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Hydrological behaviour of pastoral hill country modified by extensive landsliding, northern Hawke's Bay, New Zealand

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Abstract

The hydrological attributes of soils were investigated in three small (1.5 to 2 ha) first-order catchments affected by landslides in steep hill country near Lake Tutira, North Island, New Zealand. These attributes were related to streamflow generation during the winter months July-September 1996. The catchments were disturbed to varying degrees by landsliding before, during and after Cyclone Bola in 1988. Areas of the catchments were mapped and classified. The land surface condition classes included undisturbed land, and landslide scars and landslide deposits of three ages, with distinct differences in variables such as porosity, soil depth, water storage capacity and infiltration capacity. Streamflow hydrographs show that the catchments are very similar in the timing of runoff, which implies that their processes of streamflow generation are similar. The main processes are inferred to be saturation overland flow, subsurface stormflow along preferred pathways, and infiltration-excess overland flow. Hydrograph attributes related to volume of runoff differ between catchments. The hydrological response of the catchments is strongly controlled by topography, with variable/partial source areas in valley bottoms, swales, and a permanent wetland in one catchment. It also is controlled by the extent and distribution of landslide disturbance, and reflects landslide history. In this landscape, it is thus difficult to apply concepts of streamflow generation that assume a down-slope catenary arrangement of soils.

Introduction

Landsliding affects large areas of New Zealand's pastoral hill country, particularly in regions such as Taranaki, Marlborough, Gisborne, and

Hawke's Bay, where the bedrock consists of erodible mudstones and siltstones. The scars on the landscape left by shallow translational sliding of the regolith are a common sight, particularly in the years following major storms like Cyclone Bola in 1988. The landslides are commonly 1 to 4 metres deep and overlie a well-defined shear plane.

The effects of periodic landsliding upon soils, farm productivity, and water quality and sedimentation in downstream river systems are well recognised (Douglas and Trustrum, 1986; Hawley, 1984). The Esk Valley floods of 1938, whose severity was attributed to accelerated erosion by landsliding in the headwaters and increased sedimentation downstream, were a major influence on public thinking, and led to the enactment of the Soil Conservation and Rivers Control Act in 1941. Surprisingly, however, there has been very little evaluation of the effects of landsliding on streamflow generation, and extensive New Zealand research into runoff processes in forested or tussock grassland catchments (cf Woods and Rowe, 1996, and earlier references therein) may not be applicable directly to pastoral hill country subject to landsliding.

Many of the effects of landsliding upon the topography of hillslopes and the characteristics of the regolith should have hydrological consequences. Based on our observations of the geomorphic consequences of landsliding in the hill country, we offer several hypotheses:

1. Since regolith depth and volume decrease on the source area of a landslide and increase where the debris is deposited downslope, the soil moisture storage capacity will change accordingly.
2. Sliding of a soil mass disturbs the soil structure and texture, altering characteristics such as porosity, presence and continuity of macropores, and permeability, leading to changes in the soil moisture storage and rates of water movement through the regolith.
3. The characteristics of the ground surface and vegetation cover will be altered, particularly on landslide scars, with consequent changes in infiltration capacity and therefore in the rates of infiltration and overland flow.
4. As a consequence of these changes, the relative importance and spatial distribution of runoff-generating mechanisms (infiltration-excess overland flow, pipeflow, etc.) will be modified. So too will the locations and extent of streamflow source areas.
5. The hydrological behaviour of a catchment will thus be measurably affected by landsliding. The timing and size of streamflow peaks will be altered, and total runoff volumes may change.

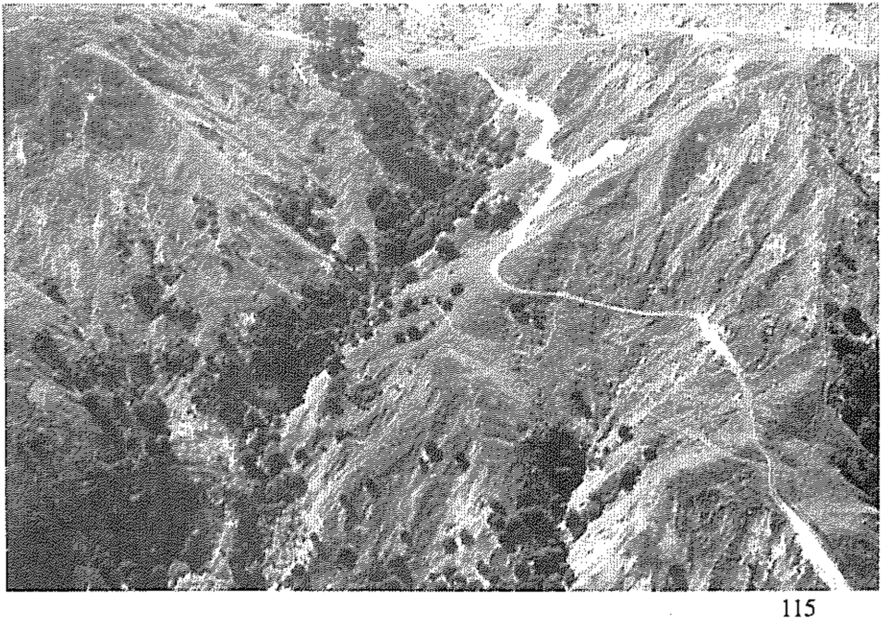
The likely directions of change are not always obvious, and may vary from place to place. This study was carried out in preparation for a study of the source areas of the contaminants in streamflow associated with pastoral agriculture in "hard" hill country. The ultimate aim is to determine whether landsliding has a significant and predictable influence on source areas and processes of streamflow, sediment and solute generation, to aid in the planning of remedial measures.

