CONTROLS ON THE ORIGIN AND RECURRENCE OF DEBRIS FLOWS IN THE HUACHUCA MOUNTAINS, SOUTHEASTERN ARIZONA

by

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ABSTRACT

Numerous debris flows occurred in the Huachuca Mountains of southeastern Arizona during the summer rainy season of 1988 in areas that were burned by a forest fire earlier in the summer. Debris flows occurred following a major forest fire in 1977 as well, suggesting a causative link beween fires and debris flows. Abundant evidence of older debris flows preserved along channels and in mountain front fans indicates that debris flows have occurred repeatedly during the Holocene in this environment. Debris flow recurrence intervals for individual drainage basins in the study area are probably in the range of 500 to 1000 years, based on soil development in sequences of debris flow deposits.

Surface runoff in the steep drainage basins of the Huachuca Mountains is greatly enhanced following forest fires, as the hillslopes are denuded of their vegetative cover. Water and sediment eroded from the hillslope regolith are rapidly introduced into the upper reaches of tributary channels by widespread rilling and slope wash during rainfall events. This influx of water and sediment destabilizes regolith previously accumulated in the channel, triggering debris flows that scour the channel to bedrock in the upper and middle reaches. Following a debris flow, the scoured, trapezoidally-shaped channel gradually assumes a swale shape and the percentage of exposed bedrock declines, as material is introduced from the slopes. Debris flows do a tremendous amount of work in a very short time, however, and are the major channel-forming events.

Where the tributary channels enter larger, trunk channels, the debris flows serve as the main source of very coarse sediment. The local slope and coarse particle distribution of the trunk channel depends on the competence of the channel to transport the material introduced by debris flows. Where the smaller channels drain directly to the mountain front, debris flows create extensive debris fans which dominate the morphology of the basin-range boundary.

Recurrence intervals between debris flows in the drainage basins of the Huachuca Mountains are probably controlled by complex interactions among climate, forest fires, and slope processes. Fires destroy the protective vegetation that stabilizes the upper catchment slopes and inhibits erosion. However, not every fire that burns a catchment causes debris flows, because sufficient weathered material must accumulate in the upper channel reaches to initiate a large debris flow. If such accumulation has not occurred, the material introduced to a channel following a forest fire will move only a short distance down the channel. Thus, the episodicity of debris flows probably depends on rates of slope weathering and erosion, which are in turn controlled by climate, both directly and through vegetation and forest fires.

INTRODUCTION

A debris flow damaged a cluster of houses on an alluvial fan at the base of the southern portion of the Huachuca Mountains in

July 1988. Initially, the intent of our study was to characterize this single debris flow, but a reconnaissance of other drainages in the area revealed evidence of many contemporary and older debris flows. By examining evidence left by historical debris flows, which occurred in 1988 and 1977, and debris-flow deposits going back to the Pleistocene, we were able to draw inferences about recurrence intervals and the geomorphic role of debris flows in this semiarid mountain range.

Debris flows are slurry flows of poorly-sorted rock and soil debris mixed with 10-20% water (Costa, 1984). Debris flows have a strength and viscosity much higher than those of water flows, and are responsible for significant erosion and deposition in a wide range of environments (Patton, 1988). They have been reported in humid temperate mountains (Pierson, 1980; Osterkamp and others, 1986; Church and Miles, 1987; Kochel, 1987; Mills, 1989), alpine regions (Eisbacher and Klague, 1984; Kotarba and others, 1987; Van Steijn and others, 1988), and arid and semiarid regions (Blackwelder, 1928; Scott, 1971; Brown, 1972; Campbell, 1975; Costa and Jarrett, 1981; Webb and others, 1987; Wells, 1987; Beaty, 1990).

Debris flow studies in the arid/semiarid southwestern United States have largely concentrated on the chaparral environments of southern California, following the lead of Eaton (1935). These ecosystems are subject to periodic fires (Hanes, 1977). The fire season is followed by the winter rainy season, when denuded hillslopes, underlain by a layer of water-repellent soil formed

during the fires, are swiftly gullied and destabilized (Wells, 1987). With the exception of the work of Beaty (1990) in the White Mountains, studies of debris flows in southern California have concentrated primarily on the hillslope processes active in a basin immediately following a fire, rather than on the long-term recurrence intervals of debris flows, and their role in channel and slope evolution. Our work in the Huachuca Mountains differs in that we are concentrating on the long-term geomorphic effects of debris flows in a tectonically stable, semiarid mountain region.

PHYSICAL SETTING

The physical characteristics of the drainage basins and the climate of the area are important variables that contribute to the occurrence of debris flows in the Huachuca Mountains of southeastern Arizona (Figure 1). The study area ranges in elevation from 1300 to 2300 meters, with vegetation grading upward from grasslands to manzanita-scrub oak, pinyon-juniper, and ponderosa pine-Douglas fir forests. The catchments drain areas of 0.25 to 13.0 km^2, on slopes underlain by siliceous volcanics, quartz monzonite, and dolomites and limestones. Basins tend to be elongate in shape (S_e averages 0.56), with steep slopes, and face north and east. Some small debris flows occurred on south-facing slopes, but these slopes tend to have lower drainage densities and less dissection than north- or east-facing slopes. Slope regolith is also thicker on north- and

east-facing slopes, reaching thicknesses of one meter, while it seldom reaches a half meter in thickness on southward slopes.

Relatively intense, short-lived precipitation events are fairly common in and around the Huachuca Mountains. Annual precipitation over the area averages 64 cm, most of which falls in the late summer rainy season (Sellers and Hill, 1974). The high intensity "summer monsoon" rains of early July to early September typically occur as scattered convectional thunderstorms triggered and enhanced by intense surface heating and orographic effects. Summer moisture comes from two sources; (1) southeasterly flow around the western limb of the Bermuda high, which entrains moist air from the Gulf of Mexico into Arizona, and (2) tropical storms and associated cutoff lows or low-pressure troughs from the eastern North Pacific that move inland or dissipate off of Baja California (Hirschboeck, 1985; Reyes and Cadet, 1988). A secondary precipitation maximum occurs in November-April, from cyclonic storms and frontal systems associated with large scale low pressure systems traveling in the belt of upper air westerly wind flow. Summer rains exhibit greater spatial variability but lesser temporal variability than winter rains.

CHARACTERISTICS OF THE 1988 DEBRIS FLOWS

A substantial portion of the southern Huachuca Mountains was burned during a forest fire in mid-June 1988. Approximately a month later, rainfall associated with summer thunderstorms

triggered a series of debris flows in small tributary canyons affected by the fire (Figure 2). Two of these debris flows, in Dorothy Ryan and Manzanita Canyons, are representative of the types of canyons in which debris flows occurred, and the effect of the flows on the surrounding geomorphic systems.

Velocities and peak discharges of debris flows can be estimated from the superelevation of flow at channel bends. Elevation difference across the bend (h_c), effective channel width (W), and the radius of curvature (R_c), may be used to calculate mean velocity (v) around a bend:

$$v = [gR_c h_c/W]^{0.5}$$

where g is gravitational acceleration (Johnson, 1979; Webb and others, 1987). The resultant discharge, Q, is then estimated from

$$Q = A\ v$$

where A is cross-sectional area. As noted by Webb and others (1987), there is substantial uncertainty in velocity estimates determined using the elevation differences in flow-surface profiles across a bend, judging by comparisons to actual velocities on the basis of measured travel times. Therefore, the velocities given above are only approximations. Costa (1984) notes that the errors in this approach are comparable to those for other indirect methods of calculating debris flow velocity.

Dorothy Ryan Canyon, named after one of the individuals who suffered property damage following the 1988 fire and debris flow,

drains the northern slope of Bob Thompson Peak. The 1.25 km^2 catchment is formed on siliceous volcanics, with a relief ratio (H/L) of 0.33. Channel slopes range from 1.5° to 40°, but tend to be in the range of 6°-15°. Hillslopes in the upper drainage basin are steep, typically 30° to 40°. The channel drains directly to the mountain front, rather than into a larger channel, and has formed a debris fan at the basin-range boundary. Measurements of the debris deposited on this fan by the 1988 flow indicate that it had a volume of approximately 13,000 m^3. Estimated peak velocities ranged from about 2 to 4 m/s , with peak discharges of 48-75 m^3/s (Table 1).

