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The influence of macropores on debris flow initiation

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Abstract

Soil structure affects the movement of water in hillslope soils and therefore exerts a strong influence on slope stability. A debris flow is analysed within the confines of an instrumented catchment on the South Island, New Zealand, in order to examine the influence of soil macropores on slope stability. Tensiometric and slope throughflow data for nearby slope areas show that vertical cracks conduct rainfall at rates well in excess of the mineral soil matrix conductivity. The presence of a well connected pipe system at the soil–bedrock interface distributes this water quickly downslope. Under exceptionally high rainfall intensities, however, this crack-pipe system may induce slope instability by increasing the rate of infiltration over lateral pipeflow rates. This results in a build-up of pore pressure at the soil–rock interface and subsequent slope failure.

Introduction

Although many studies have documented the physical properties of failed hillslopes (e.g. Shlemon, Wright & Montgomery 1987) and their rheology (e.g. Fisher 1971), few have examined the role of subsurface water movement pathways on debris flow initiation. In steep areas debris flows generally occur in response to low soil suction and high rainfall intensities and magnitudes. As the pressure potential in a sloping soil mass increases, the frictional component of the shear forces holding the soil on-slope decreases. Neary & Swift (1987) have noted that this, combined with decreased cohesion due to water displacing air in soil interstices, reduces the shear resistance force enough to produce slope failure. Several studies have also shown (e.g. Costa 1984) that factors such as thin soil conditions, steep slopes, concentrated drainage, shallow-rooted vegetation and high soil clay content, will promote increased susceptibility to failure.

Notwithstanding, increased pressure potentials and soil water movement seem to be the major controls on slope stability. Sidle, Pearce & O'Loughlin (1985) note that few data exist on pressure potential (ψ) in the soil mantle at the time of hillslope failure. Some studies (O'Loughlin & Pearce 1976; Sidle & Swanston 1981, 1982) have suggested that near-saturation of shallow soils (<1 m thick) may be necessary to induce slope failure. O'Loughlin & Pearce (1976) showed that ψ in excess of 1 m of water was required to initiate failure in soils underlain by late Tertiary sandstone (slopes >25°) in North Westland, New Zealand. Sidle & Swanston (1982) reported that a ψ shift from 0 to 0.25 m of water in hillslope depressions in coastal Alaska reduced the factor of safety from 1.49 to 1.00. Anderson & Kneale (1980) observed hillslope soil ψ values in the order of 0.12 to 0.67 m of water adjacent to a slope failure while Rogers & Selby (1980) computed a ψ value of 1.1 m of water associated with slope failure. Finally, Pierson (1980) found complete saturation of the soil mantle along axes of hillslope depressions in the Coast Ranges of Oregon during a winter storm with an estimated return period of four years.

The rate of water movement through unstable soil mantles is probably the most significant hydrological function affecting soil mass movement (Sidle *et al.* 1985). Although sparse data do exist for pre-failure ψ, subsurface run-off pathway effects on failure initiation have not been addressed. The objective of this study is to examine the influence of subsurface stormflow pathways, especially macropores, on debris flow initiation in a small steep headwater catchment. A debris flow case study is presented and related to soil physics and other surrogate information for the catchment's subsurface run-off behaviour.

Macropore effects on slope stability

Many studies over the past decade have identified preferred flow along macropores, indicating that rapid water flow in the unsaturated zone may occur under conditions of non-equilibrium between soil moisture content and moisture potential (Beven & Germann 1982). Recent literature has emphasized the importance of macropores in generating rapid subsurface run-off, in the order of 5.5 m hr^{-1} (Hammermeister, Kling & Vomocil 1982), 15 m hr^{-1} (Rahe, Hagedorn, McCoy & Kling 1978) and 33.3 m hr^{-1} (Mosley 1982) via turbulent non-Darcy type flow in large soil pipes (Jones 1971), decaying root channels (Aubertin 1971), soil cracks (Bouma & Wosten 1979), and animal burrows (Omoti & Wild 1979).

Evidence from a number of recent field monitoring programs, particularly in the United Kingdom, has shown that piping and pipeflow can be a substantial contributor to rapid preferential slope water movement (Jones 1979; McCaig 1983; Wilson & Smart 1984; Jones 1987). In addition, well structured soils often permit preferential flow through continuous cracks as shown by Bouma, Dekker & Muilwijk (1981), Van Stiphout, Van Lanen, Boesma & Bouma (1987) and others. This may result in a deeper penetration of storm rainfall than is predicted by Darcian flow. Schematic views of both pipeflow and bypassing are shown in Fig. 1.

Only a few studies have examined the role of macropores in slope stability. Perhaps the most detailed study was a laboratory investigation conducted by Pierson (1983) who used a Hele–Shaw (viscous flow) model to demonstrate the effect of a single pipe on the overall flow regime of a slope. Pierson's analogue showed that when a pipe was blocked or was a dead-end passageway (a closed pipe) the cavity could be readily filled with water during a rain event, increasing pressure potentials in the surrounding matrix. Furthermore, he found that if pipes were continuous downslope for some distance they could generate pressure potentials much greater than those generated by total saturation of the soil, enabling failure initiation at sites that would otherwise be stable.

Brand, Dale & Nash (1986) documented the effect of constricted or silt-filled pipes on Hong Kong hillslopes, which resulted in a total head increase of 4 m in 6 hrs and subsequent slope failure. The 'blocking-up' of normally hydraulically efficient pipes was seen as the major contributing factor to frequent landsliding. Anderson, Hubbard & Kneale (1982) showed that vertical bypassing in clay shrinkage cracks in a roadway embankment resulted in a faster than expected increase in pressure potential at a mid-soil profile depth. Water movement through seasonally active cracks led to the development of an upper zone where potentials exceeded zero and produced a concomitant decrease in slope stability.