Study area

The study was carried out during the winter of 1996, in steep hill country one kilometre to the east of Lake Tutira, Hawke's Bay (Merz, 1996). Three first-order catchments, referred to as Kiwi, Tui, and Weka, were studied. They face northwest, have average slopes of 31-32 degrees, range in elevation from 235 to 370 m asl, and are 1.5 to 2 hectares in area. They are typical of extensive areas of the New Zealand hill country affected by landsliding (Fig. 1). The lower parts of the catchments have well defined but ephemeral stream channels about one metre wide.

The catchments are underlain by a soft, unconsolidated marine sandstone (Darky's Spur Sandstone), blue-grey massive mudstone, and a band of coarse limestone. The strata dip at 2 to 10 degrees towards the south-east; they are of Late Pliocene age. A number of tephra layers have been

Figure 1 – Oblique aerial view of the study catchments.



identified in the area (Eden *et al.*, 1993); the Taupo Tephra (1850 years B.P.) and the Waimihia Tephra (3280 years B.P.) are the most widespread (Page *et al.*, 1994).

The hillside on which the catchments are located forms the southern boundary of the Lake Tutira catchment. The hillside is dissected by spurs and swales, and has been extensively affected by translational landslides and rapid earthflows. In the study catchments, the regolith cover over about 80% of the surface area has been disturbed by landsliding. The valleys that lead from the foot of the hillside to Lake Tutira are infilled with alluvial sediments, with landslide debris deposited mostly as colluvial footslopes at the bottom of the hillside. Pipe erosion and gully erosion are also in evidence.

The catchments are largely covered in pasture, with scattered cabbage trees, the occasional pine tree, and kanuka-manuka-gorse shrubland in places along the stream channels. The original podocarp-hardwood forest was cleared long ago, and is not considered to have any residual effects on the hydrological behavour of the catchments. The catchments are grazed by sheep and cattle, all within the same paddock, although livestock appear to prefer different localities depending on conditions. A farm track cuts through the centre of catchments Tui and Kiwi, with a steep cut face in places on the upslope side. During the measurement period, the track was bulldozed to remove landslide debris, which temporarily modified the pathway of water flowing from the cut face and led it out of the catchment.

Mean annual rainfall at Tutira, 2.5 km to the west, is 1,440 mm (1951-80). The wettest months are July-August, with 32% of annual rainfall, and the driest months are September-November, with 19% of the annual rainfall. However, rainfall is highly variable. There can be long droughts, particularly in summer, and intense rainstorms, predominantly in autumn. The most recent intense strom was Cyclone Bola in March 1988, during which 750 mm of rainfall was recorded in four days at Tutira. During July-September 1996, when hydrological observations were carried out, precipitation at Tutira was representative of long-term conditions, with a July total of 199 mm (long-term mean of 148 mm), and an August total of 111 mm (long-term mean of 131 mm); the Tutira gauge was not operating during September. Fifty-six rain events were recorded during the period, none of notable magnitude or intensity. The largest event was 72 mm on 9/10 August 1996, and the highest 10-minute intensity was 2.66 mm/10 min, on 9 August.

Instrumentation of the catchments

Discharge from each catchment was monitored using a Hydrological Services Pty quadrature water-level sensor and float, feeding into a RRDL-3 datalogger. The catchments each were equipped with a 90° V-notch weir, with an alloy weir plate, to provide a stable control; plywood cutoff walls were anchored to the bedrock surface with concrete, and buried plastic sheet was used to limit subsurface flow around the weirs. The theoretical weir rating was calibrated using volumetric measurements of discharge, since the dimensions of the weir ponds in the narrow and steep valley bottoms were less than the recommended values. The accuracy of discharges calculated from the stage-discharge rating is estimated to be +/- 0.07 l/s of the true value. Seepage of about 0.002 l/s was observed at Kiwi weir, and this figure was added to calculated discharges.

Precipitation was monitored at a site on the boundary between catchments Kiwi and Tui, using a 0.2 mm tipping-bucket raingauge (Hydrological Services Pty TB3). Comparison of daily totals with those recorded at the nearby Tutira Station raingauge indicate no consistent measurement errors.

Soils and surface condition of the catchments

Processes of streamflow generation are intimately related to the characteristics of the soil cover in a catchment, and we hypothesise that disturbance by landsliding of the soil cover in the study catchments modifies those characteristics.

Under undisturbed conditions, Patoka-Tutira soils would be expected in the catchments. These are moderately to strongly leached intergrades between yellow-brown pumice soils and yellow-brown loams (Pohlen, 1971), with an A horizon up to 30 cm thick, a B horizon that may contain pumice from the underlying layer of tephra, and a C horizon of very weathered mudstone or sandstone. However, such soils are largely restricted to the spurs and ridges.