Manzanita Canyon drains the north slope of Ash Peak, and is tributary to the South Fork of Ash Canyon. The 0.60 km^2 Manzanita catchment is underlain by siliceous volcanics and Naco Group carbonates, with a relief ratio of 0.38. Channel slopes average 6°-10°. The 1988 debris flow had a volume of about 10,000 m^3, with peak velocities of approximately 2-7 m/s; peak discharges are poorly constrained, but probably were between 20 and 100 m^3/s. Both the Dorothy Ryan and Manzanita debris flows qualify as mediumscale debris flows in Innes' (1983) classification.

EVIDENCE FOR PRE-1988 DEBRIS FLOWS

Abundant evidence of debris flows that occurred prior to 1988 in canyons of the Huachuca Mountains indicates that debris flows are important geomorphic processes in these fluvial

systems. Evidence of debris flows falls into three general categories: (1) very young deposits representing debris flows that probably occurred subsequent to a major fire in 1977; (2) older debris flow deposits in forested areas that have not burned in several decades or more; and (3) sequences of debris flow deposits along the drainages that experienced debris flows in 1988.

A major fire burned much of the central Huachuca Mountains in the summer of 1977 (see figure 2). A destructive "flood" was reported on a tributary of Miller Creek in 1977 following the fire (National Forest Service, unpublished report, 1978). We examined photographs of flood damage and deposits taken in 1977, and visited the site of the flooding. Based on the very coarse and very poorly sorted deposits, and the extent of channel scour farther upstream, we conclude that this "flood" was actually a debris flow. Similar physical evidence of recent debris flow activity was found in the steep upper portions of Stump and Hunter Canyons as well (figure 3), implying that numerous debris flows occurred following the fire of 1977.

Physical evidence of debris flows along drainages that were not burned in either 1988 or 1977 consists primarily of coarse boulder lobes in channels, exposures of very poorly sorted deposits with large clasts supported by a fine matrix, and local boulder levees. Brown Canyon, in the northernmost portion of the study area (figure 1), was not burned in either 1977 or 1988. Probable debris flow deposits are common in steep tributary

drainages to Brown Canyon and in the upper reaches of Brown Creek itself. The ages of these debris flows are not known, but mature trees growing on the deposits indicate that they are of some antiquity.

Several debris-flow deposits with soil profiles developed in them are exposed in Dorothy Ryan Canyon at a site about 200 m upstream from the head of the alluvial fan. The time that these deposits were at the surface prior to burial, and the approximate ages of these deposits, can be estimated by comparing soil properties with soils of other chronosequences developed in southern New Mexico and Arizona (for example, Gile and others, 1981; Pearthree and Calvo, 1987).

Four distinct pre-1988 sedimentary units, probably ranging in age from late Pleistocene to late Holocene, are exposed in the channel wall at one location along Dorothy Ryan Creek (figure 4; table 2). The lowermost deposit (Unit 4) is clearly a debris flow deposit, containing large boulders in a fine matrix. This unit has a moderately strong soil developed in it. The reddening and textural increase from the paleosurficial horizon (4A) to the buried argillic horizon (4Bt1, 4Bt2, and 4Bt3) implies that this unit (1) was at the surface for a substantial length of time prior to burial, and (2) dates to at least the latest Pleistocene. The next higher deposit (Unit 3) likely represents a Holocene debris flow. It is extremely poorly sorted, containing cobbles and small boulders, fine matrix, and abundant flecks of charcoal. This unit has a modest soil profile

developed on it, with a surficial horizon (3A) and a weak argillic horizon (3Bt), suggesting that it was exposed for several thousand years or more prior to burial; it may be of early Holocene age. Unit 2 is predominantly pebbles and cobbles, and clasts exhibit a weak imbrication, implying that it is a water-laid deposit. There is no clear evidence of a soil profile specifically associated with this unit, although there is a slight textural increase between the upper (2C1) and lower (2C2) horizons. The lack of soil-profile development suggests that this unit was buried by Unit 1 fairly soon after it was deposited.

Evidence for the time since the last large debris flow in Dorothy Ryan Canyon is contained in the youngest prehistoric debris flow deposit in this stratigraphic exposure (Unit 1). This deposit has a weak soil profile developed in it, composed of a surficial A horizon and cambic (weak structural) B horizon. Soil profiles like this develop over periods of several hundred to several thousand years in this region (Gile and others, 1981; Pearthree and others, 1990). The 1988 debris flow barely overtopped the bank at this location, leaving scattered debris on the surface but no clear depositional evidence at this exposure. This suggests that no debris flows large enough to overtop the bank at this location occurred for hundreds to several thousand years prior to 1988.

The soil profile developed on Unit 1 and the number of Holocene debris-flow deposits evident in this exposure suggest

that intervals between occurrences of large debris flows in this area are fairly long. There is physical evidence of only three Holocene debris flows (two in the exposure and the 1988 event), suggesting a several thousand year recurrence interval for large debris flows. Soil profiles developed in the debris flow deposits suggest hundreds to a few thousand years of nondeposition between debris flows. Clearly, however, this one exposure may not provide a complete record of Holocene debris flows. At this time, an estimate of several hundred to several thousand years for debris flow recurrence seems reasonable. Proposed radiocarbon dating and development of tree-ring chronologies may provide more accurate estimates of recurrence intervals. The estimated recurrence interval for the Huachuca debris flows is longer than the more tightly-constrained 300-350 year recurrence interval for debris flows in the White Mountains of California (Beaty, 1990).

GEOMORPHIC EFFECTS OF DEBRIS FLOWS ON FLUVIAL SYSTEMS

The Huachuca Mountains offer a unique opportunity to study the short-term recovery of channels and slopes after debris flows associated with forest fires because portions of the range were burned in 1977 and 1988, while other portions have been unaffected by forest fires or debris flows for at least twenty years. We examined the effects of debris flows on three geomorphic components; tributary channels, trunk channels, and mountain front fans.

Tributary channels

Debris flows occur in relatively small, steep drainage basins like Dorothy Ryan and Manzanita Canyons. Examination of the Dorothy Ryan catchment soon after the 1988 debris flow indicated that the flow did not have a discrete failure source, such as a slump or a landslide. Rather, the steep upper portion of the basin, which was severely burned, had widespread rilling and soil creep. Debris flow mobilization from rilling has also been described in central California (Johnson and Rodine, 1984). The rapid introduction of material into the uppermost channels of Dorothy Ryan canyon as a result of rilling and slopewash apparently destabilized the weathered material previously accumulated there, triggering the debris flow.

As the flow moved downward, it scoured the channel to bedrock, creating a cross-sectionally trapezoidal trench (Figure 5a). Deposition occurred locally where slope and/or confinement decreased. In the lower portion of the catchment the flow incised a channel into older debris flow deposits, as well as creating new overbank deposits. This flow, like most of those observed in the Huachucas, is a valley-confined flow (Brunsden, 1979; Innes, 1983), and therefore does not have the extensive, well-developed levees often seen on debris flows in alpine areas (Van Steijn and others, 1988).

Examination of tributary channels scoured by debris flows in 1977 and earlier indicates that, with time, these channels assume a more swale-like cross-section as material moves down from the

valley side walls and the upstream reaches of the catchment. The percentage of bedrock exposed in the channel decreases with time, and the percentage of material sand-sized or finer increases (Figure 5d).

Debris flows appear to be the channel-forming events on these tributary drainages. Subsequent water flows gradually modify the upper reaches of the channel, and incise the lower reaches, where the debris flows are depositional. Channel cross-sections during and immediately after the debris flow are limited on the bed by the erosional resistance of the bedrock, and in the banks by bedrock, the binding effect of tree and shrub roots, and the large particle size and induration of older debris flow deposits.

Trunk channels

Where the tributary channels drain into trunk channels, debris flows serve as the main source of coarse (greater than 1/2 m diameter) sediment. The degree to which this coarse sediment affects channel morphology depends on catchment size and discharge, as is demonstrated by comparing three trunk channels.

The South Fork of Ash Creek drains 7 km^2 and has seasonal flow. Much of the catchment was burned in 1988 (Figure 2), triggering numerous debris flows in the tributary drainages, including Manzanita Canyon. Several of these flows created fans which temporarily dammed the main channel, causing local aggradation and subsequent incision. At the mouth of the Manzanita catchment, the debris dam was breached within a few

weeks of formation (Figure 6), but it caused aggradation and subsequent incision for more than a hundred meters upstream along Ash Creek. The boulders introduced by this and other flows have not been transported any significant distance downstream, so that the South Fork has a nonuniform distribution of coarse sediments (Figure 7). This is analogous to the creation and maintenance of rapids on the Colorado River in Grand Canyon National Park through the introduction of large boulders by tributary debris flows (Webb and others, 1987).