Location of the study site

The Forest Research Centre of the New Zealand Forest Service operates a set of experimental catchments near Reefton, New Zealand. The eight Maimai study catchments between 1.6 and 8.3 ha in area are located in close proximity to each other in sharply dissected hill country. Slopes in the area generally exceed 30° and rise to narrow ridgetops. The catchments are underlain by a firmly compacted and weathered early Pleistocene conglomerate known as the Old Man Gravels. Catchment side-slopes consist of regular spurs of Old Man Gravel bedrock and linear hollows infilled with matrix-rich colluvium. Soils in the catchments are shallow (<1 m) podsolized yellow-brown earths and a sharp boundary exists between the base of the soil profile and the underlying conglomerate.

The indigenous beech–podocarp–hardwood forest was clearfelled in most of the catchments during the period 1977–1979 and then converted to *Pinus radiata*. Annual rainfall in the area averages 2600 mm. Mosley (1982) identified preferential flow paths (pipeflow and bypassing) using injected dyes at several locations in the Maimai catchments. In many zones the soil profile is drained at its base by a continuous piping system which extends laterally downslope over distances of several tens of metres. Large roots from the pre-harvest forest cover extend vertically through the shallow soil but do not penetrate the underlying conglomerate. Roots then extend laterally over the conglomerate surface for up to several metres. Mosley (1979) noted that pipes formed in this manner and by subsequent decay of root networks are enlarged by eluviation.

Regularly spaced vertical cracks, roughly 1–3 mm wide, are found in seasonally dry hollows (McDonnell 1989). Cracks show signs of organic staining along their walls and fine 'hair-like' root structures along their entire length. Dye tracer experiments (Mosley

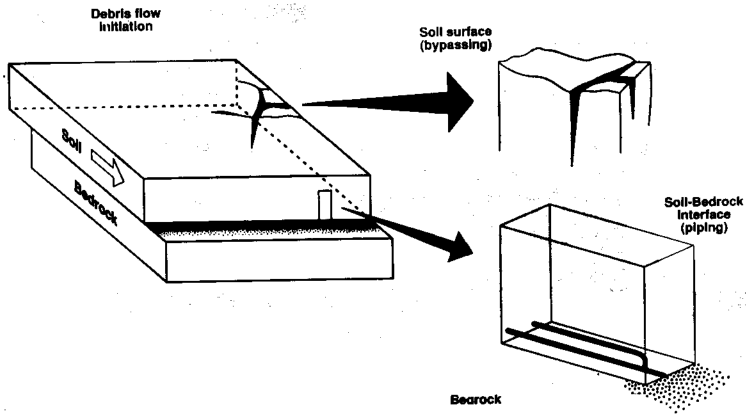


FIG. 1. Highly simplified schematic representation of bypass flow and pipeflow pathways.

1979, 1982) suggest that water regularly moves through these channels. Although never dropping significantly below 90% saturation, local soils occasionally encounter dry periods of about three weeks when surface cracking occurs.

Hillslope water-table response to storm rainfall

Soil energy conditions were monitored for several storms in a highly instrumented hollow in the Maimai 8 experimental catchment (Fig. 2). The Maimai 8 catchment is 3.8 ha in area, and was clearfelled in November 1978, burnt in February 1980 and then replanted with *Pinus radiata* in July 1981. Recording tensiometers were deployed in 1987 at various depths in a transect up the study hollow axis. Detailed information on three-dimensional pressure potential response is given in McDonnell (1990). Results discussed in this paper focus on more general storm-to-storm variations in ψ at one tensiometer location, as a precursor to the debris flow case study presented later in the text.

Soil pressure potential response was highly variable for different storm magnitudes, intensities and pre-storm soil ψ conditions. Tensiometric response indicates a erratic infiltration–ψ relationship. During a low-magnitude (25 mm rainfall) event on 23 to 24 October 1987 (Fig. 3A) tensiometric data showed a semi-constant wetting front propagation through the profile, with strong ψ response lags with depths. Although some bypass flow seemed to occur in the upper soil horizon (<0.5 m), as evidenced by the response of tensiometer T5, rainfall depth and soil moisture content were sufficiently low that the lower soil depths did not receive appreciable moisture from above until streamflow response had subsided (Fig. 3A); hence a slope water-table did not develop.

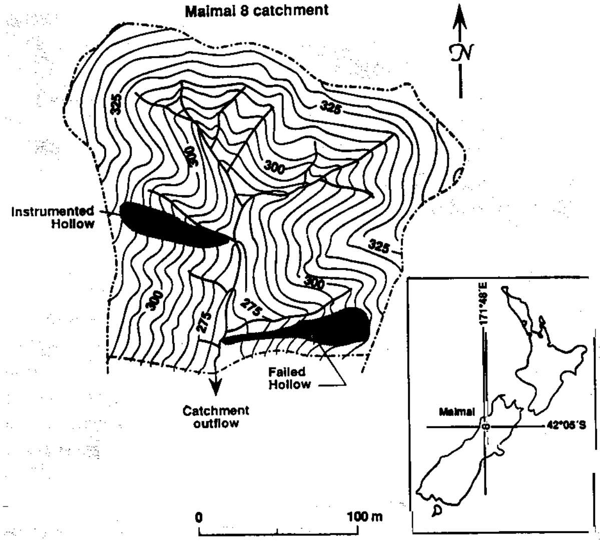


FIG. 2. The Maimai 8 catchment highlighting instrumented hollow and 19 May 1988 failed hollow. Contour lines are given at 5 m spacing.