The catchments have been extensively affected by landsliding and other processes of surface erosion, and disturbed soils are widespread. Soil profiles are truncated in the landslide scars where soil has been removed; deposition has produced composite soils profiles, with buried soil horizons, in landslide runout zones. The distribution of disturbed soils in the catchments is complex, because of the history and spatial distribution of landsliding. The distribution has been mapped using aerial photographs taken on 8 April 1988, shortly after Cyclone Bola, and a detailed field survey (Fig. 2). A classification of land surface conditions has been developed, modified from that of Preston (1996). Its nine classes are based on the age and nature of disturbance (the codes used in the figures are in parentheses):

Undisturbed material (U). No disturbance by erosion or sedimentation is apparent at the surface, and the soil profile shows well developed horizons. The presence of tephra layers may confirm lack of disturbance for some thousands of years.

Disturbed material (D). There is evidence of erosion by processes like tunnel gullying and creep, but not of translational landsliding, and the soil profile is similar to that of undisturbed sites. Only limited areas in the catchments fall into this class.

Recent landslide scar (RS). A landslide has removed some or all of the soil mantle since April 1988, vegetation has not recolonised the scar, and there has been no soil redevelopment on top of the bare bedrock surface or former soil horizon.

Bola landslide scar (BS). A landslide during Cyclone Bola created a fresh scar (visible on the April 1988 aerial photograph), on which there has been partial recolonisation of the shear plane by vegetation and very limited soil redevelopment, in the form of a thin H (humus) horizon.

Pre-Bola landslide scar (PS). Topography and the development of soil horizons provide evidence of a landslide before Cyclone Bola. The soil now shows a well-developed A horizon, although a B horizon has not yet developed, and revegetation is complete.

Recent landslide deposits (RD). The site is covered by the jumbled, redeposited material from a recent (post-Bola) landslide; the structure of the pre-existing, buried soil is visible in parts of the deposits, and there is little or no recolonisation by vegetation. Soil material transported by water may be deposited between clods, and there may be impeded drainage and weak gleying.

Bola landslide deposits (BD). The site is covered by the redeposited material from a landslide which occurred during Cyclone Bola, and which was visible on the April 1988 aerial photograph. Under a thin H horizon, soil redevelopment is in its early stages in the redeposited soils overlying the buried soil(s), and vegetation has recolonised the site.

Pre-Bola landslide deposits (PD). The site is covered by the redeposited material from a landslide which predates Cyclone Bola; with an A horizon up to 20 cm deep, the soil shows well-developed horizons above the pre-existing buried soil(s), and the site is fully vegetated.

Alluvial surface (A). The site is characterised by a soil developed in alluvial material deposited by fluvial action. Areas in this class are very limited in the catchments. Catchment Weka contains a valley bottom wetland which tended to be frequented – and disturbed – by livestock, but this has been classified as Bola landslide deposits.

The three catchments have different proportions of areas with these land surface conditions (Table 1). Kiwi is disturbed by pre-Bola landslides over 75% of its area, with a few Bola landslides but no post-Bola landslides.

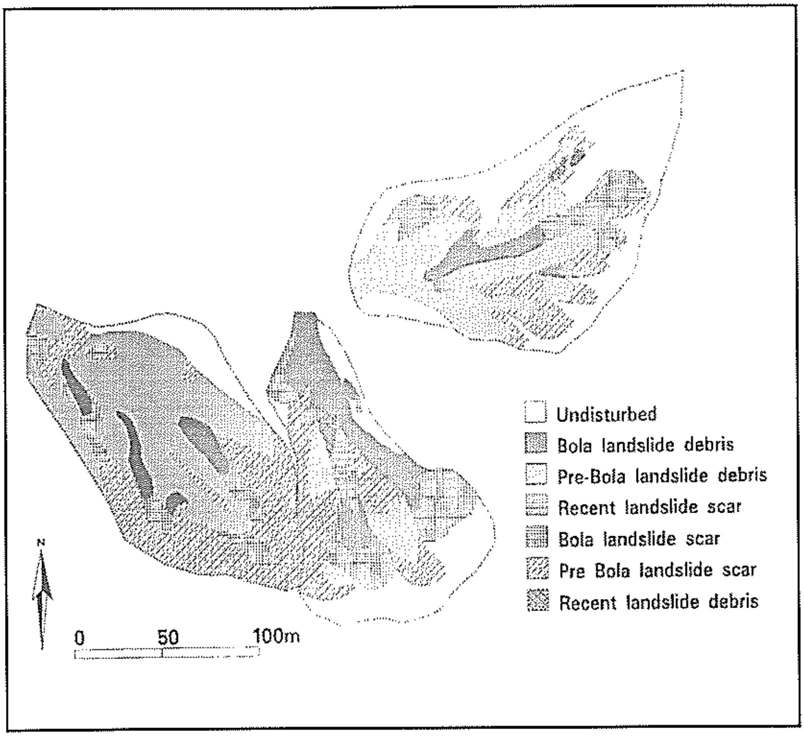


Figure 2 – Land surface conditions, August 1996.

Tui has been heavily disturbed by landsliding more recently, with 35% of its area affected by Bola landslides, and nearly 40% affected by pre-Bola landslides. Weka has the largest area, 36%, of undisturbed land surface; otherwise, it has been affected predominantly (46% of the area) by pre-Bola landsliding.