Stump Creek drains 4 km^2 and has seasonal flow. Like Ash Creek, it has a low relief ratio (0.19). The Stump Creek drainage was burned in the 1977 fire, and tributary debris flows deposited coarse sediment which subsequent water flows have not been powerful enough to re-work. These eleven-year-old boulder accumulations preserve boulder lobe and levee morphology characteristic of debris flow deposits, although the finer sediments have been winnowed by water flows (Figure 4).

Miller Creek drains 13 km^2 and has perennial flow. Much of the Miller Creek catchment was burned in the 1977 fire, and many of the tributaries contain debris flow deposits, but the main channel preserves no compelling evidence of debris flows in the form of boulder levees or lobes, or nonuniform downstream boulder distributions. The large, rounded boulders present throughout the channel appear to have been thoroughly redistributed by water flows, unlike the transport-limited Ash and Stump Creeks. Apparently the greater discharge of Miller Creek is the decisive

factor; basin elongation, relief ratio, aspect, lithology, average channel slope, and drainage density do not differ significantly among the three drainages.

There is thus a continuum in terms of the degree to which debris flow deposits affect the morphology of secondary channels. Water flows in the smallest channels, as exemplified by Stump Creek, are completely unable to re-work the debris flow deposits, so that characteristic debris flow deposit morphologies, such as boulder lobes and levees, are preserved. The water flows in larger channels, like the South Fork of Ash Creek, are competent to transport the coarse sediment introduced by debris flows short distances downstream, although the channel retains an uneven longitudinal distribution of boulders. The largest channels, such as Miller Creek, completely redistribute the boulders introduced by debris flows, so that evidence of debris flows is preserved only in tributary channels.

Mountain front alluvial fans

Where tributary channels subject to debris flows drain directly into the inter-range basin, they have created debris fans and aprons along the mountain front. Fan size and slope are controlled by the size of the contributing catchment, and the nature and frequency of debris flows. The fan deposited by the 1988 debris flow at the base of the Dorothy Ryan catchment has an areal extent of about 22,000 m^3, with slopes of 2°-3°. Water floods subsequent to the debris flow have incised to bedrock; the maximum thickness of the 1988 debris fan is about 1.5 m. The

1988 debris flow deposited boulders up to one meter in diameter on the distal portions of the fan. Following a debris flow, the debris fans are incised by water flows, so that subsequent debris flows tend to be channeled along the incised paths. The location of debris deposition shifts across the fan with time, however, creating a complex mosaic of deposits of various ages. Older deposits are well-indurated due to secondary carbonate and clay accumulation.

Geomorphic work and effectiveness of debris flows

Debris flows in the Huachucas can be considered in terms of geomorphic work, which Wolman and Miller (1960) equated with the amount of sediment transported during individual events, and geomorphic effectiveness, defined as the persistence of the effects of an individual event (Wolman and Gerson, 1978). For the tributary catchments and debris fans, debris flows are clearly the dominant events in terms of both geomorphic work and effectiveness; they transport the majority of coarse sediment carried in the tributary channels, and the impact of individual events persists longer than the recurrence interval of the events.

The geometry of the tributary channels and fans reflects the erosional and depositional action of debris flows, despite slight modification by moderately sized water flows. Similar situations have been observed in the small mountain streams of Colorado, where debris flows transport an increasingly larger percentage of material in progressively smaller and steeper basins (Costa and

Jarrett, 1981), and in the Oregon Coast Range, where episodic debris flows are the dominant sediment-transporting agent in first- and second-order basins (Benda and Dunne, 1987).

For the larger channels, the effect of moderate, more frequent water flows becomes increasingly important as catchment size increases. Debris flows perform little geomorphic work in these channels, but rather introduce coarse sediment that may be difficult for water floods to transport.

CONTROLS ON DEBRIS FLOW RECURRENCE

Several factors interact to control the occurrence of debris flows in the Huachuca Mountains. These include; (i) basin lithology, (ii) climate, particularly precipitation frequency, intensity and duration, (iii) basin slope, (iv) forest fire frequency, and extent and severity of burn, (v) thickness and extent of slope regolith, (vi) vegetation cover, particularly forest maturation time and character of ground cover, (vii) runoff and sediment yield, and (viii) channel sediment storage.

Basin lithology, in terms of the type and erosional resistance of the uppermost bedrock unit in each drainage basin, is assumed to have been constant throughout the late Quaternary. All of the other controls on debris flow occurrence are to a large extent dependent on the interrelationships among climate, forest fires, and vegetation. The record of the past 15 years indicates that debris flows in the Huachuca Mountains tend to occur after a forest fire has destroyed the vegetation on the

upper basin slopes, exposing the regolith to erosion. Charcoal was found in about one-half of the older debris flow deposits exposed along Dorothy Ryan wash, suggesting a persistent link between debris flow occurrence and fires. Therefore, the dynamics of forest fires are of prime importance in understanding debris flow occurrence.

Occurrence of Forest Fires

Forest fires in the Huachuca Mountains typically occur during the summer and autumn due to lightning strikes. The hot, dry early summer is the main fire season because lightning strikes associated with the beginning of the summer monsoon season often precede the more substantial rainfalls that occur later in the monsoon season.

The fire histories of several mountain ranges in southeastern Arizona have been compiled from Forest Service documents and fire-scar records on trees (Swetnam and Betancourt, 1990). These fire histories indicate that regional climate patterns linked to the El Nino-Southern Oscillation (ENSO) correlate with fire frequency over the last 300 years, such that ENSO events correlate with years of reduced burned acreage (Swetnam, in press; Swetnam and Betancourt, 1990). The ENSO circulation is a coupled ocean-atmosphere phenomenon that produces major sea surface temperature anomalies in the Pacific Ocean and causes large-scale disruptions of tropical and extra-tropical atmospheric circulation patterns (Rasmusson and Wallace, 1983). In the southwestern United States, ENSO events are

associated with enhanced spring and fall precipitation (Andrade and Sellers, 1988) due to a more sinuous, or meridional, flow of the westerlies, which allows dissipating tropical cyclones off the coast of Baja California to move northeast into the study region (Webb and Betancourt, in press). This influx of moisture during the critical burning period reduces fire frequency during periods of ENSO circulation (Swetnam, in press).

Forest fires in the Huachuca Mountains are also influenced by the management practices of the United States Forest Service. Rigorous fire suppression began in the early 1930s, and was associated with larger and more severe, but less frequent, fires. In the 1970s policy shifted toward controlled burns, a closer approximation of the naturally-occurring, high frequency, low intensity burns (Swetnam, in press).

The effects of management practices are superimposed on the larger-scale controls of forest maturation and climate. Swetnam (in press) found that large fire years tend to occur a year or two after severe ENSO events, regardless of management strategies, and that there are regional-fire years in the southwestern United States, in which many sites simultaneously have large fires. Over several centuries prior to the fire suppression era, mean fire recurrence intervals throughout the southwestern United States for the mixed-conifer vegetation of the mountane canyons range from six to ten years. Intervals between intense, crown-burning fires like those that swept the mountain sides of the Huachucas in 1977 and 1988 must be longer,

however, because the trees were essentially completely burned in much of the fire area. Recurrence intervals between fires in the oak-juniper woodlands on the lower slopes are probably closer to fifty to a hundred years, based on analogy with the chaparral areas of southern California. Historically, even large fires have not extended over the entire Huachuca range, creating a mosaic effect with burned and unburned areas.

Precipitation Characteristics

The rainfall that triggered the debris flow in Dorothy Ryan Canyon apparently was not extreme. Figure 8a shows the daily rainfall totals for the summer of 1988 from Coronado National Monument headquarters, located about 3 km southeast of Dorothy Ryan Canyon. The debris flow occurred on July 11; although recorded rainfall on this date was modest, it was the fifth consecutive day with measurable precipitation, so soil moisture content may have been high. Measurements of rainfall intensity are not available, but local residents reported that it rained heavily on the mountain for about 10 to 15 minutes prior to occurrence of the debris flow. Figure 8b illustrates monthly precipitation values for the period of record. Although the total precipitation for July 1988 was above average, it did not reach the historical extreme, and much of the rainfall occurred late in the month, after the debris flow at Dorothy Ryan Canyon.

