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Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California

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ABSTRACT

Rainfall intensity and duration of storms has been shown to influence the triggering of debris flows. After examining storm records of the San Francisco Bay region, documenting when debris flows occurred, and measuring piezometric levels in shallow hillside soils, continuous high-intensity rainfall was found to play a key role in building pore-water pressures that trigger debris flows.

Debris flows in 10 storms between 1975 and 1984 in a 10-km^2 area near La Honda, California, were examined, and their rainfall records compared to the records of other storms to determine the antecedent conditions and the levels of continuous, high-intensity rainfall necessary for triggering debris flows. No flows were triggered before 28 cm of rainfall had accumulated each season, which suggests that prestorm soil-moisture conditions are important. After this sufficient antecedent rainfall, a threshold of rainfall duration and intensity—which accounted for triggering at least one debris flow per storm within the study area—was identified. The number of debris flows increased in storms with intensity and duration characteristics significantly above this threshold.

By studying where debris flows initiated in storms of different intensity and duration, debris flow susceptibility was found to depend on soil thickness and hillside concavity and steepness. Moderate intensity storms of long duration triggered complex soil slump/debris flows in thick soils on concave slopes below large drainage areas, whereas high-intensity storms of short duration caused complex soil slide/debris flows in thinner soils without respect to size of drainage area. From these observations, an empirical model based on geology, hydrology, and topography is proposed to account for the triggering of debris flows at selective sites by storms with different combinations of intensity and duration once the antecedent and intensity-duration thresholds are exceeded.

INTRODUCTION

The importance of antecedent rainfall prior to storms triggering debris flows has been identified in many places, including Southern California (Campbell, 1975), New Zealand (Eyles, 1979), and Alaska (Sidle and Swanston, 1982). The significant period of antecedent rainfall, however, may vary from days to months, depending on local site conditions, particularly soil permeability and thickness. In the case of high-permeability soils such as those of Hong Kong (Brand and others, 1984), the period of necessary antecedent rainfall may be extremely short or the amount of necessary antecedent rainfall may be supplied by the early part of a storm.

Although the association between high-intensity rainfall and debris flows has been documented in Japan (Fukuoka, 1980), New Zealand (Selby, 1976), and Brazil (Jones, 1973), as well as in many other places worldwide, the significance of the duration of continuous high-intensity rainfall in triggering debris flows has not been thoroughly examined. Geologic, climatologic, hydrologic, and topographic factors have been identified that contribute to debris flow susceptibility (Campbell, 1975; Ellen and others, 1982; Reneau and others, 1984; Smith, 1987), but the combined effect of these factors with storm intensity and duration on triggering debris flows has not been adequately examined.

In Southern California, Campbell (1975) correlated known times of observed debris flows with specific rates of high-intensity rainfall, and postulated that high-intensity rainfall caused the build-up of high positive pore-water pressures that in turn triggered debris flows. Since then, Wu and Swanston (1980), Sidle and Swanston (1982), and Nielsen (1984) have measured high positive pore-water pressures during high-intensity rainfall associated with the nearby triggering of debris flows.

Several studies have examined thresholds of storm intensity and duration with respect to triggering debris flows. Caine (1980), using published worldwide data based principally on average storm intensity, developed an equation relating intensity and duration of storms that had triggered debris flows. Within the San Francisco Bay region, Cannon and Ellen (1985) identified a threshold for abundant debris flows based on hourly intensities and storm duration. They documented times of debris flows during the January 3–5, 1982, storm and found a strong correlation with periods of continuous high-intensity rainfall during the storm exceeding the threshold.

Several investigators have noted geologic, hydrologic, or topographic factors favorable for locations of debris flow initiation; however, no correlation between these factors and storm intensity and duration has been proposed to account for sites where debris flows initiate. Campbell (1975), as well as others, have generally identified slopes ranging in steepness from 26° to 45° mantled with soil as most likely sites for debris flow initiation. Reneau and others (1984) identified colluvium-filled bedrock hollows as being particularly susceptible to initiating debris flows because of ground-water flow convergence. During numerous storms, investigators have noted a propensity for debris flows initiating in first-order drainages or on hillsides with concave topography suggestive of colluvial hollows (for example, Hack and Goodlet, 1960). However, debris flows have also been noted, albeit less frequently, on planar to slightly convex hillsides (Smith, 1987; Moser and Hohensinn, 1983; and Tsukamoto and others, 1982). Sassa (1984) identified three typical situations, dependent on surface topography, bedrock profile, and the presence of loose soil, where debris flows are likely to initiate because of the convergence of ground-water flow.

I examined debris flow scars in a selected area and noted soil properties and thickness, as well as hillside steepness, profile, and concavity. Continuous rainfall data were used to characterize the intensity and duration of storms that triggered debris flows. Based on comparisons of the intensity and duration of storms that triggered debris flows, I have postulated an empirical model to account for the triggering of debris flows in selected areas by storms with different intensity and duration.

SETTING

The central Santa Cruz Mountains of Northern California consist mainly of Tertiary sedimentary rocks with some interspersed volcanic rocks (Brabb and Pampeyan, 1983). The mountains rise gradually from the sea coast to heights as much as 1,000 m some 10 to 15 km inland. The mountains have never been glaciated and a thick cover of soil and vegetation mantles most of the area. The area has a mild Mediterranean climate, with the majority (about 85 percent) of the annual precipitation falling as rainfall from November through March (Rantz, 1971) during the cool winter and spring seasons.