Table 1 – Catchment characteristics

Catchment	Total deposits	Undisturbed scar	Recent scar deposits	Recent deposits	Bola scar	Bola deposits	pre-Bola scar	pre-Bola deposits
	Area (square metres, and %)							
Weka	20260	7290 (36%)	205 (1.0%)	100 (0.5%)	1590 (7.8%)	1720 (8.5%)	3800 (19%)	5550 (27%)
Kiwi	20140	1730 (8.6%)	0	0	1950 (9.7%)	1280 (6.4%)	7830 (39%)	7350 (37%)
Tui	15320	3420 (22%)	260 (1.7%)	340 (2.2%)	2870 (19%)	2480 (16%)	3450 (23%)	2520 (17%)
Combined	55720	12440	465	440	6410	5480	15080	15420
(percentage)		22%	1%	1%	12%	10%	27%	28%

	Mean slope (degrees	Elevation range (m asl)	Mean soil depth (m)
Weka	31	280 to 380	0.97
Kiwi	32	235 to 370	0.85
Tui	31	280 to 370	0.82

Soil characteristics affecting hydrology

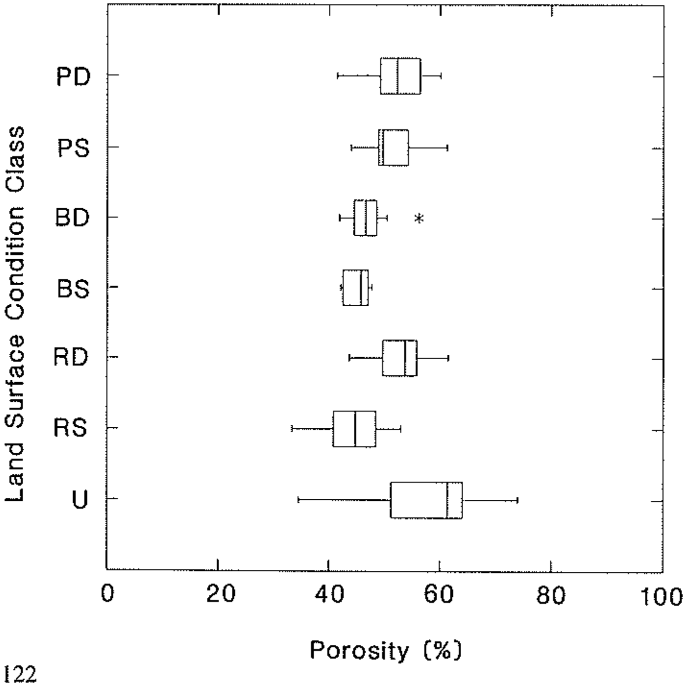
Because of extensive disturbance of the study catchments by translational landsliding, the classic catena model does not apply well to their soils. The hydrological characteristics of soils have therefore been investigated by sampling at representative sites for each of the land surface condition classes identified above, in each of the three catchments (Fig. 2). Soil samples were taken with cylinders of known volume and weight, and weighed in the field and after oven-drying for 24 hours. Samples were analysed for a total of 107 sites (Merz, 1997, Appendix IX). As is normal, there was a high degree of variability among sites in each class, apparent in the box and whisker plots of Figures 3 and 5. No spatial pattern was evident in the within-class variability in soil characteristics, and sample sizes are too small to discriminate among the land surface condition classes in the three catchments. The data for all samples in each class have been aggregated for the three catchments, to estimate overall averages for the classes.

Porosity

Porosity, the ratio of the volume of voids to the total volume of a soil sample, together with texture, influences the water-holding capacity and hydraulic conductivity of a soil, and is an indicator of its degree of compaction. Typically, New Zealand soils have porosities of 30-60% (McLaren and Cameron, 1990). Porosities tend to increase with increasing organic matter content and with the presence of macropores such as wormholes, and may be reduced by stock trampling and other compaction. Porosity normally decreases with depth, due to reduced organic matter, fewer roots, compaction by the overlying soil, and less aggregation at depth. Landsliding alters regolith porosity at the source by removing the upper soil horizons of higher porosity, leaving the lower horizons of lesser porosity. At other sites those same soil horizons are deposited on the pre-existing soil, and the porosity of the soil mass may be further modified during translation downslope.

In the study catchments, porosity generally lies in the range 40-60%. Considerable spatial variability within each land surface condition class means that pair-wise differences in average porosity of the classes are statistically significant in only a few cases (Fig. 3, based on 107 measurements of porosity). Average porosity on undisturbed sites is higher than on areas in other land surface condition classes, which is ascribed to deep A and B horizons, macropores created by plant roots and animal burrowing, and the presence of tephra. Mean porosity of the upper (A/B) horizons is 65%, and of the C horizon is 48%. Regolith on areas in the erosional land surface condition classes tends to consist of the former low-porosity C horizon, although their mean porosities increase with increasing age, as soil redevelops by addition of organic matter and bioturbation. Depositional land surface condition classes have higher mean porosities than erosional surfaces of the same age, because the former upper horizons from the landslide source area are added to the pre-existing soil profile (it should be noted that a landslide may come to rest on an earlier erosional surface, and not necessarily on a well-developed soil). Recent landslide deposits tend to have higher average porosity than earlier deposits, because the landsliding creates ruptures and fissures, and the newly exposed soil may crack when desiccated. Such macropores tend to collapse and fill with time, reducing porosity, but porosity may increase again as vegetation re-establishes and animal burrowing adds organic matter and creates new macropores.