An extreme rainfall apparently is not necessary to trigger a debris flow in the Huachuca Mountains, although a period of frequent rains may be required. Similar conclusions have been

reached for southwestern British Columbia (Church and Miles, 1987), New Zealand (Pierson, 1980), southern California (Weirich, 1987; Wells and others, 1987), and Colorado (Costa and Jarrett, 1981). Caine (1980) has expressed the threshold for debris flow occurrence numerically through a limiting curve relating rainfall intensity and duration. Unfortunately, precipitation intensity and duration values are not available for the Huachuca Mountains.

Channel Sediment Accumulation

Accumulation of sediment in the channel, particularly in the upper reaches, is probably the primary limiting control on debris flows. We have reached this conclusion because the fires in any one basin that heads in the upper elevations of the range occur fairly frequently, and relatively intense rainfall is quite common during the summer "monsoon" season in southeastern Arizona.

Rainfall following a forest fire will not necessarily trigger a debris flow. We observed a tributary drainage on the upper reaches of the South Fork of Ash Creek that was burned in the 1988 fire, but did not have any debris flows. In terms of size, slope, lithology, vegetation, and degree of burn, this tributary was similar to neighboring small drainages that did have debris flows in 1988. However, we observed relatively young, pre-1988 debris flow deposits, indicating that the tributary had a recent debris flow prior to the fire of 1988. The absence of a 1988 debris flow suggests that not enough weathered material had accumulated in the channel to facilitate

destabilization and debris flow. Costa and Jarrett (1981) noted that the rates of weathering and colluvium formation are an important control on debris flow occurrence in the small mountain basins of Colorado, and similar conclusions were reached for southern California (Florsheim and Keller, 1987), southwestern Norway (Innes, 1985), China (Zicheng and Jing, 1987), British Columbia (Bovis and Dagg, 1987), and the Scottish highlands (Ballantyne, 1986; Brazier and Ballantyne, 1989).

Sediment likely accumulates in channels in upper watershed areas through the gradual introduction of weathered hillslope materials by processes like rilling and soil creep. These slope processes operate continuously, but they are greatly enhanced following a forest fire, when the ground cover of leaf litter and small shrubs is destroyed. We observed the formation of 5 cm deep rills within minutes during a heavy thunderstorm rainfall on the burned upper slopes of the Dorothy Ryan drainage in September 1988. The enhancement of rilling is probably due to a combination of destruction of the surface vegetation, enhancing the erosive impact of raindrops, and formation of a hydrophobic soil layer during the fire. Organic molecules formed by the burning of surface litter are driven a few millimeters downward into the regolith, where they coat individual soil particles, creating a water-repellent layer (Wells, 1987). The presence of a hydrophobic soil layer, and the shallow depth to bedrock both on the slopes and in the tributary channels, would promote high pore water pressures and the buildup of a temporary perched water

table during heavy thunderstorm rains, facilitating soil movement (Howard and others, 1982; Innes, 1983; Van Steijn and others, 1988). The rapid development of extensive rill networks on burned slopes in southern California due to a hydrophobic soil layer has been described by Wells (1987).

When slope material is introduced into the channel, particularly the steep upper reaches, it may; (1) remain essentially in place, because the resistance to movement caused by roughness or other retarding factors is greater than the transporting ability of the water flow, (2) flow a short way down the channel as a water flow or a small debris flow that stops at the first local reduction in slope, or (3) become incorporated in a full-scale debris flow which sweeps down the entire length of the channel, scouring the channel to bedrock as it goes. The distinction between these three alternatives will depend on; (i) the amount of water and sediment entering the channel from the slopes, and thus the antecedent soil moisture conditions, the thickness of slope regolith, the characteristics of the rainfall, and the extent, severity, and timing of the burn, and (ii) the condition of the channel itself - specifically, channel slope, cross-sectional geometry, and irregularity, and the stability and amount of material overlying bedrock in the channel. In order for a full-scale debris flow to occur in the Huachuca channels, where moderate amounts of material are introduced by rilling during rainstorms, rather than large amounts by slope failure, sufficient material must have accumulated in the channel prior to

the fire-rainfall events (Figure 9).

This requirement imposes a minimum recurrence interval on debris flows, and is presumably more of a limiting factor than either sufficient rainfall, which occurs frequently, or forest fires, which may recur every few decades on the basin hillsides. Based on surveys of channels affected by debris flows in 1977, at least ten years, and probably many more, are required before sufficient material accumulates in a channel following a debris flow.

The slope of the channel, and the amount of exposed bedrock, may also be crucial in triggering large debris flows. The upper reaches of tributary channels in the Huachucas have irregular, stepped gradients, with very steep bedrock reaches alternating with reaches of lower slope. These steep reaches may serve as collecting or concentrating areas for water and sediment, which accelerate down the steep reaches and can then rip out material stabilized by vegetation in the reaches of lower slope. Erosion by strong gushes of water has been considered one of the four general means by which debris flows can mobilize by Johnson and Hampton (1969).

CONCLUSIONS

Debris flows originating in tributary catchments on the upper slopes of the Huachuca Mountains play an important role in shaping channel morphology in the region. These flows have occurred throughout the late Quaternary, indicating that they are

a normal geomorphic process in this region of tectonic stability and resistant bedrock. Debris flows probably occur very infrequently in individual drainage basins. Because of the tremendous amount of work they accomplish, however, they are the major channel-forming events in the tributary catchments, scouring to bedrock and creating channels that are trapezoidal in cross-section. The angles between the bed and banks, and the percentage of exposed bedrock, gradually decrease as weathered slope material accumulates, but the channel retains its overall trapezoidal shape. Where these tributary channels drain directly to the inter-range basin, debris flow deposits form fans and aprons of varying steepness and size. Where the tributary channels enter larger channels, debris flow deposits affect channel morphology through the introduction of very coarse sediment. The degree to which channel slope and the downstream distribution of coarse particles are controlled by debris flow deposits depends on the size and discharge of the main channel.

Debris flows in the Huachucas originate from widespread rilling and slope wash in the upper tributary catchments following destabilization of the upper slopes after forest fires. In order to understand the long-term controls on debris flow recurrence, and thus the geomorphic effectiveness of debris flows, the relationship of forest fires and climate, and of fires and debris flows, must be determined. Because debris flows exert a significant control on channel morphology in the Huachuca Mountains, their episodic nature raises interesting

possibilities. If the frequency of debris flow occurrence has varied through time, then presumably the rate and nature of channel adjustment to debris flows has also varied. It may be that climate and fire control the tempo of debris-flow-related geomorphic change in the Huachucas. Periods of enhanced ENSO circulation and reduced fire frequency produce fewer, but larger, fires, which may facilitate the initiation of debris flows in the steep upper reaches of drainage basins; periods of fairly frequent, small fires may result in more rapid rates of channel and hillslope erosion and more rapid accumulation of weathered material in the channels, leading to a shorter recurrence interval for debris flows. Increased understanding of the factors that control of debris flow occurrence in this semiarid montane environment would provide a baseline for comparison with debris flows in other regions.

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List of Figures

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4. Schematic illustration of the stratigraphic units and soils exposed in a natural exposure near the mouth of Dorothy Ryan Canyon. Four distinct pre-1988 depositional units are apparent,

Canyon. Four distinct pre-1988 depositional units are apparent, three of which are interpreted to be debris flow deposits. A fairly distinct soil profile developed in each of the debris flow deposits, indicating that its upper surface formed the land surface for a substantial period. Soil profiles and sedimentologic characteristics of the various units are summarized in table 2.

5. The dependence of channel geometries on the time since the last debris flow.
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7. Illustration of clumped boulder distribution along the South Fork of Ash Creek. Medium and large boulders in Ash Creek are concentrated at or just downstream from tributary debris flow fan localities, indicated by arrows on the longitudinal profile segments of Ash Creek.

8.a. Daily precipitation for the Coronado National Monument headquarters, located 2 km south of Dorothy Ryan Canyon, for summer 1988.
   b. Average, extreme, and 1988 monthly precipitation for Coronado National Monument.