During a larger magnitude (58 mm rainfall) event on 29 October 1987, pressure potential in the lower soil horizons (>0.75 m) responded to infiltrating rain almost instantaneously (Fig. 3B). McDonnell (1990, see Figure 10 therein) showed that this response was a function of a disequilibrium in soil pressure potentials during wetting, caused by the presence of soil macropores. Furthermore, much of the matrix exhibited unrequited storage during this type of wetting, indicative of a two-component flow system of rapid macropore flow and slow matrix flow. For the largest event monitored (103 mm rainfall) on 13 October 1987 soil pressure potential remained relatively constant throughout the profile during the limited period of tensiometer coverage (Fig. 3C). Most of the soil profile remained saturated during this episode.

Generally, when rainfall intensities were low but pre-storm soil water content was high, any additional rainfall input rapidly filled the limited soil moisture storage and perched water-table conditions quickly developed at the bedrock interface. On the other hand, if short-term rainfall intensities were high, rainfall bypassed the upper soil horizons (<0.5 m) and moved to the profile base via semi-vertical cracks so that tensiometers in the lower half of the profile responded ahead or independent of the upper tensiometers. Water-table longevity was very short and showed a close correspondence with hillslope throughflow rate as recorded by McDonnell (1989). Downslope drainage of perched groundwater was extremely efficient and showed no lag with recorded throughflow for storms where this data was available. This indicates that lateral saturated flow was rapid, probably moving through pipes formed at the soil–bedrock interface. The rapidity of tensiometric recession in the lower half of the soil profile in events with perched water-table conditions, supports the idea of rapid downslope drainage through pipes. The interconnectedness of pipes in this zone must be high to account for the rapidity of water-table decline.

Debris flow case study

On 19 May 1988, 160 mm of rain fell over the Maimai 8 catchment, after a prolonged eleven-day period of intermittent rainfall totalling approximately 250 mm. Figure 4 shows the rainfall conditions during this period, recorded by a raingauge located 2 km from the Maimai 8 catchment. A debris flow was initiated in a

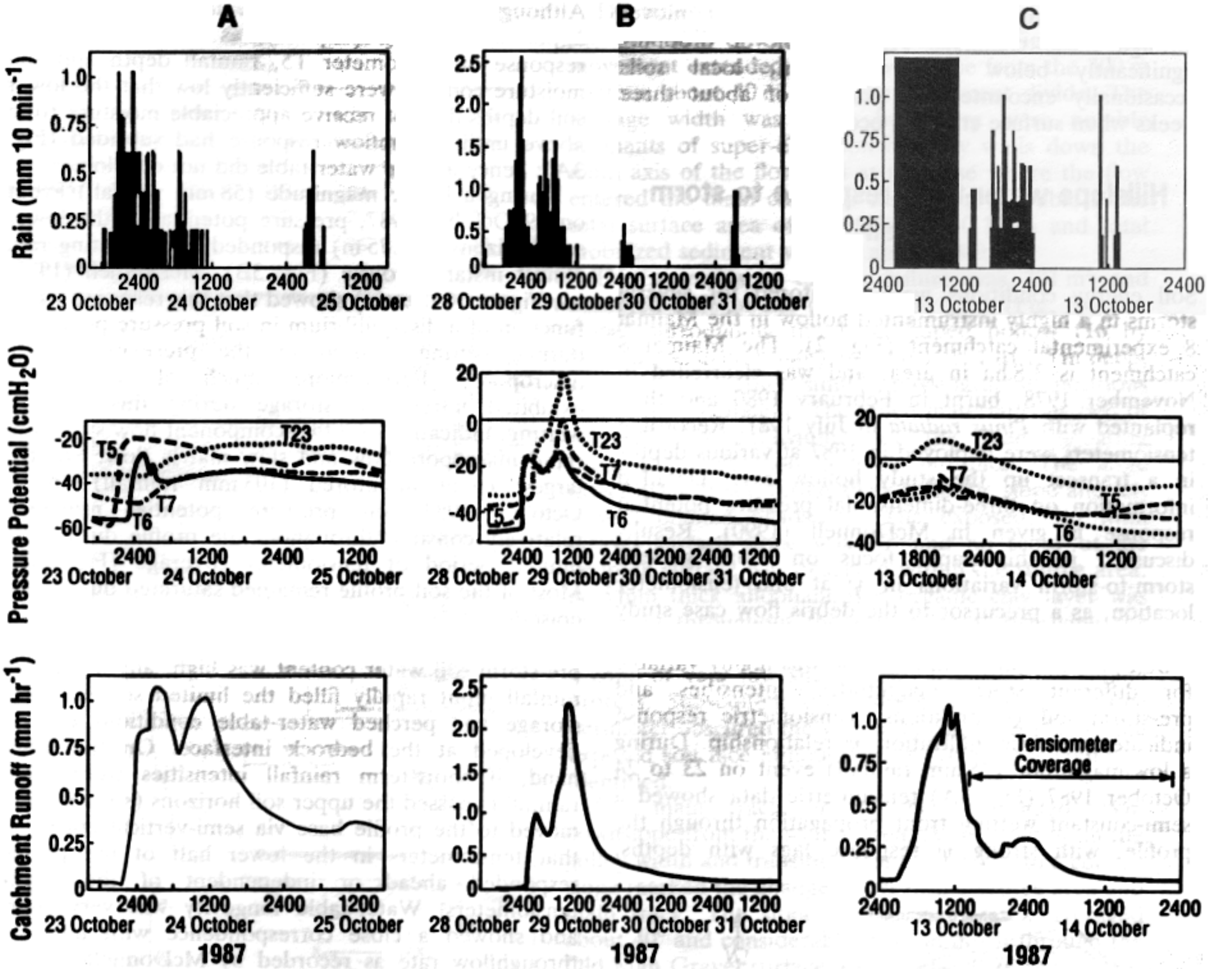


FIG. 3. **Pressure potential response for tensiometers located in instrumented hollow, showing relationship between ψ and rainfall-catchment run-off condition. Three storms are shown, representing rainfall totals of (A) 25 mm, (B) 58 mm and (C) 103 mm. Soil depth 1–1.5 m, slope angle 35–40°. Tensiometers T5, T6, T7 and T23 inserted at 170, 410, 820 and 1080 mm below soil surface respectively.**