Figure 3 – Mean soil porosites in seven land surface condition classes. The left and right sides of the 'boxes' show the 25th and 75th percentiles, the inner vertical shows the median, and the 'whiskers' show the extreme values. An asterisk is an outlying data point.



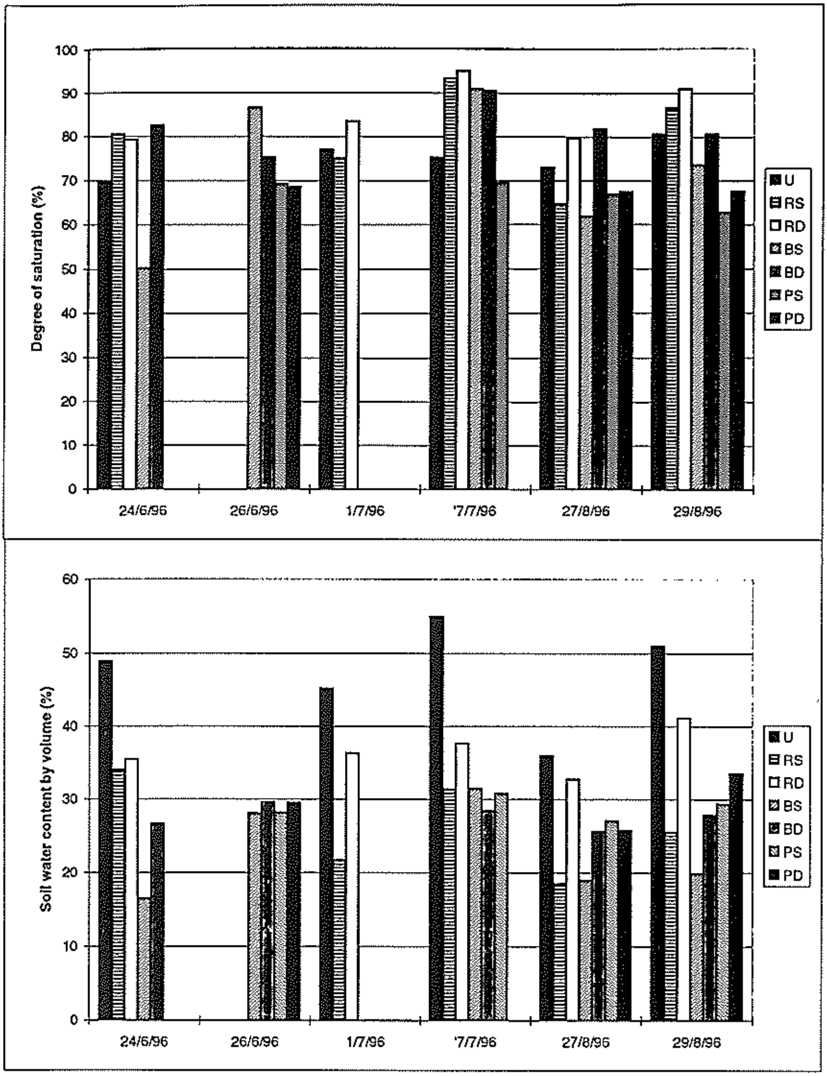
Volumetric soil water content and saturation

The water-holding capacity of a soil is influenced by porosity, depth and grain size distribution, and the soil water content at a given time determines the ability of the soil to absorb more water during rainfall. Volumetric soil water content (the ratio of volume of water to total volume of soil sample, expressed as a percentage) was sampled at sites representative of all the land surface condition classes on four separate occasions (Fig. 4). Undisturbed sites (which are found on the spurs and ridges around the catchment perimeters, and should dry out most readily) always have the highest average soil water content, and their water content tends to vary least with time. Recent and Bola landslide scars have the lowest soil water contents, lower than those of the landslide deposits of similar age. These scars appear to dry out rapidly after rainfall, since their soil water content varies substantially. Their limited ability to retain the water which infiltrates is probably due to their lack of protection by vegetation or an upper organic horizon, permitting high rates of evaporation.

Pre-Bola landslide scars and deposits had very similar average soil water contents on all sampling occasions, higher than all other classes except for undisturbed sites and recent landslide deposits. This indicates that soil development is returning their hydrological characteristics towards those of the undisturbed sites. The average soil water contents of recent landslide deposits are closest to, but still significantly less than, those of undisturbed sites. This may be because the fissures and other macropores created during the landsliding are unconnected, allowing storage but not downslope transmission of water.

From measurements of porosity and percentage soil moisture content, we calculated the degree of saturation, an indicator of the ability of the soil to absorb additional moisture at the time of sampling (Fig. 4; Table 2). Recent and Bola landslide scars show the greatest variability over time, ranging from 65% to 93% and from 50% to 91% saturation respectively. They probably dry out rapidly after rainfall because they have the greatest exposure to the drying effect of wind and sun. Recent and Bola landslide deposits have intermediate variability, ranging from 79% to 95% and from 75% to 90% respectively. This probably reflects the presence of fissures and poorly developed soil structure, which allow rapid re-wetting and drainage during and after rain. The degree of saturation on undisturbed sites ranges between only 70% and 81%, indicating both that these soils are unlikely to reach saturation during a rain event and also that, because of their well-developed structure, they can hold moisture after an event.