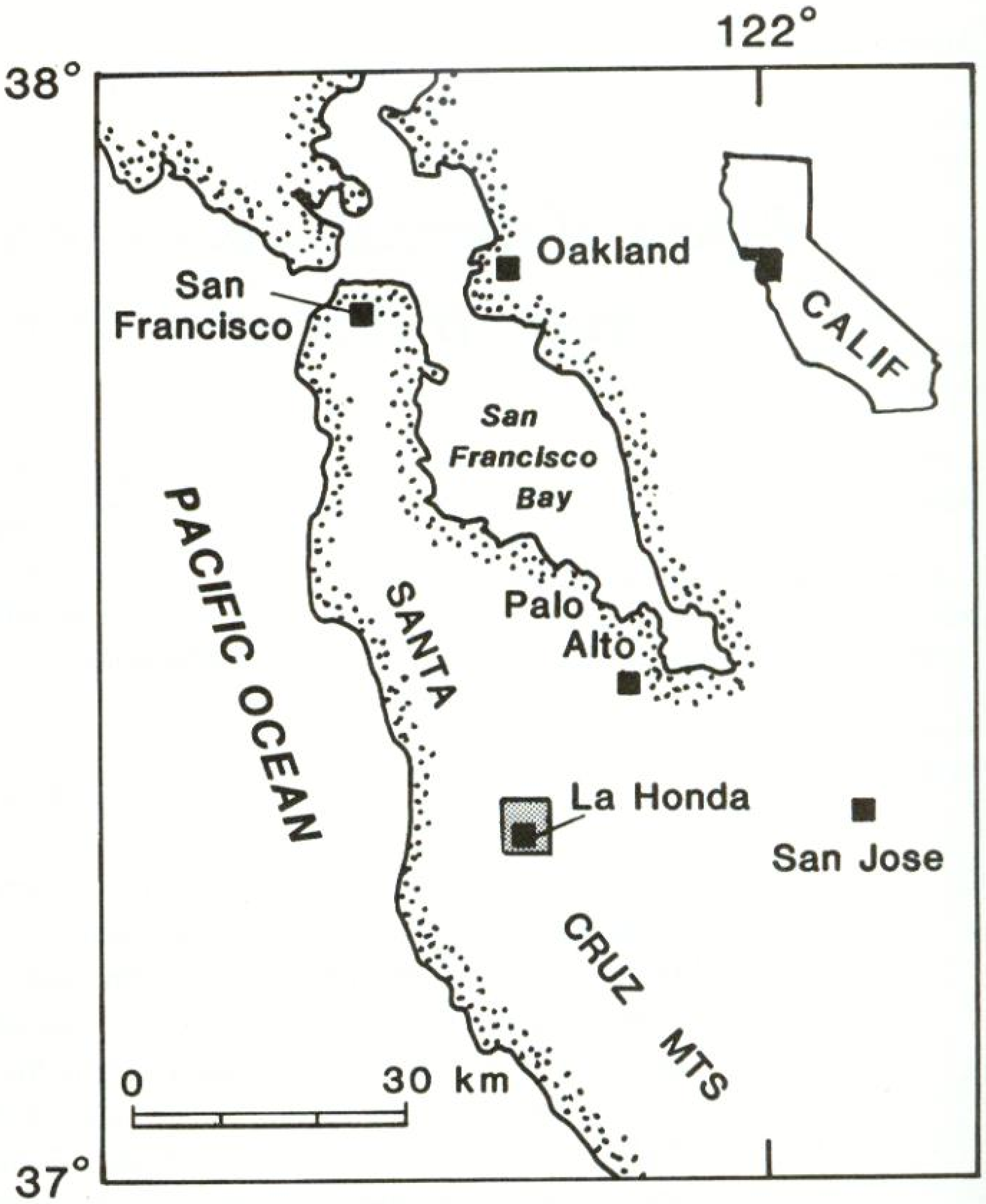

Figure 1. Location of study area near La Honda, in central Santa Cruz Mountains of the San Francisco Bay region, California.

STUDY AREA

A 10-km^2 area northwest of the town of La Honda, California (Fig. 1), was chosen for study: the slope movement processes observed there are believed to be representative of those in most of the central Santa Cruz Mountains. The study area ranges in elevation from 60 to 360 m; it contains both gently sloping areas in which grasses, chaparral, and oaks predominate, and steep canyons in which a variety of conifers and redwoods are concentrated. The area receives, on the average, 76 cm/yr of seasonal rainfall (Rantz, 1971), measured between July 1 and June 30.

Bedrock geology (Brabb, 1980) consists of three Tertiary units: (1) the Tahana Member of the Purisima Formation (Miocene and Pliocene); (2) the Mindego Basalt and related volcanic rocks (Oligocene and/or Miocene); and (3) the Lambert Shale and San Lorenzo Formation, undivided (Eocene, Oligocene, and Miocene). The Tahana Member of the Purisima Formation consists principally of very fine grained sandstone and siltstone. The Mindego Basalt consists of basaltic volcanic rocks, including flow breccia, pillow lava, and lithic tuff. The Lambert Shale and San Lorenzo Formation contain mudstone, siltstone, and shale. Soils developed on all three bedrock units are inorganic clays, silts, or clayey silts of medium to high plasticity, with a clay-size fraction composed predominantly of smectites (Wieczorek, 1982).

METHODOLOGY

Between 1975 and 1984 I inventoried slope failures in the study area and measured rainfall using continuously recording gauges, hourly recording gauges, and bucket gauges during major storms. To determine the storm characteristics required for triggering debris flows, meteorologic data were collected for those storms that triggered debris flows, and these data were compared with similar data on other storms. Several measures of prestorm and storm rainfall were compared.

During this period 10 storms triggered a total of 110 debris flows; the majority (74) occurred during the January 3-5, 1982, storm. Examination of rainfall records for 22 major storms revealed two general conditions necessary for storms to initiate debris flows: antecedent rainfall at the time of the storm had to exceed a minimum threshold, and the duration of rainfall had to exceed certain levels of intensity for specified duration.

Antecedent Rainfall

Antecedent rainfall is important for establishing soil-moisture conditions conducive to rapid infiltration and build-up of high pore-water pressures during subsequent major storms. Prior to the development of positive pore-water pressures, the infiltration of rainfall reduces intergranular capillary tension (alternately referred to as soil suction or negative pore-water pressure) in unsaturated or partly saturated soils. The reduction of capillary tension and the increase of positive pore-water pressure reduces soil strength and has been linked with triggering debris flows in many parts of the world.

In the generally low-permeability clay, silt, and clayey-silt soils of the study area, antecedent rainfall is important over a period from probably as short as 7 days to perhaps 2 months. Antecedent seasonal rainfall of at least 28 cm was observed before subsequent storms triggered debris flows, as noted by comparing antecedent rainfall for storms in groups 1 and 2 in Table 1. The rainy season generally starts in October or November, so the required antecedent rainfall is not generally reached until December or January.

Closer examination of antecedent rainfall records revealed that rainfall values during the preceding 7- to 30-day period accounted for about 80 percent of the antecedent seasonal value and that 7- to 30-day antecedent values for debris flow–triggering storms were about twice those of storms that did not trigger debris flows.

Continuous Intense Rainfall

During this study, a new measure, intensity-duration (ID), which defines the duration (in hours) that rainfall intensity (in centimeters per hour) exceeds a particular value was developed to characterize continuous periods of intense rainfall. For example, an $ID_{0.50}$ = 3 hr signifies that an intensity of at least 0.50 cm/hr lasted 3 hr. This measure permits a precise determination of the effect of the time distribution of rainfall in the triggering of debris flows.

By comparing values of intensity-duration for the different storms in groups 1 and 3 (Table 1), a minimum value or threshold intensity-duration was identified for storms that triggered at least one debris flow within the study area. A plot of duration for different levels of intensity for storms in groups 1 and 3 of Table 1 shows a threshold that separates storms that triggered debris flows from storms that did not (Fig. 2A). Each storm is represented by a family of circles, each value corresponding to a duration of each particular intensity. The two empty circles which lie to the left of the threshold are minimum values, and the error of measurement associated with these spans the threshold and confirms the trend.