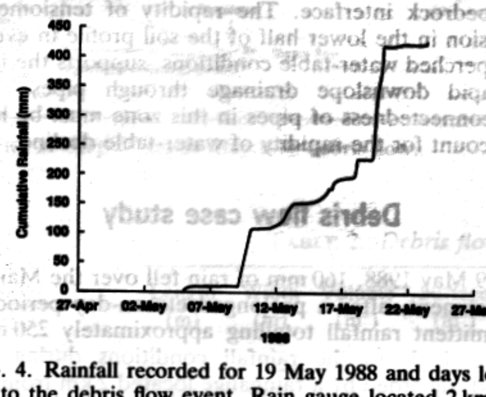
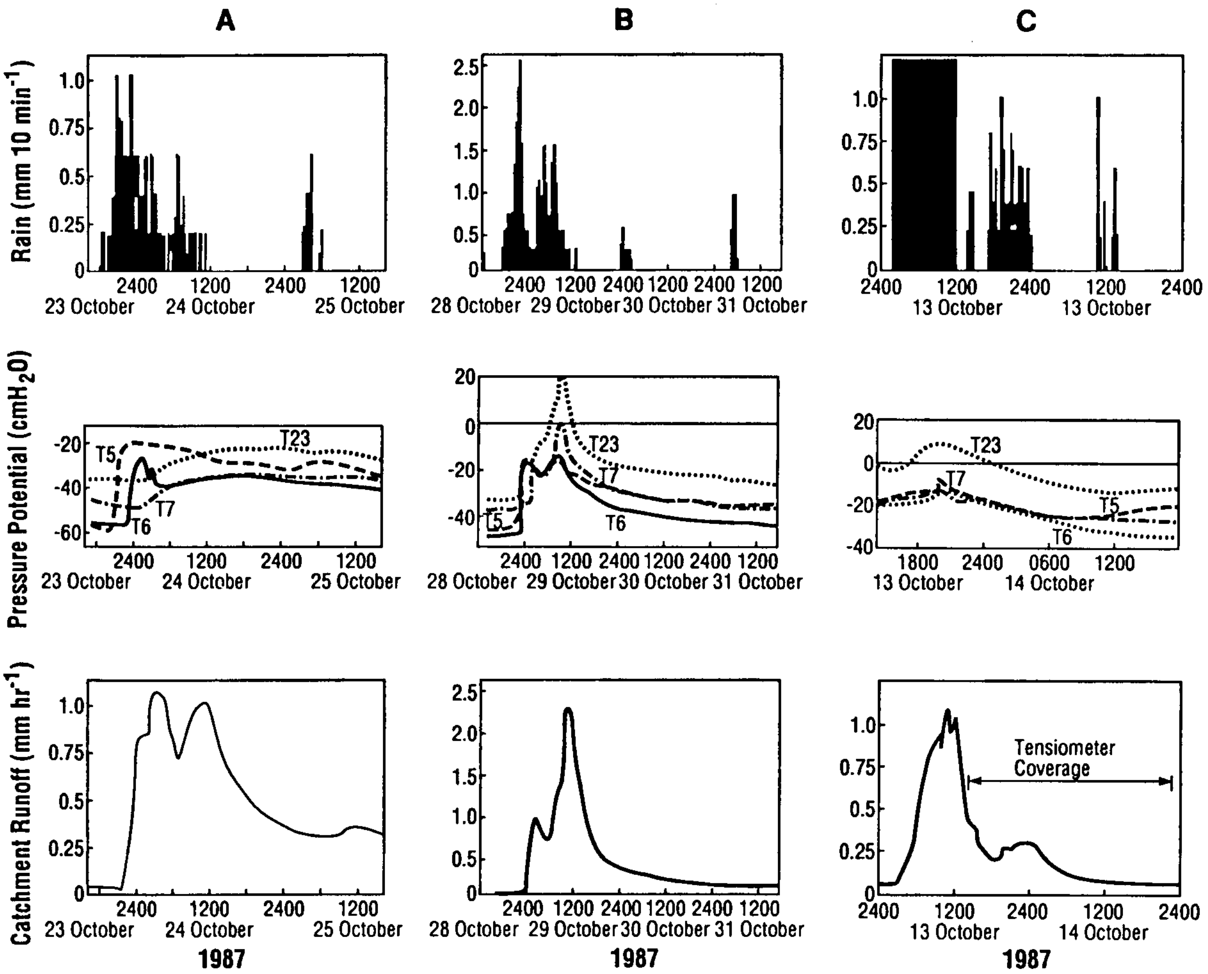


FIG. 4. **Rainfall recorded for 19 May 1988 and days leading up to the debris flow event. Rain gauge located 2 km from failed hollow.**

small northeast-facing hillslope hollow (Fig. 2), normal to the main stream, roughly 25 m upstream from the gauged catchment outflow. More than 1000 m³ of debris moved rapidly downstream, destroying the weir, stilling well and stage recorder. The storm started at 0100 hrs on 19 May 1988 and maintained low rain (<11 mm) and intensities (2 mm hr⁻¹) for the first four hours. Between 0500 hrs and 1200 hrs, 77 mm of rain fell with average intensities in the order of 10 mm hr⁻¹.