9. Possible process-response models for debris flow occurrence in the Huachuca Mountains.
   a. Fires result in increased runoff and sediment yield on hillslopes and the occurrence of debris flows. After the debris flow occurs, sediment accumulates quickly in channels, so that the next fire can also trigger a debris flow.
   b. Processes are as in model 1, but sufficient sediment does not accumulate in channels between fires to permit debris flow occurrence after every fire.

Tables

1. Velocities and peak discharges for 1988 debris flows in Dorothy Ryan and Manzanita Canyons, estimated from superelevation

discharge estimates for each reach, but the averages from each section along Dorothy Ryan Canyon are reasonably consistent. The scatter in the data from Manzanita Canyon is severe, making the discharge estimate suspect.

2. Description of soil profiles and stratigraphic relationships from the exposure in Dorothy Ryan Canyon illustrated in figure 3. Abbreviations are as follows: soil structure size, f is fine, m is medium; structure strength of development, wk is weak, mod is moderate; structure type, sbk is subangular blocky; dry consistence, so is soft, sh is slightly hard; wet consistence, ns, np are non- (sticky, plastic), vss, vsp are very slightly (sticky, plastic), ss, sp are slightly (sticky, plastic), s is sticky; carbonate stages are from Machette (1985).

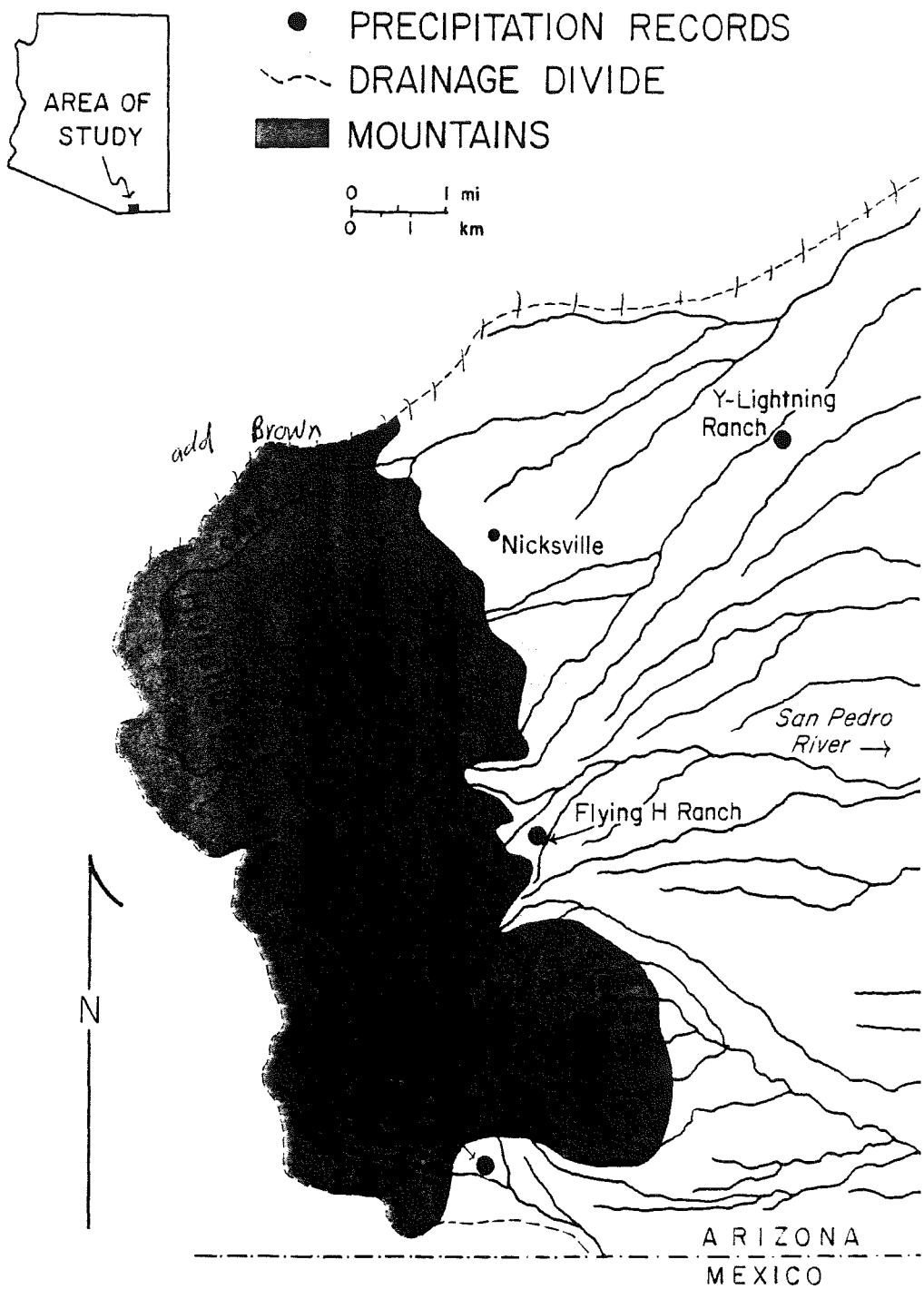

AREA OF STUDY
PRECIPITATION RECORDS
DRAINAGE DIVIDE
MOUNTAINS
0 1 mi
0 1 km
add Brown
Y-Lightning Ranch
Nicksville
San Pedro River →
Flying H Ranch
N
ARIZONA
MEXICO

figure 1

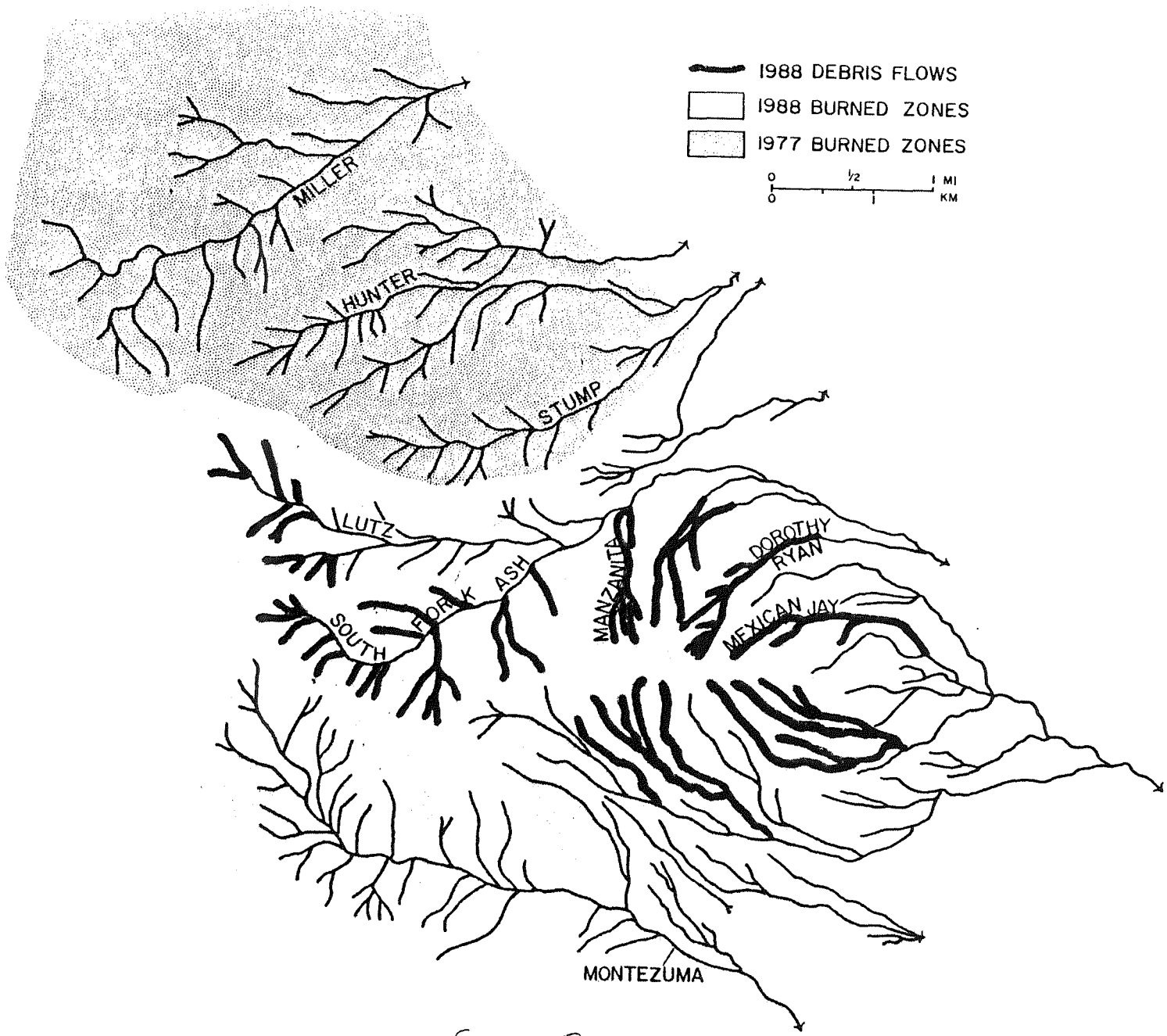

1988 DEBRIS FLOWS
1988 BURNED ZONES
1977 BURNED ZONES
0
1/2
1 MI
0
1 KM
MILLER
HUNTER
STUMP
LUTZ
SOUTH FORK ASH
MANZANITA
DOROTHY
RYAN
MEXICAN JAY
MONTEZUMA

