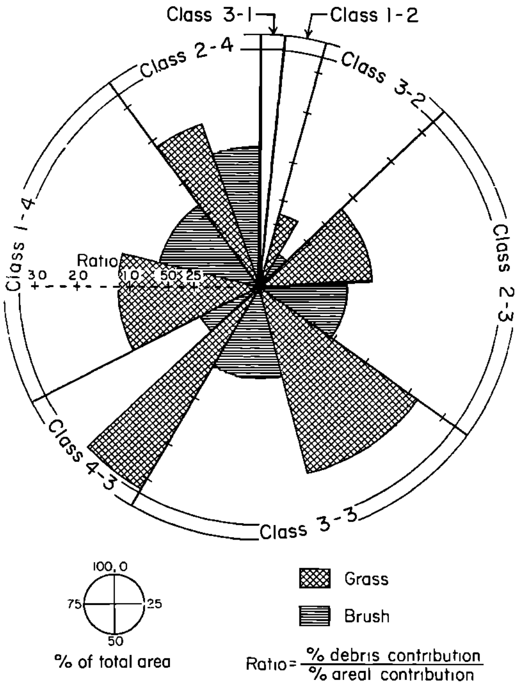

Fig. 3. Relative contributions to total debris (163,853 m^3) by land class within the total study area (288 ha). The relative size of each land class is indicated by the size of the angle devoted to that class. The relative contribution of each land class to the total debris produced in each vegetation type for the 1969 season is proportional to the area of each shaded segment.

of the area on the brush-covered ridges to be in slippage.

SUMMARY AND CONCLUSION

The major conclusion of this study is that in all probability the thresholds of the various environmental factors affecting slip occurrence are not linear. Therefore as conditions change for any one parameter, the thresholds for the other parameters will respond and adjust accordingly. The magnitude of the 1969 storm period caused the thresholds of several factors to be crossed. This condition reduced the effectiveness of a linear discriminant analysis in comparison to the 1966 study.

Slope was the leading factor contributing to slippage. The more intense rainfall lowered the threshold of slip occurrences from 80% in 1966 to 60% in 1969. Aspect continued to play a moderate role in brush areas. In grass areas the appearance of aspect as an important variable may be explained by the more advanced stage of decay of the preconversion brush root systems. Because stability thresholds were lowered on more midslope portions of watersheds, the importance of proximity to stream channels was reduced.

The size of the 1969 storm affected theinfluence of conversion on slip erosion. In the winter of 1966 brush areas produced 21.1 m^3/ha of erosion, and grass areas 156 m^3/ha, the grass production being 7.4 times the brush production for a storm having a return period of about 9 years. In 1969 brush areas produced 298 m^3/ha and grass areas 844 m^3/ha, the grass production being 2.8 times the brush production for a storm having a return period of about 32 years. In other words the larger storm of 1969 amplified the 1966 brush slip erosion by about 14 times but the 1966 grass slip erosion by only about 5.4 times. Scant comfort can be taken from this decreasing ratio between grass and brush since the absolute difference between grass and brush increased from 135 m^3/ha in 1966 to 546 m^3/ha in 1969. Clearly, conversion to grass reduced slope stability in the study area. Consequently, the potential for increased erosion should be weighed when one is determining the desirability of conversion from brush to grass on steep terrain.

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