From maps presented in Tomlinson (1980), the 19 May event has an estimated 24 hr return period of about 10 to 20 years. As shown in Table 1, Rowe (1988) compiled data from three previous extreme rainfall events recorded at the Maimai study area, which show that the 19 May storm is not exceptional



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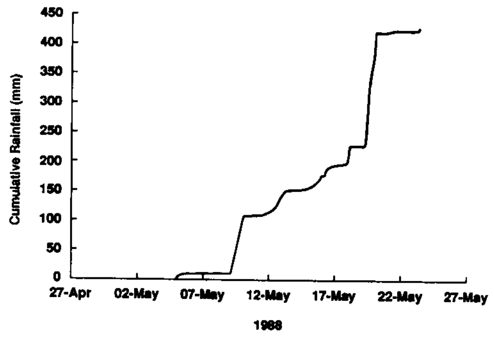

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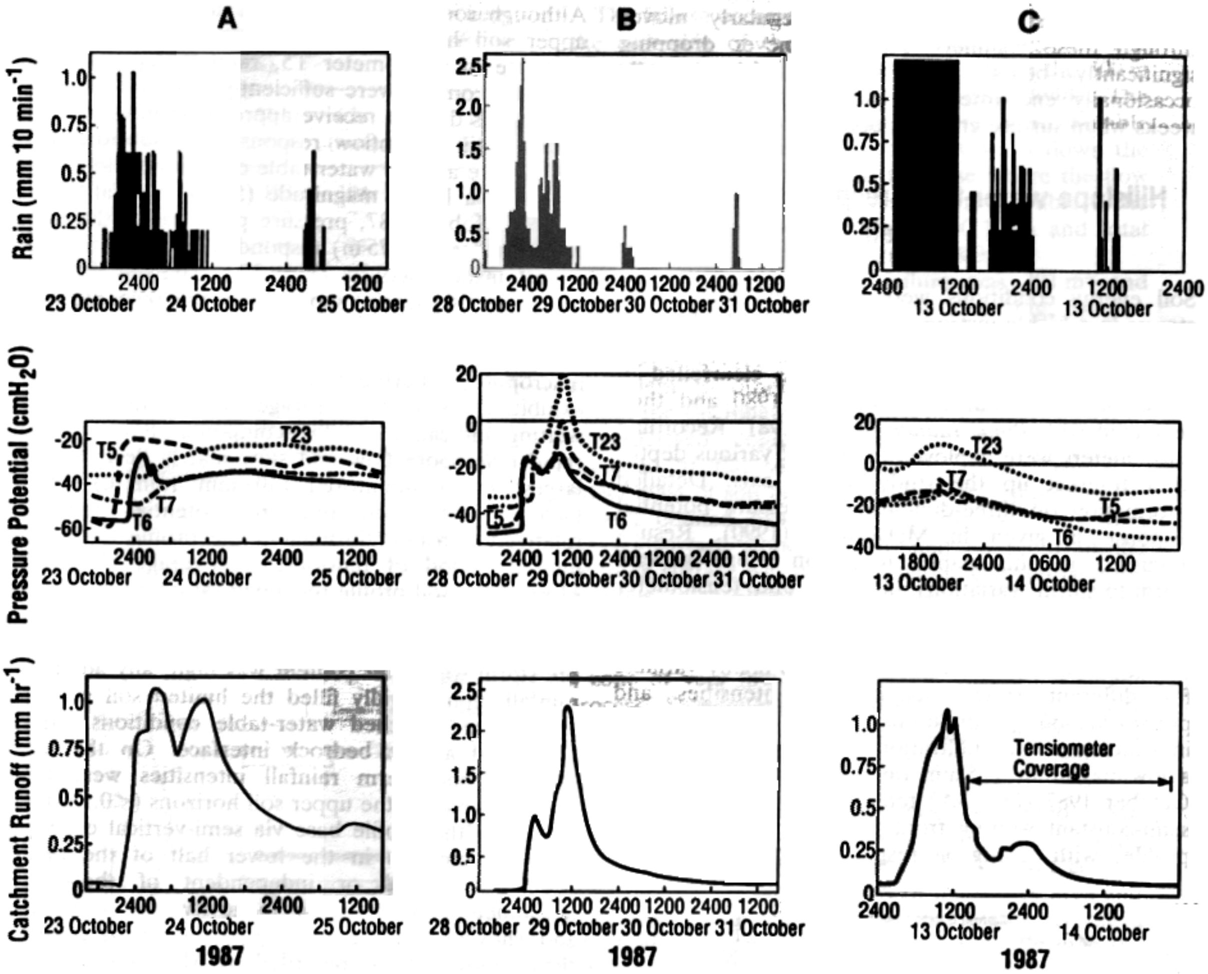

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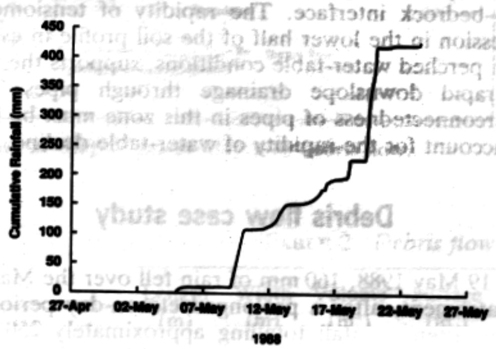