Figure 4 – Volumetric soil water content and degree of saturation of sites in different land surface condition classes.



Interestingly, the degree of saturation of both pre-Bola landslide scars and deposits has the smallest range of values, for reasons that are unclear.

The degree of saturation in the valley bottoms, measured on four occasions, ranges from 80 to 90%, irrespective of antecedent precipitation. Flow from the hillslopes above presumably maintains the moisture content at these sites.

Table 2 – Selected soil characteristics of sites in the land surface condition classes

				Degree of saturation (%)			Infiltration capacity			
	Percent area of 3 catchments	Mean regolith depth (cm)*	Mean porosity (%)	Minimum	Maximum	Range	Mean (mm/h)	Standard deviation (mm/h)	Sample size	water holding capacity (mm)**
Undisturbed	22	111	62	70	81	11	37	25	10	169
Recent landslide scar	1	2	44	65	93	28	4	4	6	2
Recent deposits	1	91	55	79	95	16	64	53	5	65
Bola landslide scar	12	10	45	50	91	41	27	34	8	13
Bola deposits	10	120	46	75	90	15	23	22	7	97
pre-Bola landslide scar	27	44	49	63	70	7	115	71	5	72
pre-Bola deposits	28	129	52	67	69	2	68	44	6	215

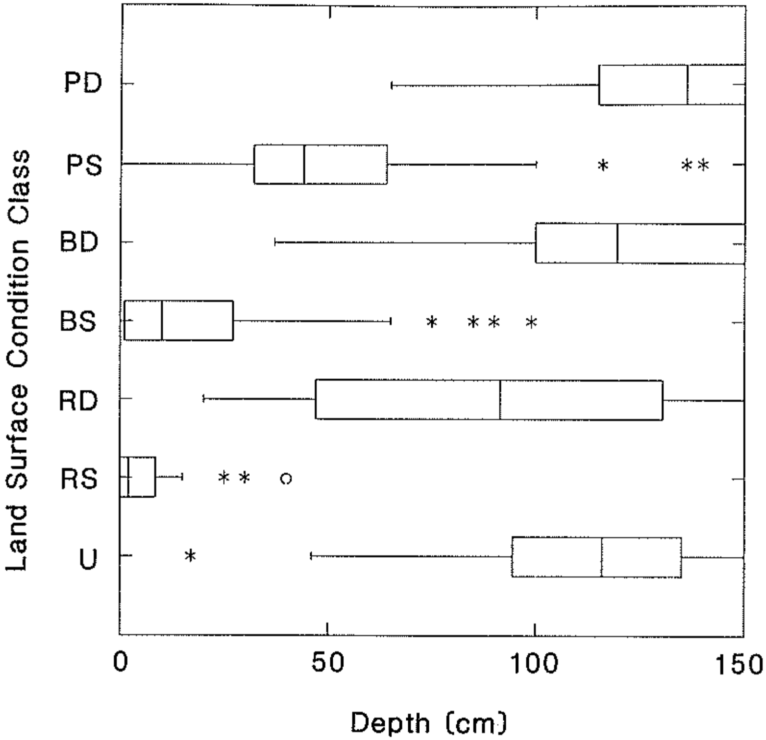
* Values are a minimum, since the bedrock surface was not reached at all measurement points.

** Calculated as the product of mean regolith depth, mean porosity, and 100 less the average of minimum and maximum % saturation."

Regolith depth

Regolith depth to the bedrock interface was measured perpendicular to the ground surface, using a steel probe of 1.5 m length. Over 360 measurements were made, distributed randomly over the land surface condition classes (Fig. 5). Depths greater than 1.5 m were encountered on depositional sites (38% of pre-Bola, 32% of Bola, and 5% of recent) and undisturbed sites (9%), and were recorded as >1.5m. There were no evident differences in regolith depths for a given class in the three study catchments. However, a Kruskal-Wallis H test indicates significant differences in mean regolith depths among the classes (Table 2). Depths on erosional surfaces are less than on undisturbed surfaces, and on Bola and pre-Bola depositional surfaces they are greater than on undisturbed surfaces (average depths for these surfaces are underestimates, because depths exceeded the length of probe available). Regolith depth on erosional surfaces tends to increase with increasing age of the surface.

Figure 5 – Regolith depth of different land surface condition classes. See the caption of Figure 3 for an explanation of the box and whisker plots.



Infiltration capacity

Infiltration capacity was measured with a single ring infiltrometer at nearly fifty sample sites distributed randomly across the land surface condition classes. Several measurements were made in a 1 m^2 area around each site, after periods of no rainfall (Table 2). As is usual with measurements of infiltration capacity (Sharma *et al.*, 1980), a large variation at sites and within classes was observed, presumably due to variations in macropores, vegetation root mats, etc., as well as to difficulties in measuring infiltration on the steep hillslopes. Consequently, statistically significant differences between classes cannot be determined. Recent landslide scars have markedly lower infiltration capacities than land in any other class, but otherwise there is no clearly interpretable pattern.