figure 2

figure 3

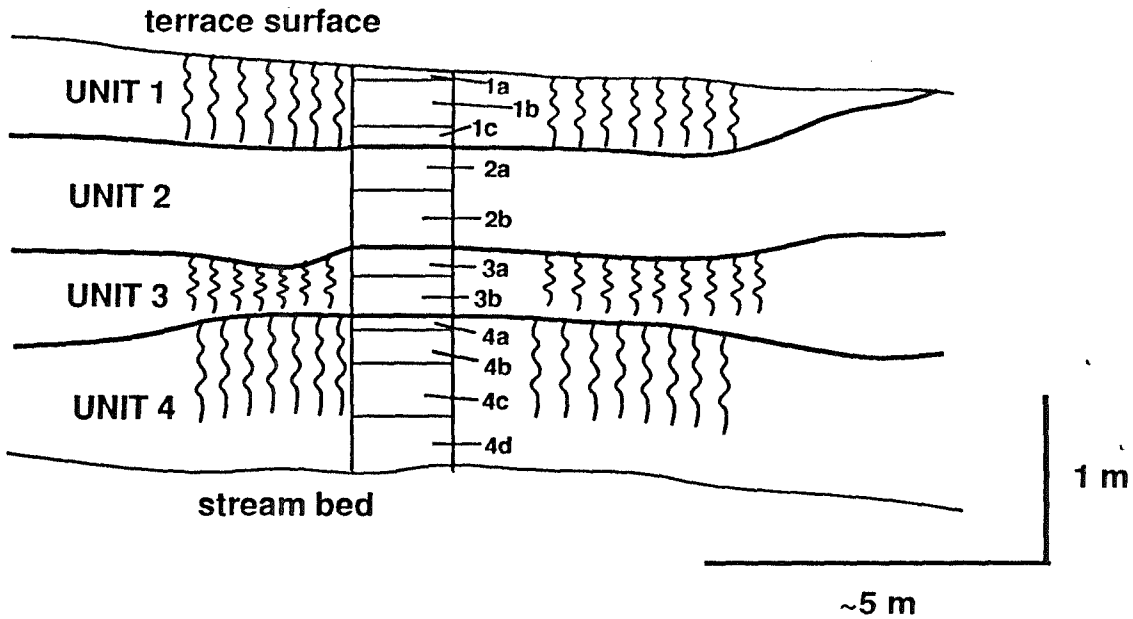
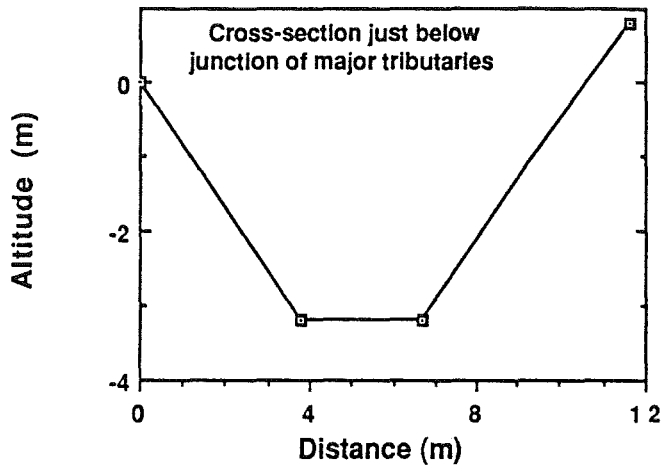

terrace surface
UNIT 1
UNIT 2
UNIT 3
UNIT 4
1a
1b
1c
2a
2b
3a
3b
4a
4b
4c
4d
stream bed
1 m
~5 m

figure 4


Cross-section just below
junction of major tributaries
Altitude (m)
0
-2
-4
0
4
8
12
Distance (m)

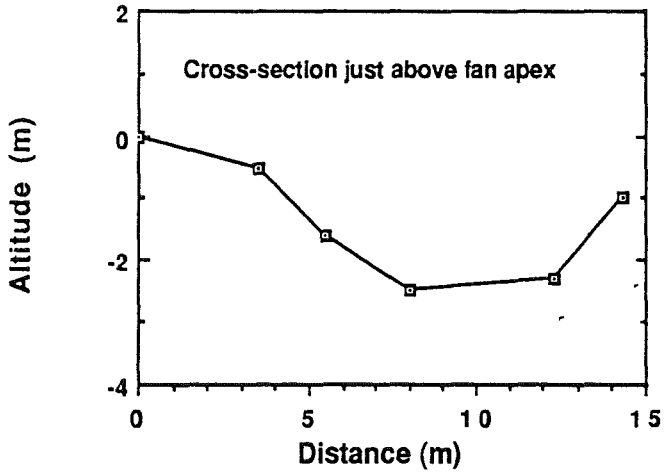

Cross-section just above fan apex
Altitude (m)
2
0
-2
-4
0
5
10
15
Distance (m)

Figure 5a

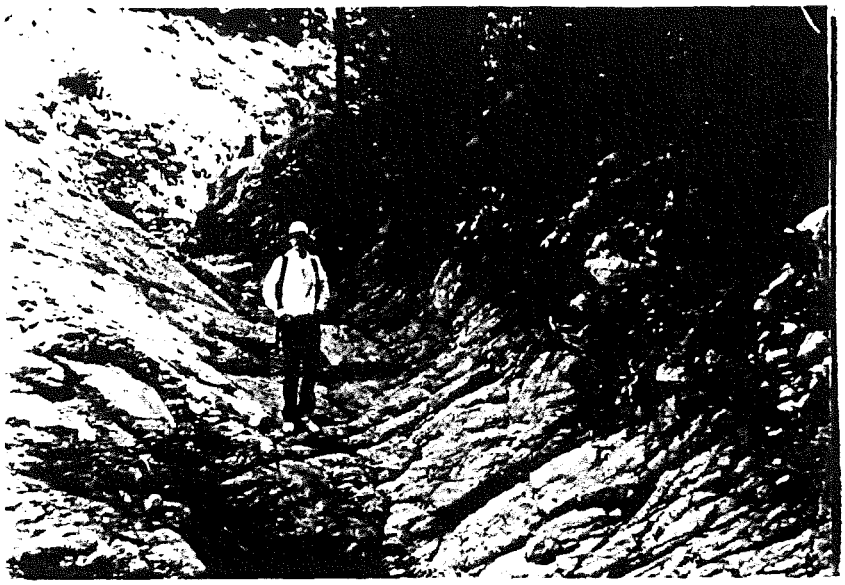


figure 5 b

figure 5c

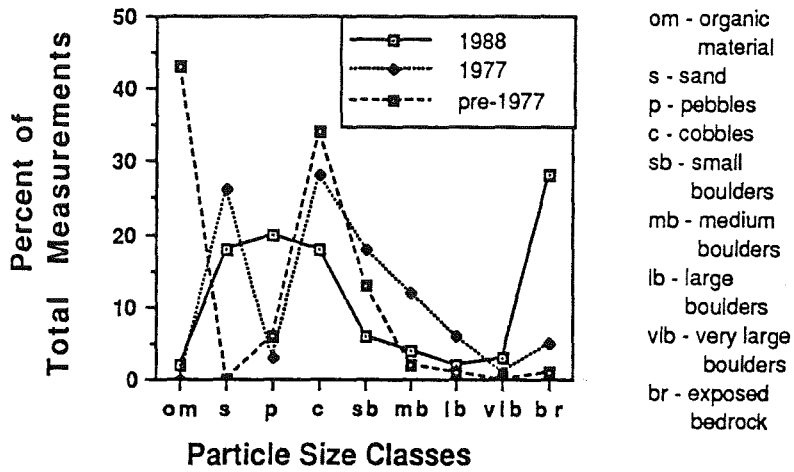

Percent of Total Measurements
50
40
30
20
10
0
1988
1977
pre-1977
om s p c sb mb lb vlb br
Particle Size Classes
om - organic material
s - sand
p - pebbles
c - cobbles
sb - small boulders
mb - medium boulders
lb - large boulders
vlb - very large boulders
br - exposed bedrock