At low intensity of approximately 0.25 cm/hr, the threshold in Figure 2A is not particularly well constrained. Physically, the independence of duration and intensity on triggering debris flows in this low-intensity range may correspond to the ability of soils on steep slopes to drain under low rates of rainfall infiltration without appreciable build-up of pore-water pressure. The data are not sufficiently accurate to extend the threshold for high intensities with duration less than 1 hr. High-intensity rainfall of this short duration may not be as significant for triggering debris flows in the cohesive, low-permeability soils of this area, as in other areas of more highly permeable cohesionless soils where pore pressures can rapidly respond to high-intensity rainfall (Sidle and Swanston, 1982).

The threshold is best defined within the range of intensities from 0.5 to 1.0 cm/hr. If the threshold is considered as asymptotic at its extremes, then for debris flows to be triggered, the relation between continuous rainfall duration and intensity can be expressed by the equation:

$$D = 0.90/(I - 0.17),$$

where D = continuous duration of rainfall (in hours) equal to or exceeding intensity I (in centimeters per hour) (Raymond Wilson, written communication, November 1985).

The effect of antecedent rainfall is illustrated in Figure 2B, in which duration and intensity for storms with less than 28-cm antecedent rainfall (group 2 in Table 1) are plotted. The triangles (representing storms in group 2 in Table 1) are distributed on both sides of the indicated threshold line. Significantly higher

TABLE 1. STORM-RAINFALL CHARACTERISTICS RELATED TO DEBRIS FLOWS IN LA HONDA STUDY AREA, 1975-1983

Storm (no.)	Date	Prestorm Seasonal Rainfall (cm)	Total Storm Rainfall (cm)	Maximum 1 hr (cm)	$ID_{0.25}$ (hr)	$ID_{0.5}$ (hr)	$ID_{0.65}$ (hr)	$ID_{0.75}$ (hr)	$ID_{1.02}$ (hr)	Debris Flows
Group 1										
1	1/13-14/78*	38.8	7.0	0.81	4**	3**	2**	2**	0**	3
2	2/13/79*	28.2	5.6	1.02	9	3	1.5	1	1	1
3	2/18/80*	49.2	4.6	1.02	7	3	2.5	2	1	1
4	12/29/81	39.6	5.7	0.81	6.7	6.3	5.5	2.4	0	5
5	1/3-5/82	48.0	15.3	1.07	19.2	16.5	13.8	4.3	1.7	74
6	12/20-22/82	35.1	10.4	1.09	3.8	3.3	3.2	2.8	1.3	2
7	1/22-23/83	49.5	9.8	1.42	6.4	3.1	2.2	2.1	1.3	8
8	1/26/83	60.1	7.7	2.44	6.1	5.0	4.8	4.5	2.0	13
9	2/25-3/2/83	87.3	15.5	1.09	3.5	3.1	2.3	2.1	1.2	1
10	3/12-13/83*	105.9	5.6	1.02	6	5	3.5	3	1	2
Group 2										
11	3/15-16/77	26.4	5.2	0.64	8.7	3.1	1.0	0	0	0
12	1/7-11/79	9.0	10.4	1.52	5.5	2.0	1.6	1.6	1.6	0
13	1/14-15/79	19.7	6.9	1.40	5.5	3.4	1.6	1.6	1.3	0
14	12/23-24/79*	23.1	12.7	2.03	10	4	3	3	2	0
15	1/26-29/81	16.5	12.3	1.09	5.2	3.5	2.5	1.2	1.0	0
16	11/18/82	16.8	8.1	1.02	9.3	7.4	5.5	5.3	1.0	0
17	11/27-30/82	25.6	8.2	1.27	4.9	2.4	2.3	2.1	1.4	0
Group 3										
18	3/12-13/81	37.6	6.0	1.19	7.9	2.2	2.0	1.7	1.0	0
19	2/13-17/82	72.3	12.8	0.89	8.1	2.7	1.5	1.0	0	0
20	3/28-4/3/82	94.9	14.0	0.89	7.0	2.4	1.7	1.5	0	0
21	4/10-11/82	109.7	6.0	0.69	3.8	1.7	1.2	0	0	0
22	2/5-8/83	70.8	10.1	0.89	2.4	1.7	1.6	1.2	0	0

Note: Group 1 includes storms that triggered debris flows; Group 2, storms without sufficient antecedent rainfall to trigger debris flows; Group 3, storms without sufficient intensity and duration to trigger debris flows.

*Data for storm numbers 1, 2, 3, 10, and 14 are from hourly recording rain gauges, and therefore ID values are not reported to same precision as values for other storms.

**Intensity-duration values for storm number 1 averaged from National Oceanic and Atmospheric Administration continuously recording rain gauges at Berkeley and San Francisco Airport for similar total rainfall measured at La Honda.

intensities and longer durations, above the threshold in some of these storms, confirms strong influence of antecedent rainfall on triggering debris flows within the range of storm intensity and duration observed.

This threshold is notably less than that identified for abundant debris flows in the San Francisco Bay region (Cannon and Ellen, 1985) and less than that proposed by Caine (1980) for debris flows reported worldwide. However, because the threshold for the study area is based on storms that caused as few as one debris flow in the 10-km^2 study area, this difference is not too surprising. A comparison among these various thresholds plus two major storms in the study area in terms of values of average intensity for 2- and 3-hr duration are presented in Table 2.

Storms that caused more than one debris flow per square kilometer area (Table 1, storms 5 and 8) had higher values of intensity-duration that are more nearly comparable with the threshold for worldwide data and approach the threshold for abundant debris flows in the San Francisco Bay region. Within the study area, the number of debris flows generally increased with increasing values of intensity-duration above the threshold shown in Figure 2A.

Debris Flow Initiation Sites

After debris flows occurred, I examined the source areas where the slope movements started. The debris flows were actually complex types of movement, involving either a rotational or translational soil slide that subsequently mobilized into a debris flow (terminology of slope movement according to Varnes, 1978). In the source area where sliding started, I noted the shape and dimensions of the slide and the geometry of the basal shear surface (if exposed) or the orientation of the displaced surface material relative to the original ground surface to detect rotation.