Summary: effect of landsliding on the hydrological characteristics of the regolith

Regolith in the three catchments displays significant features associated with landsliding. At a "typical" undisturbed sample site, the soil has well-developed structure and horizons, a mean depth to bedrock of at least 111 cm, a mean porosity of 60-65%, a saturation in the range 70-80%, and a mean infiltration capacity of 37 mm/h. With these values of depth, porosity and saturation, the undisturbed soil would be able to absorb about 170 mm of precipitation before reaching saturation. Except in the most extreme storms, it would be unlikely to become saturated and be a source of overland flow, but because of the abundance of macropores (root channels, wormholes, pipes), it might be a source of rapid subsurface stormflow, as well as delayed subsurface flow as water moves downslope. Land in the undisturbed land surface condition class forms only 22% of the total area of the catchments.

A series of landsliding episodes has created a complex pattern of truncated (landslide scar classes) and composite (landslide deposit classes) soils, whose hydrological characteristics and behaviour may differ significantly from those of the undisturbed sites and land in the other classes (Table 2). Recent and Bola landslide scars, which constitute only 13% of the total area of the catchments, have average regolith depths of less than 10 cm, mean porosities of about 45%, a wide range of values of percent saturation, and infiltration capacities that are markedly lower than those of the undisturbed sites. In contrast to the 169 mm mean capacity of the undisturbed soils, their water-holding capacity is only a few mm, and they would be likely to generate both infiltration-excess overland flow or saturated overland flow much more frequently.

Only pre-Bola landslide deposits, which form 28% of the catchments, on average have a water-holding capacity greater than that of the undisturbed soils, 215 mm (Table 2). Where these deposits are located in the valley bottoms, they tend to be close to saturation, because of topographic position. The remaining classes, Recent deposits, pre-Bola scars, and Bola deposits, have average available water-holding capacities that are intermediate between those of undisturbed soils and recent/Bola landslide scars, in the range 60-100 mm (Table 2). However, these classes do not have a great deal of similarity in terms of the other soil characteristics (Table 2), and their hydrological behaviour is unlikely to be the same.

In total, about 22% of the land in the three catchments is in land surface condition classes with lower than average available water-holding capacity and/or valley bottom locations, with catchment Tui having 37% of its area in such classes.

Runoff characteristics

Runoff from the three catchments was monitored over the three-month period July-September during the winter of 1996, to explore whether runoff reflects the varying extent of disturbance by landsliding within the catchments (Table 1). July and August are normally the wettest months, and evapotranspiration is at a minimum, so it was expected that streams would flow during this period, whereas during other months, especially during summer, they might not. However, a more comprehensive understanding of runoff in the catchments requires observations throughout the year.

Fifty-six rainfall events were recorded at the recording raingauge in catchment Tui, of which 18 produced hydrograph rises. The total 3-month rainfall was 383 mm, in comparison with a long-term (1895-1994) mean of 380 mm at the nearby Tutira raingauge. No notably large daily totals or intensities were recorded during the period; the largest event total was 72 mm, and the highest intensity was 2.66 mm/10 minutes. Mean potential evapotranspiration was estimated, using the Thornthwaite method, to be 0.8, 1.0 and 1.4 mm/day in July, August, and September.

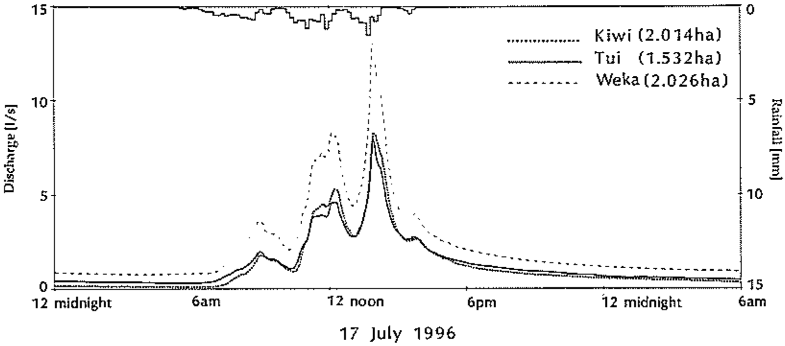
The hydrological behaviour of the three catchments can be described and compared using characteristics of their hydrographs. Quickflow and baseflow are separated by the straight-line method, with a line drawn from the start of the hydrograph rise to the breakpoint on the recession limb. With the hydrograph drawn on semi-log graph paper, the breakpoint was easily defined (cf Fig. 6).

Hydrograph shape

Hydrograph shapes are very similar in the three catchments, down to the smallest detail of rises and falls, with steep rising and falling limbs (Fig. 6). It is inferred that streamflow during storm periods is generated by processes which respond rapidly to precipitation, and also that the same processes are operating in all three catchments.