Figure 5d

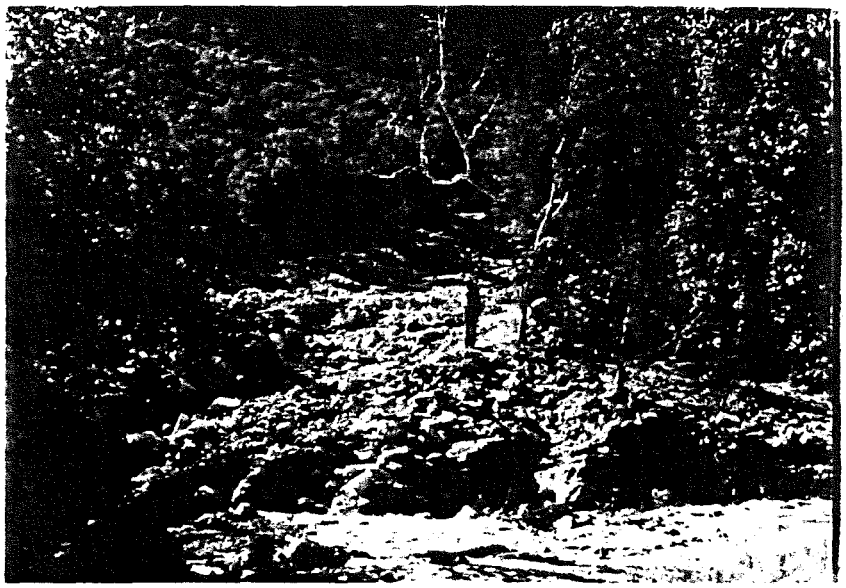


figure 6

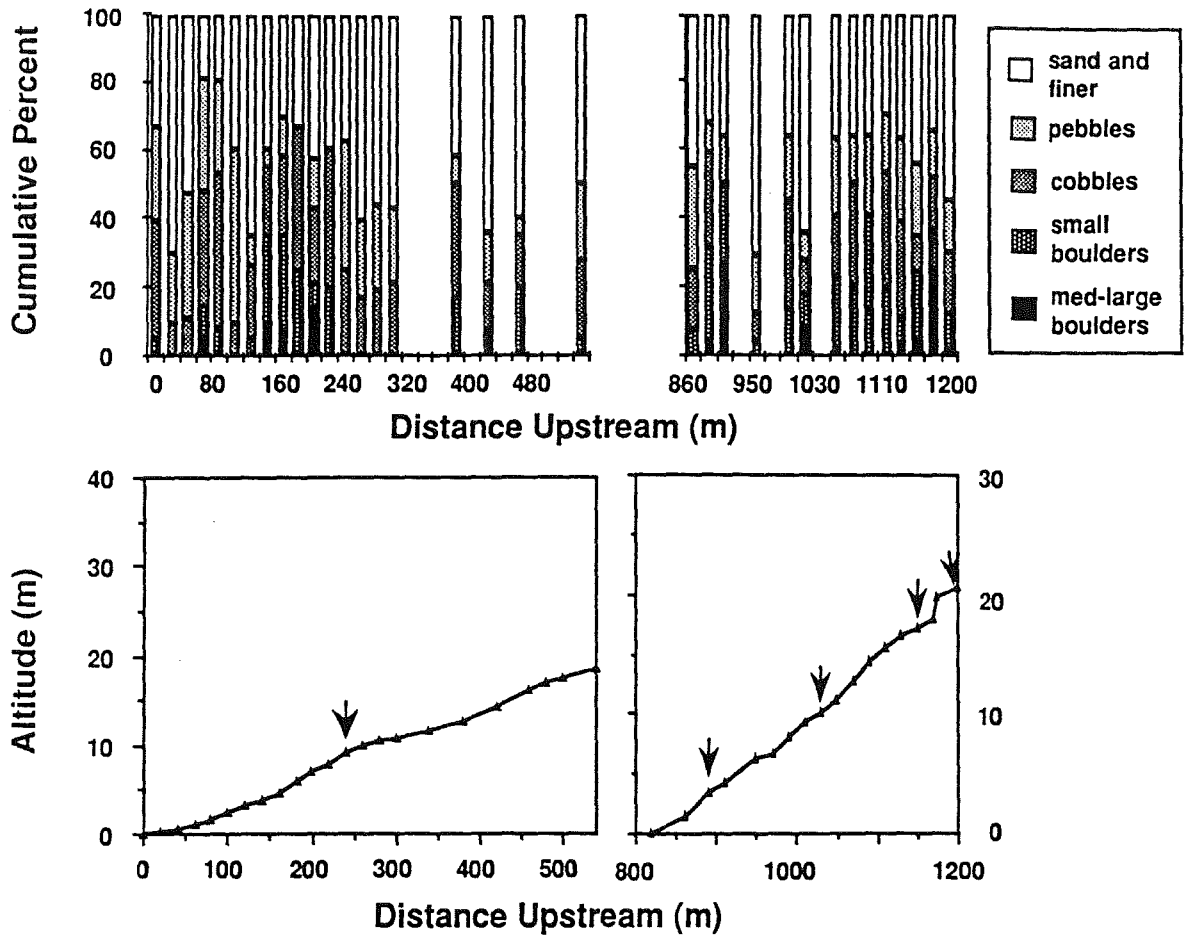

Cumulative Percent
100
80
60
40
20
0
0
80
160
240
320
400
480
860
950
1030
1110
1200
Distance Upstream (m)
sand and finer
pebbles
cobbles
small boulders
med-large boulders
Altitude (m)
40
30
20
10
0
0
100
200
300
400
500
800
1000
1200
30
20
10
0
Distance Upstream (m)

Figure 7

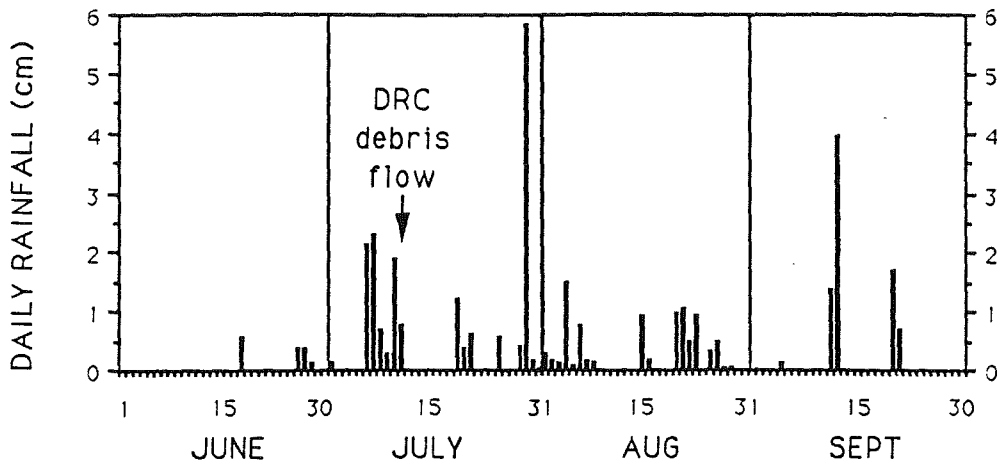

DAILY RAINFALL (cm)
DRC
debris
flow
0
1
2
3
4
5
6
1
15
30
15
31
15
31
15
30
JUNE
JULY
AUG
SEPT