In exposures of the main scarp, lateral flanks, or basal shear surface, I documented geologic conditions such as composition and profile of soil-bedrock materials, paying particular attention to presence of impermeable layers and zones of contrasting strength. Soil samples from scarp and flanks, representing original

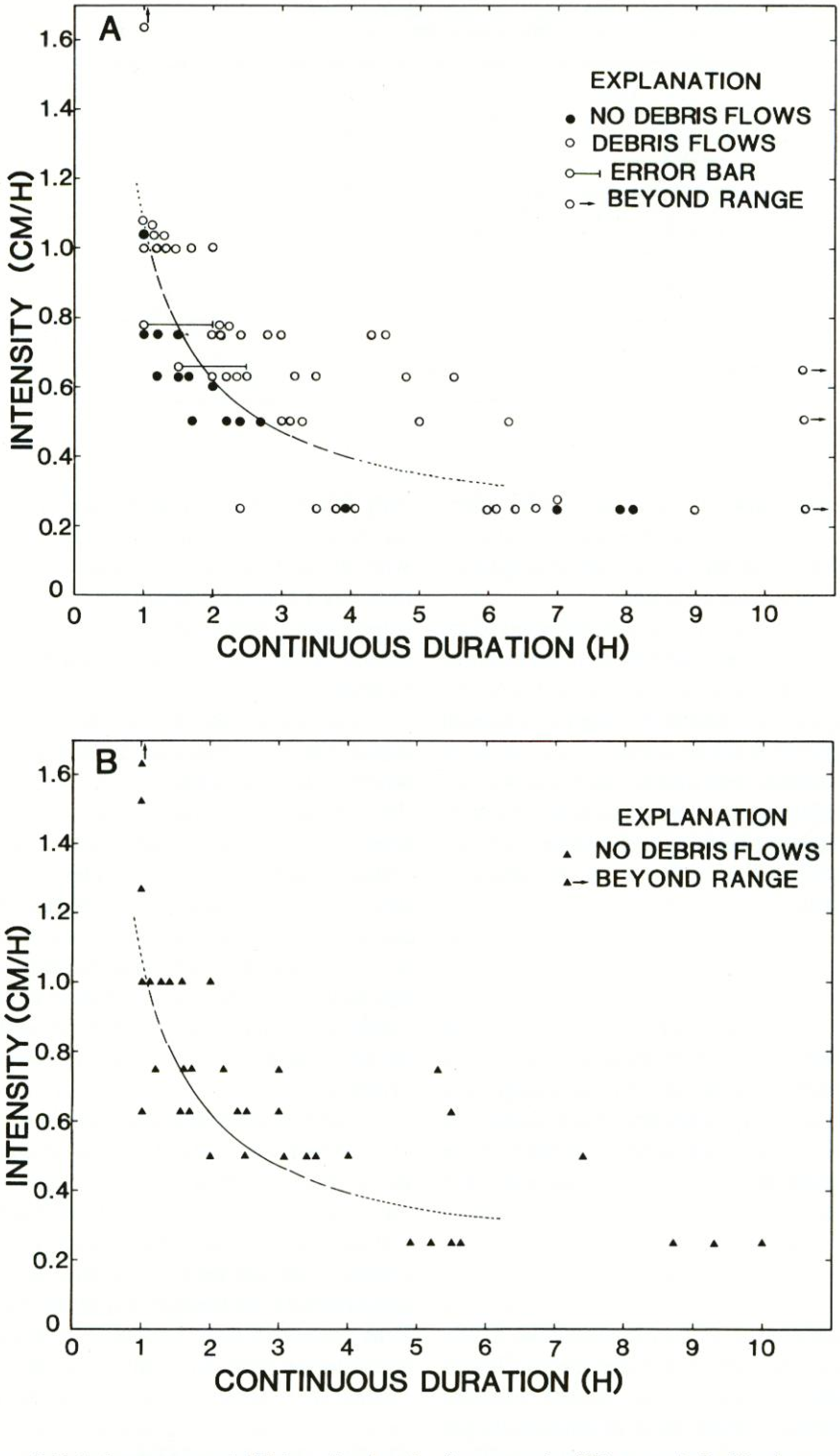

Figure 2. Relations among rainfall intensity-duration from records of 22 storms in La Honda area from data in Table 1. A, Values from storms that occurred after seasonal antecedent rainfall threshold of 28 cm. Solid line represents intensity-duration threshold that delineates storm-rainfall conditions that resulted in debris flows; line is dashed and dotted where threshold is less certain. B, Values from storms that occurred before seasonal antecedent rainfall threshold of 28 cm had been achieved. For comparison, threshold line from (*A*) is shown.

TABLE 2. COMPARISON OF SELECTED STORMS IN LA HONDA AREA AND VARIOUS THRESHOLDS FOR TRIGGERING DEBRIS FLOWS

	2-hr Duration Intensity (cm/hr)	3-hr Duration Intensity (cm/hr)
Threshold-La Honda area	0.63	0.48
Storm 1/3-5/82, La Honda area	0.98	0.87
Storm 1/26/83, La Honda area	1.02	0.90
Threshold-worldwide data*	1.13	0.97
Threshold-San Francisco Bay region**	1.79	1.67

*From Caine (1980).
**From Cannon and Ellen (1985).

slide material, and soil samples from the basal shear surface were tested to determine geotechnical index properties. At one location, seismic-refraction geophysical testing was used in conjuction with augering to examine subsurface conditions.

Hillside morphology near source areas was inspected to ascertain if convergence of ground-water flow from adjacent slopes influenced the development of critical pore pressures near slides. Hillside shape, both along a vertical profile and along a horizontal planar cross section, was noted in the field and on contour maps at a scale of 1:4,800. These maps were used to determine whether the source area was located on planar, convex, or concave slopes. In measuring profiles, the relative hillside position of the slide was noted to ascertain whether the slide occurred in a segment near the crest, midsection, or bottom of a slope.

RESULTS

Three categories of debris flows were observed based on type of initial slope movement, depth of movement, profile of materials involved, steepness of slope, and hillside topography: deep slumps in thick soil, shallow slumps and slides in soil, and very shallow slides in soil over bedrock surfaces. Table 3 shows the distribution of each category of failure associated with each particular storm.

Deep Slumps

Deep slumps, ranging from 1 to 3 m in maximum depth, occurred at middle to low positions on concave slopes. Despite their low relative position on hillsides, these failures were not associated with gully erosion or undercutting by streams. Slopes where failures initiated were relatively gentle, ranging from 20° to 28°. In terms of the ratio of maximum depth to length of initial failure (D/L), measurements on two slumps of 0.16 and 0.18 agree with an average value of 0.17 (Moser and Hohensinn, 1983) from a large sample of partly rotational slides in Alpine regions that led to debris flows.

A profile exposed in the main scarp of a deep slump typically showed at least 1 m of uniform black, organic-rich, loose clayey-silt soil sometimes overlying a matrix of tan, stiff, silty soil with interspersed hard rock fragments. Weathered bedrock was only rarely exposed beneath these soils. At one such site, a downslope seismic refraction profile detected a soil-colluvial wedge, several meters thick, with weathered bedrock boundaries beneath.