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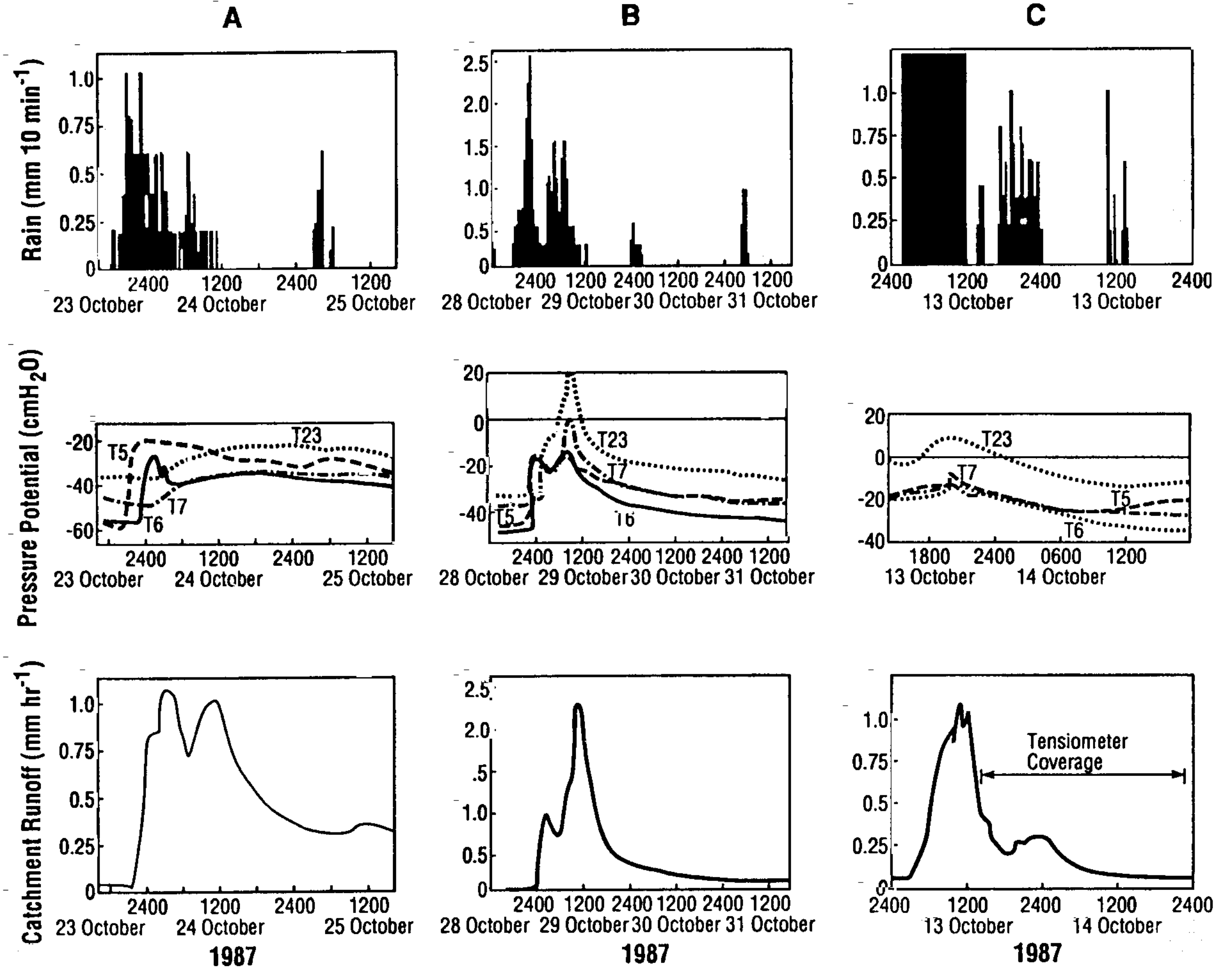

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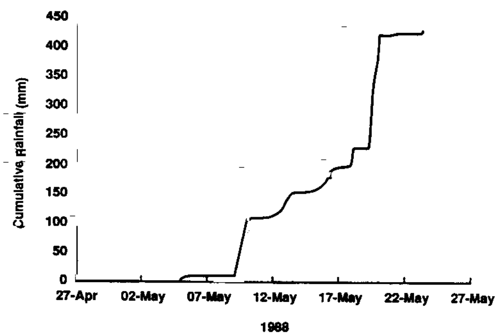