Figure 8a

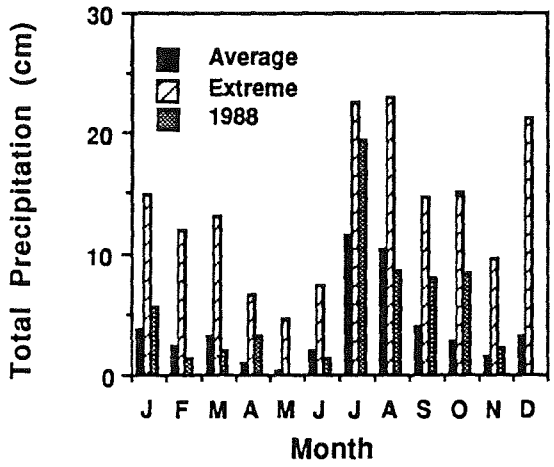

Total Precipitation (cm)
30
20
10
0
Average
Extreme
1988
J F M A M J J A S O N D
Month

Figure 86

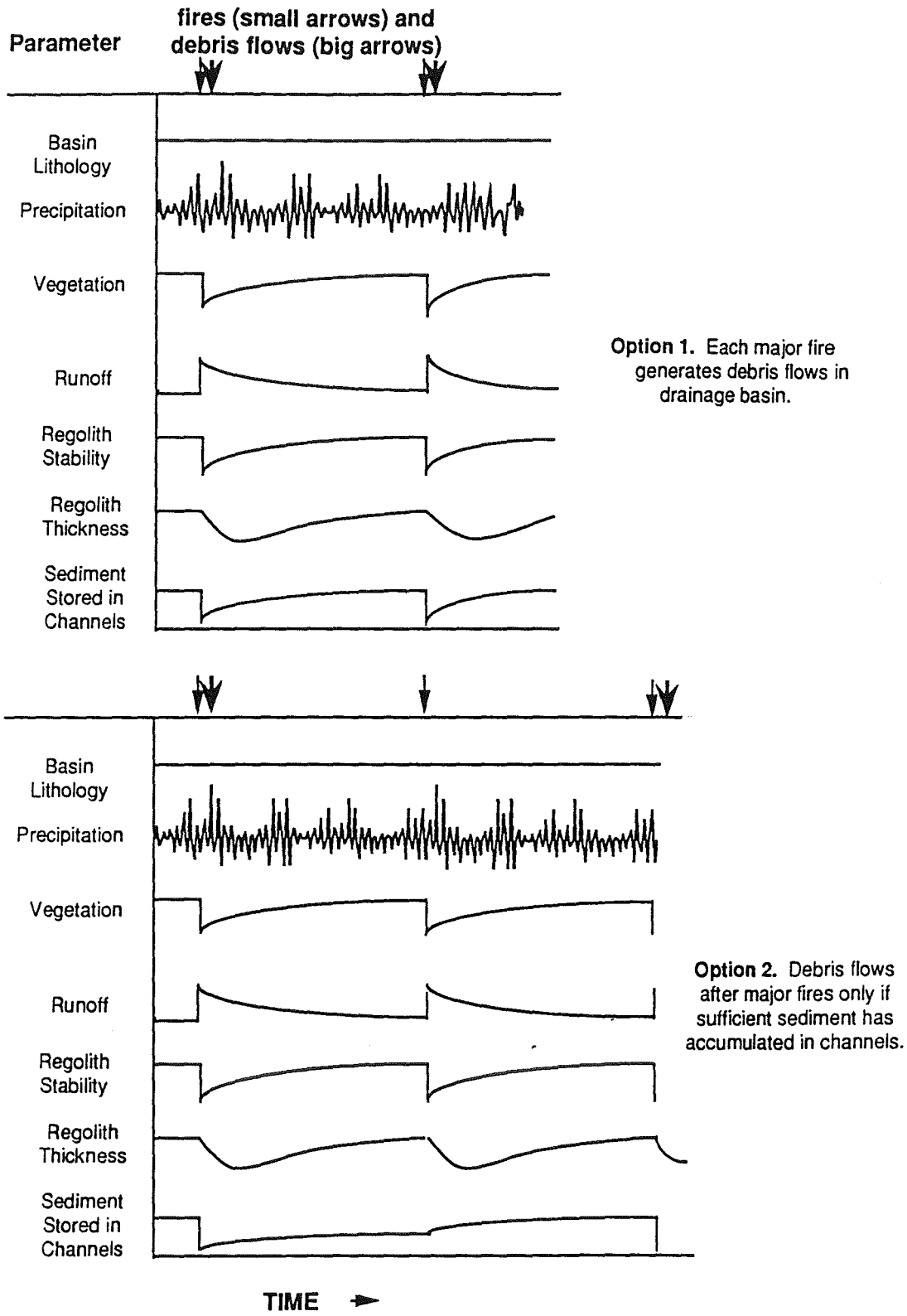

Parameter
fires (small arrows) and debris flows (big arrows)
Basin Lithology
Precipitation
Vegetation
Runoff
Regolith Stability
Regolith Thickness
Sediment Stored in Channels
Option 1. Each major fire generates debris flows in drainage basin.
Basin Lithology
Precipitation
Vegetation
Runoff
Regolith Stability
Regolith Thickness
Sediment Stored in Channels
Option 2. Debris flows after major fires only if sufficient sediment has accumulated in channels.
TIME

Figure ~~8~~ 9

Cross-section	Super Elevation	Rc	Velocity	Channel Area	Est. Discharge	Section Avg.
DRC MAIN CHANNEL						
70	1.0	20	3.8	15.5	58	
89	0.5	21	1.9	36.1	69	
98	1.0	9	1.9	28.2	52	
115	1.6	22	3.2	37.4	121	75
142	0.1	15	0.9	25.6	23	
158	0.2	11	1.2	23.9	28	
178	0.6	15	2.8	24	67	
199	0.9	20	4.1	18	74	48
620	2.2	45	8.9	8.6	76	
632	0.8	25	3.8	15.5	59	
642	0.3	40	3.5	15.5	54	63
876	0.5	17	2.8	28.2	79	
885	0.8	8.5	2.3	26.6	62	
887	0.9	8.5	2.5	19.2	48	
894	0.5	24	3.3	24.3	81	67
DRC RIGHT TRIBUTARY						
989	0.5	15	3.0	11.3	34	
1007	0.1	36	2.2	9	20	27
DRC LEFT TRIBUTARY						
931	0.1	9	1.2	12.4	15	
948	2.0	14	6.3	8.8	55	
973	0.2	35	2.7	11.7	32	34
MANZANITA CANYON						
15	1.2	40	6.0	18.0	108.6	
56	2.7	18	7.3	18.7	137.1	
72	1.0	8	2.9	15.8	45.6	
84	0.3	15	1.8	11.3	20.8	78

Table 1

Horizon (depth, cm)	Color (dry)	Structure	Consistence Dry	Consistence Wet	Texture	Carbonate Stage	Sedimentology
1A1 (0-10)	7.5 YR 5/3	f-m granular	so	vss, vsp	sandy loam	0	Unit 1
1A2 (10-37)	7.5 YR 5/3	f granular	so	vss, vsp	sandy loam	I	extremely poorly sorted sand to small boulders, 60% gravel, debris flow deposit
1Bw (37-47)	7.5 YR 5/3	wk f-m sbk	so	ns, vsp	loamy sand	I	
2C1 (47-76)	7.5 YR 5/3	m granular	so	vss, np	loamy sand	I+	Unit 2
2C2 (76-111)	7.5 YR 4/2	f granular	so	ss, sp	sandy loam	I+	very poorly sorted sand to cobbles, 80% gravel, wk clast orientation, water-laid deposit?
3A (111-130)	7.5 YR 5/2	f granular	so	vss, vsp	sandy loam	I	Unit 3
3Bt (130-150)	5 YR 4/2	wk f-m sbk	sh	ss, sp	loam	I	extremely poorly sorted sand to small boulders, 50% gravel, flecks of charcoal, debris flow deposit
4A (150-158)	7.5 YR 5/4	f granular	so	ss, vsp	sandy loam	II	Unit 4
4Bt1 (158-178)	5 YR 5/4	wk f-m sbk	sh	ss, sp	loam	II	extremely poorly sorted sand to large boulders, 70% gravel, debris flow deposit
4Bt2 (178-208)	5 YR 5/4	mod f-m sbk	sh	s,sp	sandy clay loam	II	
4Bt3 (208-253)	5 YR 5/4	mod f-m sbk	sh	s, sp	sandy clay loam	II	

Table 2