The concave topography and the thick accumulation of soils suggest that these sites may be colluvium-filled bedrock hollows where soils accumulate only to be periodically flushed out as debris flows (Dietrich and Dunne, 1978). If the majority of such sites are emptied in a major storm and if the accumulation of colluvium is slow—taking decades or even longer (Dietrich and others, 1986)—a quantitative analysis of debris flow recurrence is complicated, because future storms will not have the same opportunity to trigger as many failures. This factor was not considered significant in the field area, because following the January 3–5, 1982, storm that caused the majority of failures in the area over the period of observation many sites failed subsequently in 1983 (Table 1).

The concave topography and the location of ground failures at middle to low positions of concave slopes suggest that convergence of throughflow from site slopes may be responsible for initiating slumps at these sites. After major storms, the water table was quite close to the surface at these positions. In some instances artesian pressures were measured, suggesting that ground-water convergence from upslope may result in springs at such locations. Such extremely high pore-water pressures indicated by springs and artesian conditions reduce effective soil strength and help account for initiation of sliding on these relatively flat slopes.

Shallow Slumps and Slides

Shallow slumps and slides within soil occurred on slopes of intermediate steepness ranging from 24° to 40°. They occurred predominantly at middle to upper positions of planar to slightly concave hillsides in uniform, black, loose, clayey-silt soils. Several of these shallow failures, between 0.3 to 1.0 m in depth, had D/L

TABLE 3. DISTRIBUTION OF DEBRIS FLOWS (IN PERCENT) ACCORDING TO CHARACTERISTICS OF INITIAL SLOPE MOVEMENT

Storm	Date	Total Debris Flows	Slope Movement			
			Deep Slump	Shallow Slump	Shallow Slide	Shallow Slide over Bedrock
1	1/13-14/78	3	67	0	0	33
2	2/13/79	1	100	0	0	0
3	2/18/80	1	0	0	100	0
4	12/29/81	5	0	0	80	20
5	1/3-5/82	74*	14	23	43	20
6	12/20-23/82	2	0	50	50	0
7	1/22-23/83	8	13	87	0	0
8	1/26/83	13	0	23	15	62
9	2/25-3/2/83	1	0	0	100	0
10	3/12-13/83	2	0	50	50	0

*Only 30 of these 74 were field-checked for this characterization; remainder identified from aerial photographs, but not characterized.

ratios ranging from 0.08 to 0.23, indicating a range of values from planar to rotational geometrics. They frequently occurred at or near sites of previous instability, either on oversteepened scarps of massive, deeper seated landslides or adjacent to scars of previous debris flows. Their location is thus significantly influenced by oversteepening or modifications in local hillside geometry.

These failures showed little preference for hillside location conducive to ground-water flow convergence. Because of generally steeper slopes for these failures, the pore-water pressure on the slip surface need not be as great for failure of deep slumps on flatter slopes. Ground-water levels were still relatively high, as indicated by water seeping from the main scarp after failure and by levels measured in a few nearby wells within hours after major storms, but did not reach excessive levels achieved beneath concave slopes. Subsequent to storms such levels dropped rapidly within hours due to greater drainage of short steep slopes and relatively small upslope drainage areas.

Very Shallow Slides Over Bedrock

Very shallow slides of soil over planar bedrock surfaces, between 0.2 and 0.5 m deep, occurred on steep slopes ranging from 26° to 47°. The extremely planar geometry of several of these features is indicated by low D/L values, ranging from 0.03 to 0.07, comparable to those cited by Moser and Hohensinn (1983) for planar slides. These slides occurred on planar and even slightly convex middle and upper portions of hillsides.

A marked contrast in consistency was noted between the upper loosely cemented soil and the lower, weathered, well-cemented, harder bedrock. Such a contrast establishes a permeability barrier, ideal for the rapid build-up of pore-water pressures during intense rainfall (Campbell, 1975). No ground-water level measurements were available near such sites; however, because no seepage was observed from scars following major storms, dissipation of pore pressures is probably very rapid. These slides were neither associated with topographic locations of ground-water flow convergence nor with sites of previous instability, but showed preference for locations where bedrock could serve as a shallow permeability barrier and infiltration of rainwater above the drainage capacity of the soil rapidly raised the pore-water pressure.

Storm Intensity and Duration

The frequency and distribution of these three categories of ground failures was related to the intensity and duration characteristics of individual storms. Although in most instances several types of ground failures occurred in a given storm, deep slumps in soils usually occurred only for long duration, moderate intensity storms (Table 1; storms 1, 2, 5); whereas, very shallow slides of soil over bedrock occurred for short-duration, high-intensity storms (Table 1; storms 4 and 8). Shallow slumps and slides occurred during both types of storms and in the other storms whose characteristics fell in the intermediate range of these two extremes.

The February 13, 1979, storm (Table 1, storm 2) is the best example of a storm of long duration and moderate intensity that triggered a deep slump in thick soil. The maximum hourly intensity was a moderate 1.0 cm/hr; however, the storm maintained an intensity of at least 0.25 cm/hr for 9 consecutive hr. With the exception of the January 3–5, 1982, storm, this duration of moderate intensity continuous rainfall was unequalled by any other storm (Table 1).

This slump started on a slope of only 20° at a low position below an extremely concave drainage (see Fig. 3). Because of this concave topography, ground water would discharge and pore