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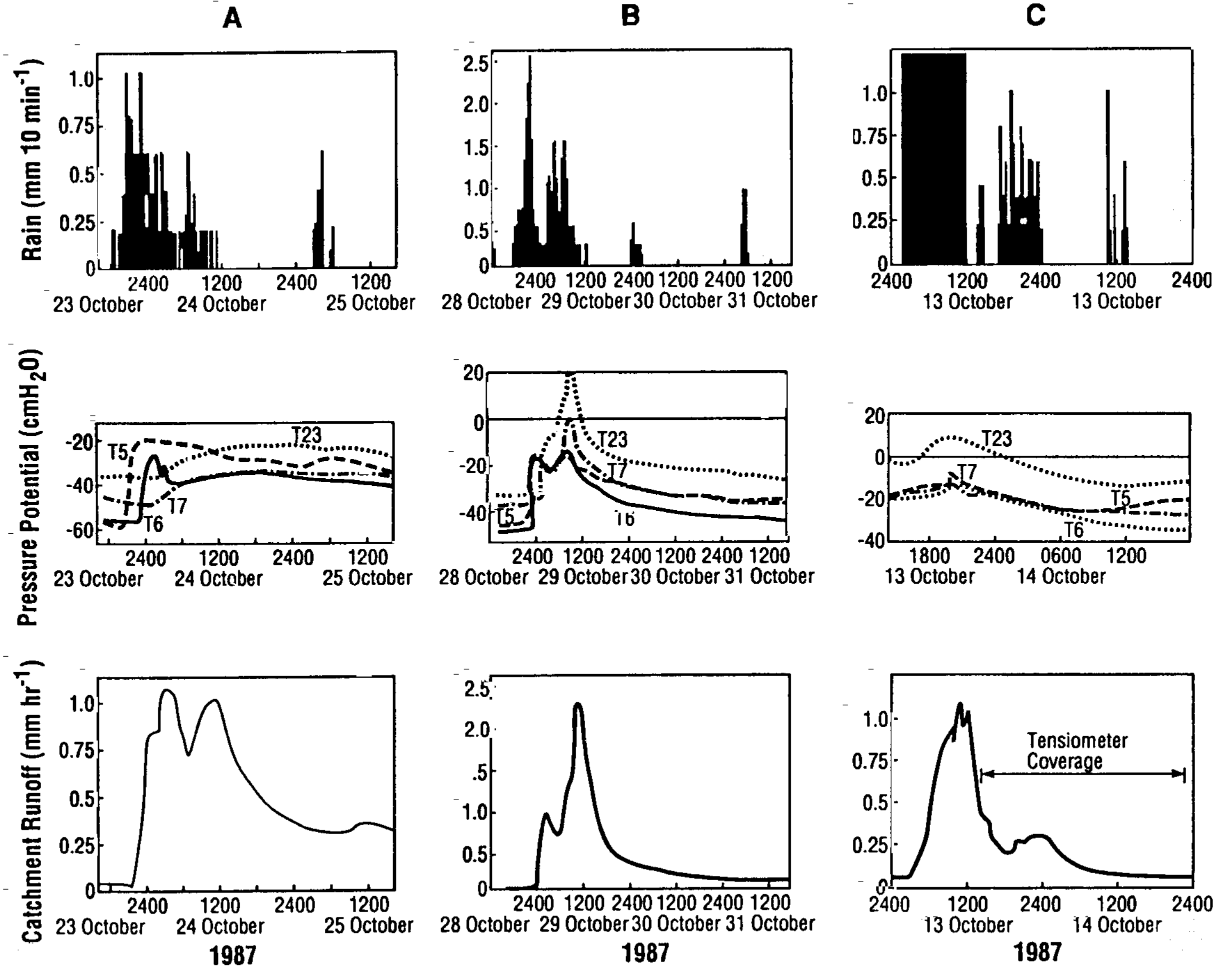

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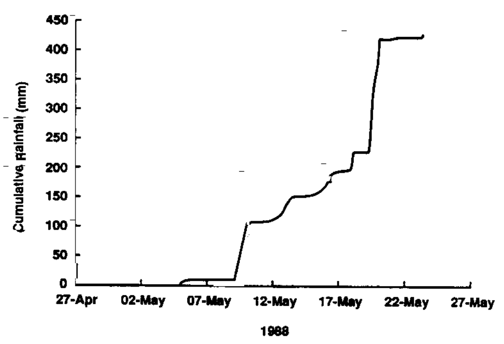

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TABLE 1. *Rainfall intensity characteristics for large storms monitored at Maimai (data from Rowe 1988)*

Date	24 hr (mm)	12 hr (mm)	6 hr (mm)	3 hr (mm)	1 hr (mm)
April 1975	177	153	104	59	22
December 1979	110	107	79	58	26
July 1983	216	134	75	41	15
19 May 1988	145	98	66	34	16

(compared to other large recorded events) in terms of 1, 3, 6, 12 or 24 hr intensities. However, the geomorphic importance of the 19 May storm was accentuated by the effects of prolonged steady rain, high antecedent wetness conditions and, to a lesser extent, rainfall intensity.

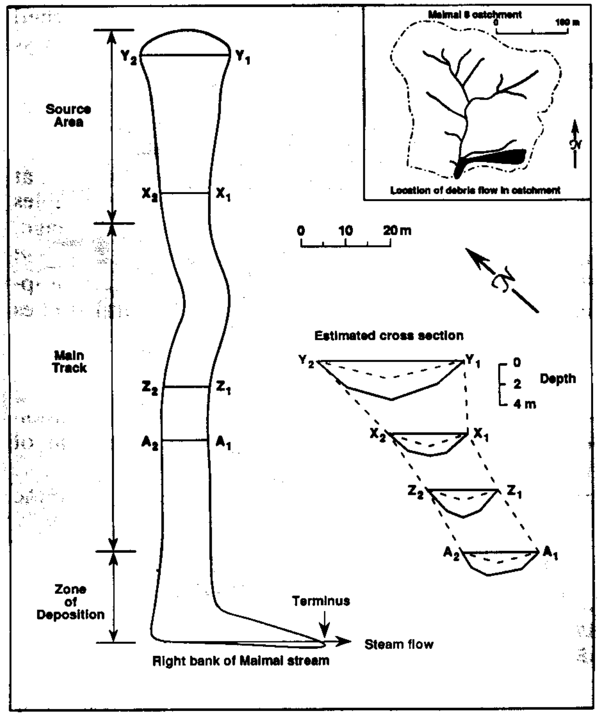

FIG. 5. Map of the 19 May 1988 debris flow.

The failure occurred in a small undrained hollow on the east side of the main catchment (Fig. 5). The movement extended 113 m downslope from the 300 m contour about 40 m from the catchment divide. The average width was 10 m, but there were notable remnants of super-elevation of gully walls down the main axis of the flow and at the base where the flow entered the main channel. As shown in Table 2 the total surface area of the flow was 0.11 ha and total mobilized sediment volume about 1000 m^3.