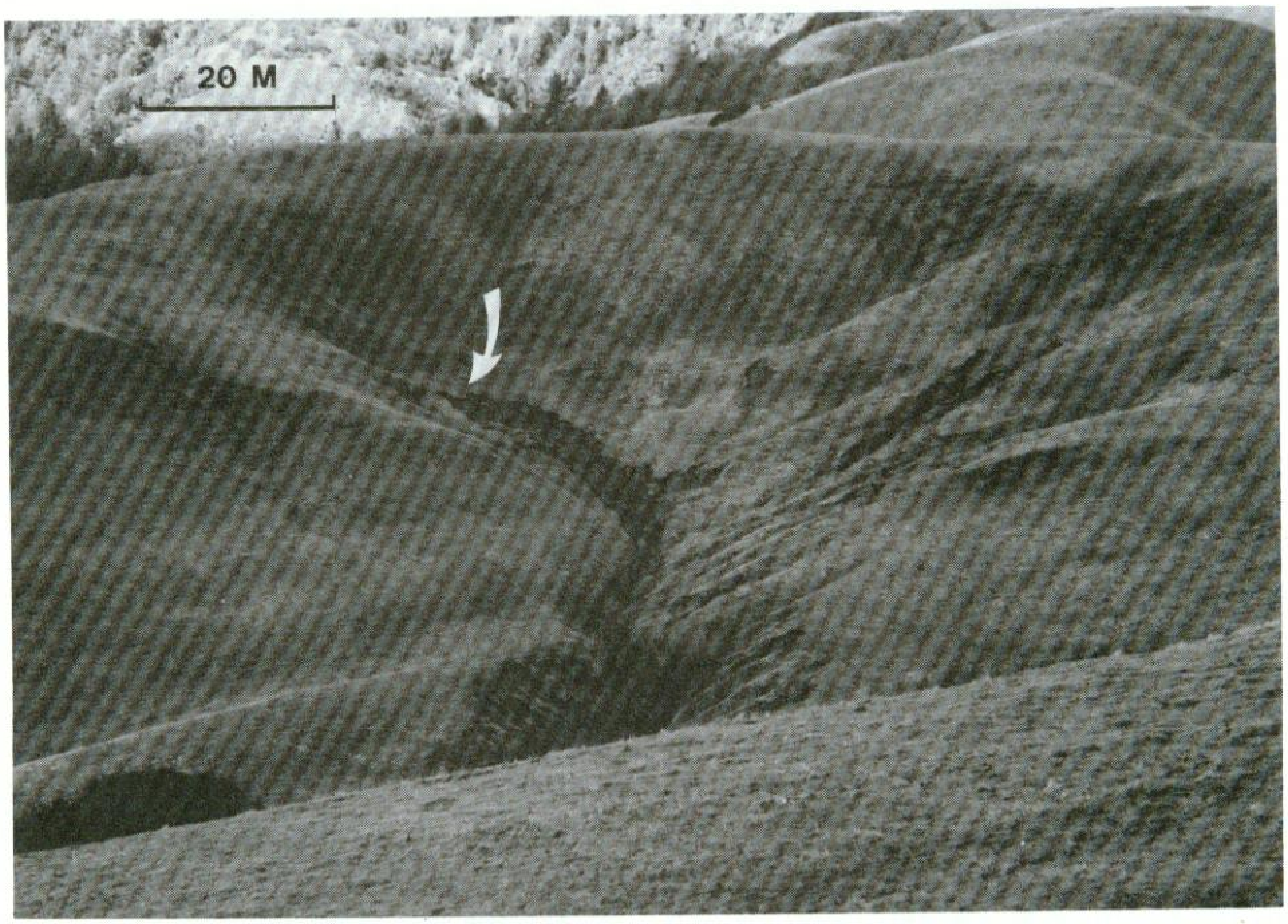

Figure 3. Debris flow from February 13, 1979, storm that originated as deep slump in soil below concave hillside. Width of main scarp (arrow) is approximately 11 m across. Average slope near slump is 20°. From scarp, debris flow traveled approximately 60 m.

pressures would be exceptionally high where this slump initiated during rainfall of long duration and moderate intensity.

The January 26, 1983, storm (Table 1, storm 8) best illustrates a short-duration, high-intensity storm that predominantly triggered shallow soil slides over bedrock (Table 3). The main burst of the storm lasted only 4 hr, during which 6.35 cm of rain fell; toward the end of the burst, a maximum hourly intensity of 2.44 cm/hr was achieved. This high intensity far exceeded that measured in any storm in this area during the period of observation (Table 1).

In this storm debris flows started on steep, planar slopes ranging from 32° to 43°, where ground-water flow convergence from adjacent hillsides was minimal. In the empty scar from where the soil mobilized (Fig. 4), no seepage from underlying bedrock was observed, so these failures resulted from rainfall having an intensity exceeding percolation and from interflow rates that saturated the soil and developed high pore-water pressures in the thin soil over less permeable bedrock.

The January 3–5, 1982, storm (Table 1, storm 5) was exceptional, because both abundant deep slumps and shallow slides over bedrock occurred (Table 3). The maximum hourly intensity—1.07 cm/hr after 16 consecutive hr of moderate-intensity rainfall—was only moderately high but probably sufficient to build high pore-water pressures that triggered the very shallow soil slides over bedrock surfaces. Likewise, the long total duration (19.2 hr) of moderate intensity rainfall (equal to or exceeding 0.25 cm/hr) was probably sufficient to build high pore pressures in deep soils that started deep slumps.

DISCUSSION

A preliminary model is proposed to account for the types of initial ground failures where debris flows occurred in this area during storms with different combinations of intensity and duration. The model qualitatively relates the rates of infiltration of rainfall to storage, drainage, and pore-water pressure with respect to different geologic and topographic hillside conditions. The model considers only a few basic factors that were observed or measured and relies on several assumptions. The following factors act as independent variables influencing pore-water pressure: relative depth of soil, position on a hillside profile, hillside shape, and storm intensity and duration. Increases in pore-water pressure are assumed to have been the principal triggering mechanism of debris flows.

Soils were assumed uniform with respect to strength and drainage characteristics with depth because soils from the several different geologic units are similar in grain size, plasticity, and mineralogy (Wieczorek, 1982). A relatively impermeable stratum, such as weathered bedrock, was assumed to exist beneath the soil. This impermeable stratum is necessary for the build-up of temporary pore-water pressures in a manner similar to that proposed by Campbell (1975). In situations in which the bedrock

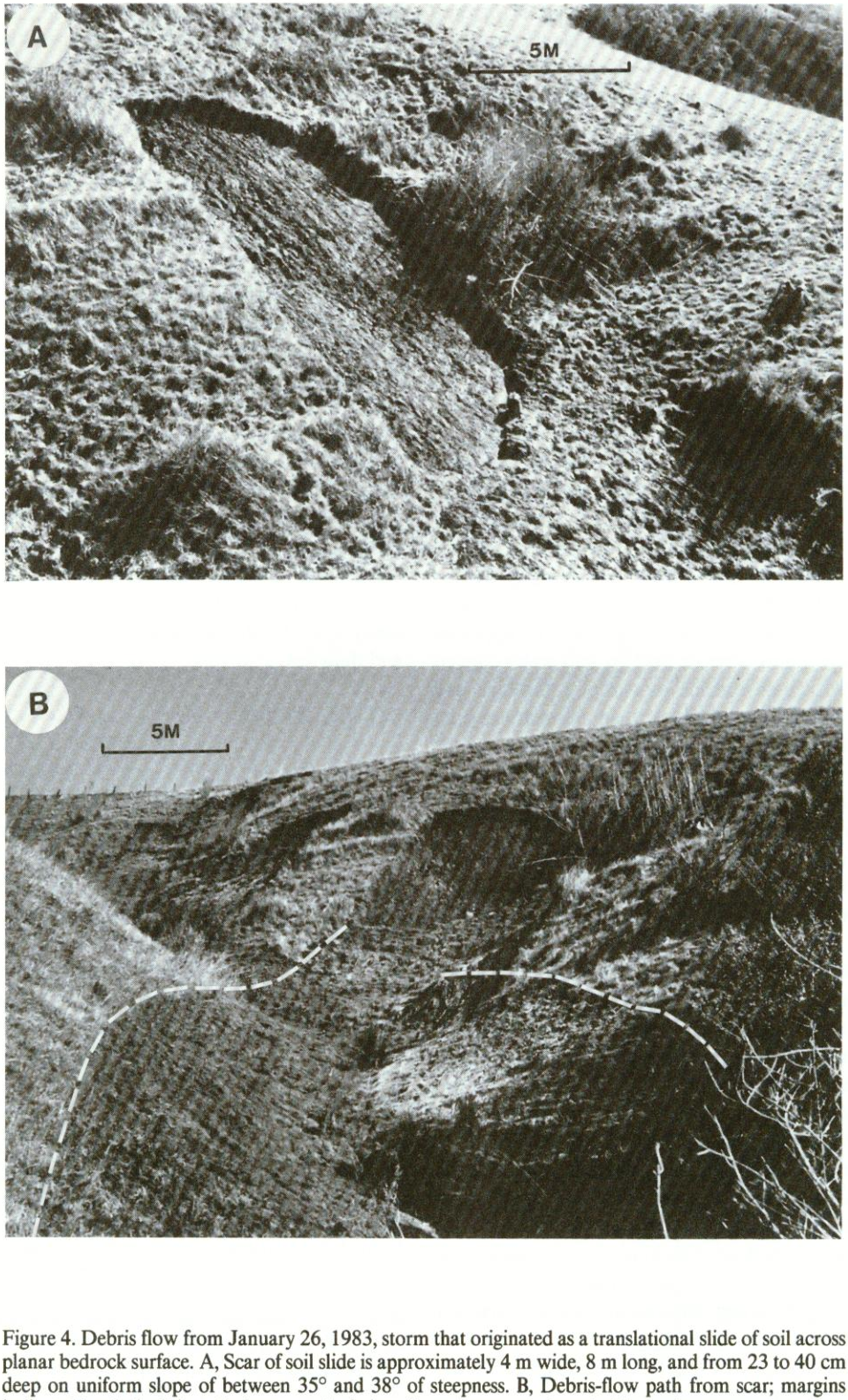

Figure 4. Debris flow from January 26, 1983, storm that originated as a translational slide of soil across planar bedrock surface. A, Scar of soil slide is approximately 4 m wide, 8 m long, and from 23 to 40 cm deep on uniform slope of between 35° and 38° of steepness. B, Debris-flow path from scar; margins indicated by dashed lines. In foreground of view, flow was approximately 70 cm deep.

surface was exposed at the base of debris flow scars, the marked contrast in strength and permeability was noticeable. However, in deeper soils in which bedrock was not directly observed, the impermeable stratum influencing pore-water pressure exists at some undetermined shallow depth.

Several additional assumptions have been made for this model: (1) flow and development of pore pressure occurred in a fully saturated soil, without separately accounting for the partly saturated zone; (2) there was no significant inflow or outflow from bedrock; (3) because of low amounts of runoff observed in intermittent streams during storms, infiltration was the dominant hillside process; and (4) gully erosion caused by surface runoff or undercutting of slopes by streams had minimal effect on triggering debris flows.

The model to depict the hillside conditions where the ground failures led to debris flows can be represented by three geologic settings and flow conditions within soil-block elements. In the first case (Fig. 5A), a shallow bedrock surface exists beneath a thin soil on a planar slope at the middle to upper part of a very steep hillside. Permeability of soil (K_S) greatly exceeds that of bedrock (K_{BD}), resulting in a shallow permeability barrier. Low-intensity rainfall infiltrates and drains (Q_{OUT}) rapidly through the thin soil because of the steep slope, without appreciable build-up of pore pressure. There is little ground-water convergence because of the planar upslope topography; through- and side-flow contributions (Q_{TF} and Q_{SF}) to an element are minimal, and direct infiltration (Q_{INF}) supplies most of the ground water. Because soil elements of this type are quite thin ($D = 0.2$ to 0.5 m) and moisture storage is small, direct infiltration of high-intensity rainfall for relatively short duration is sufficient for saturation. As subsequent high-intensity rainfall infiltrates more rapidly than the soil can drain, the soil builds a perched ground-water table that can reach critical values of pore pressure and cause failure.

An example at the other end of the spectrum is a thick soil ($D = 1$ to 3 m) on a middle to low position below a concave hillside (Fig. 5B). In this situation thick soils require more water than thin soils for saturation before downslope drainage begins. Bedrock or another low-permeability barrier perches ground water during the later stages of and/or following long-duration storms. Contributions of base flow (Q_{BF}) may be into or out of this soil-block element; small flow contributions from bedrock have even been measured in some situations (Hayes, 1985), although they are not judged significant for this model. In the element, through- and side-flow contributions (Q_{TF} and Q_{SF}) from upslope concave hillsides converge and may greatly exceed direct infiltration (Q_{INF}). When infiltration, through-flow and side-flow contributions (Q_{INF}, Q_{TF}, Q_{SF}) combine to exceed outflow and base flow (Q_{OUT} and Q_{BF}), a perched ground-water table is formed and pore pressures develop.

Because of the greater soil thickness and longer flow paths down the hillsides for side-flow and through-flow, greater time is required to maximize flow and the pore-water pressure response. This response time depends on the size of the drainage and the location within the drainage. The longer the flow paths are, the longer is the time necessary for pore pressure to maximize.

Because of the maximizing effect of flow convergence from through- and side-flow contributions, rainfall intensity and direct infiltration need not be as great to generate similar values of pore pressure as for planar slopes (Reneau and others, 1984). However, with lower intensity rainfall, storms of long duration are necessary to develop critical levels of pore pressures at such locations.

An intermediate condition to these first two cases is represented in Figure 5C. In this case, shallow soil slumps and slides occurred on steep planar and slightly concave slopes without any particular preferred hillside location with respect to ground-water convergence. The intermediate range of depth ($D = 0.3$ to 1.0 m) and the planar to slightly concave location suggest that direct infiltration, as well as some minor contribution from through-flow and side-flow, combine to generate high pore-water pressures. These ground failures occurred in storms without exceptionally high values of duration and intensity, such as storms 3, 4, 6, 9, and 10 (Table 1). Because they frequently occurred at oversteepened locations or at locations modified by previous slope failures, their stability was initially marginal and easily upset by storms having an intermediate range of intensity and duration.