The source area of the failure was 391 m^2 and occupied 35% of the overall flow area (Fig. 5). The slopes surrounding the bowl-shaped hollow (16 by 30 m) were steep (>40°) and the soils 1 to 1.5 m deep, equivalent to other similar physiographic positions within the catchment. The failed material consisted of slope-derived colluvium and the main shearing occurred at the soil–bedrock interface. The large intact mass of soil broke away from the slope and left a well defined headscarp. The exposed Old Man Gravel surface slope was 30° and no scour of the bedrock surface was observed within the source area. A 5 mm thick allophane-rich organic clay layer was observed throughout the source area, overlying the exposed bedrock surface. This layer probably formed a zone of very low shear strength during the sliding process. Subsequent soil erosion around the source perimeter obscured the structural characteristics of the exposed soil face although some large pipes could be identified.

The main track of the flow extended 75 m downslope from the source area. A constriction in the gulley width and transition from a concave to a convex slope marked the change between the source area and main track. The slope of the main track averaged about 40° and considerable incision down through the Old Man Gravel surface was observed. In some cases as much as 1.5 m of conglomerate was excavated from the central track channel. The main track was V-shaped in cross section (Fig. 5) and showed signs of superelevation. The physical destruction observed in the main track area and downslope zone, combined with the superelevation remnant in the main track and runout zone, suggests that the flow travelled downslope at possibly 5–10 m s^{-1} (from similar flows reported in the literature). Track walls maintained very steep angles (>40°) with some asymmetry of channel form further downslope. The main track

TABLE 2. *Debris flow physical characteristics*

Length (m)	Width (m)	Volume (m^3)	Surface (m^2)	Surface area Source area (m^2)	Track (m^2)	Deposition (m^2)
113	10	1050	1102	391	480	231

occupied 480 m^3, representing 35% of the total debris flow area.

The deposition zone was located in and around the Maimai 8 main stream channel bed and extended about 40 m downstream from where the debris flow intersected the channel. Failed debris covered 232 m^2, representing 21% of the debris flow area. Poorly sorted, hyper-concentrated depositional material averaged 2 to 3 m deep and dammed streamflow in the main channel for several days. Failed material was still in its original position on 31 October 1988.

Although all tensiometric recording equipment had been removed from the Maimai 8 catchment prior to the 19 May debris flow, some general inferences can be made regarding the possible pre-storm ψ conditions in the failed hollow. The topographic position, elevation, soil characteristics and soil depths of the failed hollow are roughly similar to the instrumented hollow (identified in Fig. 2). It is assumed that soil structure characteristics and macropore development were also similar at both sites.

Pre-storm ψ conditions can be compared readily to those in a period after the 10 October 1987 event (McDonnell 1989) when catchment antecedent wetness conditions were roughly similar. In this event the lower soil horizon in the instrumented hollow was near saturation. The deepest tensiometer, at about 1 m below the ground surface, showed ψ in the order of -0.1 to -0.25 m water. Closer to the ground surface, soil ψ was -0.35 to -0.45 m. Bypass flow and piping, however, would affect the development and longevity of perched water-table conditions on the slope. As shown in previous storm event analyses (Fig. 3), groundwater development in the hillslope hollow zone is extremely rapid and transient. Given the high rainfall intensities, bypass flow would have augmented perched water-table development. It is assumed that during the 19 May event complete saturation of the soil matrix probably occurred in the failed hollow, given the magnitude of the rainfall and high pre-storm ψ conditions.

Concluding remarks

The soil–bedrock interface represents a structurally weak part of the regolith profile and is where most shearing failures are located in the Maimai study area (O'Loughlin & Pearce 1976). This zone is also the location for rapid development of perched water-table conditions where rainfall is able to infiltrate rapidly to depth via cracks. Hillslope failure probably occurred at this site due to a number of contributing factors:

(i) water became perched at the soil–bedrock interface and remained highly sensitive to increases in rainfall intensity;
(ii) complete saturation of the soil mantle developed;
(iii) three-dimensional drainage (i.e. convergence) into the hollow from highly conductive sideslopes would have further exacerbated the build-up of saturated conditions;
(iv) the highly concave shape of the hollow base was such that it could not distribute the perched groundwater sufficiently to prevent rapid water-table elevational increases;
(v) the Old Man Gravel bedrock surface was covered by a thin layer of allophane-rich organic clay.

Bypassing and pipeflow, in association with the above factors were probably the most important causal factors in initiating slope failure. In some situations pipes may improve slope stability by increasing the rate of soil drainage and limiting the development and longevity of perched water-table conditions. On the other hand, if bypass flow increases the rate of vertical infiltration and exceeds the rate at which the anastomosing pipes transmit recently infiltrated water downslope, a perched water-table quickly develops. In this example bypass flow certainly occurred under the storm rainfall intensities experienced and probably exceeded pipeflow drainage.

The relative hydraulic efficiency of bypass flow and pipeflow in the Maimai 8 hillslope zones is such that under 'normal' rainfall conditions perched water-tables develop and are quickly dissipated by pipe drainage. Even under reasonably high rainfall depths, perched water-tables in the monitored mid-slope area disappeared <12 hr after rainfall cessation. Several studies (e.g. Pierson 1980) have shown, however, that soils in apparently similar hollows (even on the same slope) may vary greatly in their susceptibility to slope failure due to subtle differences in soil moisture retention capacity, macropore configuration, etc. Blockage of pipes in the hollow area could be a possible factor, particularly since pipes were identified near the headscarp.

The build-up of hydrostatic pressures, both along the vertical cracks and at the soil–bedrock interface, may also be a contributing factor in flow initiation for the 19 May 1988 event. If the rate of water movement down a vertical crack is in excess of pipeflow transmission rates, water 'backs up' within the crack, exerting hydrostatic pressure on the crack walls and contributing to the overall disturbing forces. At the same time, rapidly moving pipeflow at the mineral soil base may produce upthrust pressures or buoyancy effects (Rogers & Selby 1980). Combined with drainage from surrounding topographic units this would be sufficient to generate failure, possibly aided by macropore blockage, as outlined by Pierson (1983).

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