CONCLUSIONS

Antecedent rainfall and duration of continuous moderate- to high-intensity rainfall are important factors determining *whether* debris flows will occur. Rainfall intensity and duration, are also significant in determining *where* debris flows initiate; however, other factors including slope steepness, hillside topography, soil thickness, and the presence of an impermeable barrier are important as well. Storms of long duration and moderate intensity can cause debris flows that initiate as slumps in thick soils on moderate slopes beneath concave hillsides where ground-water flow converges. Storms of short duration and high-intensity can trigger

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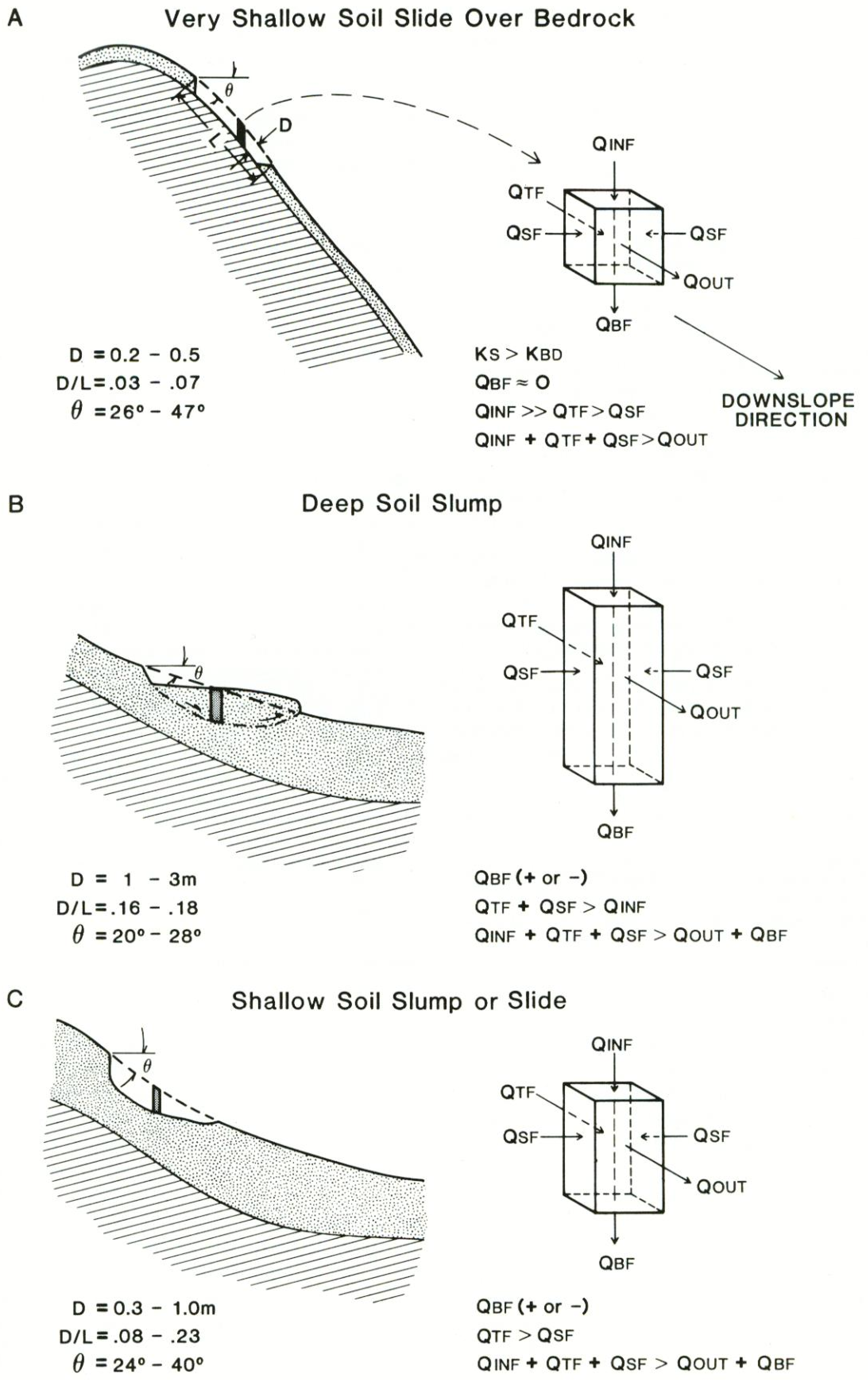
Figure 5. Typical sites of debris-flow initiation and soil-block elements to represent permeability and flow conditions. Sites have original average ground-surface slope of angle, θ; maximum depth of slide, D; maximum length, L. Original slope indicated by dashed line; soil, by dotted pattern; bedrock, by slanted pattern. Key abbreviations for flow, Q, and permeability K for the soil-block elements; Q_{INF} = infiltration, Q_{TF} = throughflow into element from upslope, Q_{SF} = sideflow, Q_{BF} = base flow, Q_{OUT} = outflow, K_{BD} = permeability of bedrock, K_S = permeability of soil. A, Very shallow soil slide over planar bedrock surface, commonly on planar to convex middle to upper portion of hillside. B, Deep soil slump at middle to low position on concave hillside, influenced by ground-water flow convergence from upslope drainage. Rotational movement of slump over basal slide surface indicated by arrows. C, Shallow soil slump or slide at middle to upper portion of planar to slightly concave hillside. Location is influenced by oversteepening or modifications in local hillside geometry.


A
Very Shallow Soil Slide Over Bedrock
θ
D
L
QINF
QTF
QSF
QSF
QOUT
QBF
DOWNSLOPE DIRECTION
D = 0.2 - 0.5
D/L = .03 - .07
θ = 26° - 47°
KS > KBD
QBF ≈ O
QINF >> QTF > QSF
QINF + QTF + QSF > QOUT
B
Deep Soil Slump
θ
QINF
QTF
QSF
QSF
QOUT
QBF
D = 1 - 3m
D/L = .16 - .18
θ = 20° - 28°
QBF (+ or -)
QTF + QSF > QINF
QINF + QTF + QSF > QOUT + QBF
C
Shallow Soil Slump or Slide
θ
QINF
QTF
QSF
QSF
QOUT
QBF
D = 0.3 - 1.0m
D/L = .08 - .23
θ = 24° - 40°
QBF (+ or -)
QTF > QSF
QINF + QTF + QSF > QOUT + QBF

debris flows on steep planar hillsides where shallow bedrock surfaces beneath a thin soil mantle serve as an effective permeability barrier for rapid infiltration and build-up of high pore-water pressures. These observations fit a qualitative model that links geology, hydrology, and topography with storm intensity and duration.

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