Flow occurred in catchments Kiwi, Tui, and Weka during 10%, 25%, and 100% of the time, respectively. The continuous runoff from Weka during the study period is probably sustained by flow from a wetland near the top of the catchment. The wetland is downslope from an extensive, rounded ridge-top at the northeast corner of the catchment that is mantled with soils largely undisturbed by mass movement (Fig. 10; see also the top left of Fig. 1). Delayed flow from the ridge-tops and slopes above the wetland (the area of which is 960 m^2 and the contributing area to which is approximately 5,000 m^2) would be sufficient to maintain the 0.3 l/s baseflow observed in Weka during July, when total precipitation was 232 mm. During visits in April and December 1996, there was no flow, which indicates that long-term flow in Weka is ephemeral.

Figure 6 – Discharges during the event of 17 July 1996. Note the relationship between discharges from the three catchments and their areas.



Wetting rainfall (P_w, rainfall between start of precipitation and start of hydrograph rise)

Median values are 0.4 mm (range 0 to 3.2 mm) for Weka, 1.2 mm (range 0 to 7.2 mm) for Tui, and 3.2 mm (range 1.2 to 6.6 mm) for Kiwi, reflecting the wetland in Weka, the lesser degree of Bola and recent landsliding in Kiwi, and the relative extent and spatial distribution of source areas (see below, and Fig. 9). Several rainfalls generated runoff only in Weka, all less than 2 mm total. There is a significant correlation of 0.52 between P_w and Antecedent Precipitation Index API, where API $=\sum_{i=1}^{30} P_i/i$, in which P_i is precipitation (mm) on the ith preceding day. There are no significant correlations between P_w and other rainfall characteristics, such as intensity. Since the catchments are steep and distances from runoff source areas to the weirs are short, P_w probably is influenced predominantly by antecedent soil and vegetation conditions, rather than by routing of runoff through the channel system.

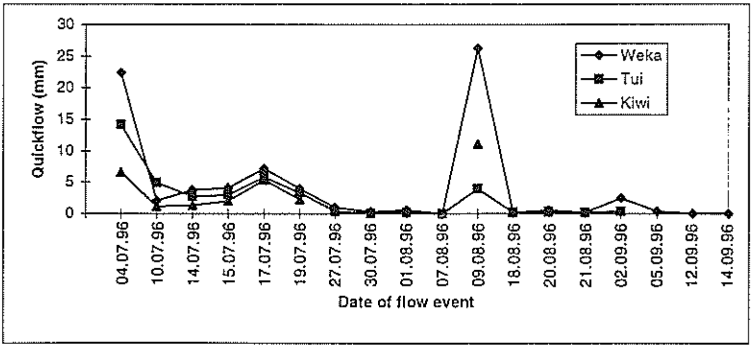
Lag time (T_{lag}, the time between the maximum 10-minute rainfall intensity and the hydrograph peak).

There are no significant correlations between T_{lag} and any other rainfall or flow characteristic. For a given flow event, all three catchments peak within 1-2 minutes of each other. The median value is 23 minutes (range 3 to 83 minutes) for the 18 events in Weka, with two modes at around 25 and 75 minutes. The similarity of lag times is inferred to reflect similarities in the shape, steepness, and drainage networks of the three catchments.

Quickflow (Q_{sum}, the depth of runoff during the event, contained in the hydrograph above the baseflow separation line).

The correlation between quickflow volume in Weka and both total rainfall P and net rainfall $(P - P_w)$ is 0.96, and between quickflow volume and peak discharge it is 0.91. Quickflow is responsible for up to 97% (with an average of 59%) of the flow during an event in Weka, and up to 100% (with an average of 85%) in Tui. It is usually greatest in Weka and smallest in Kiwi (with very similar catchment areas of 2.026 and 2.014 ha respectively), and intermediate in Tui (area of 1.532 ha) (Fig. 7).

Figure 7 – Quickflows during flow events of July-September 1996. On 9 August, water was lost from Tui because of diversion along the farm track, so the recorded quickflow value is an underestimate.



Runoff coefficient (Q_{roc}, the ratio of quickflow and net rainfall)

Q_{roc} varies widely, up to about 35% in Weka during the two largest (66 and 72 mm) rainfall events. Weka had the largest value in ten events, and Tui the largest value in three events (Fig. 8). Kiwi, disturbed least by recent and Bola landslides, almost always had the smallest value.

The generally low value of Q_{roc} suggests that a large part of precipitation does not leave the study catchments as streamflow. An approximate water balance for July and August can be calculated for Weka and Tui, using measured rainfall, estimated potential evapotranspiration, measured streamflow, and changes in soil water storage estimated from catchment-wide soil moisture samples obtained on 24 June and 27 August (Table 3). The water balance for Kiwi cannot be calculated because of gaps in the streamflow record. There is a large uncertainty in the estimate of potential evapotranspiration, but the amount of precipitation unaccounted for as measured or estimated output indicates that a substantial percentage– 65% in Tui and 36% in Weka during the two-month period–infiltrates the underlying sandstone and limestone bedrock, and leaves the catchments as groundwater flow. During summer months, average precipitation is less and potential evapotranspiration is greater than during the winter, so soil moisture storage is likely to be reduced. A year-round monitoring programme, including improved estimation of evapotranspiration, would be necessary to clarify the water balance of the catchments, but groundwater flux would be difficult to measure.

Figure 8 – Runoff coefficients during flow events of July-September 1996. On 9 August, water was lost from Tui because of diversion along the farm track, so the value of runoff coefficient is an underestimate.

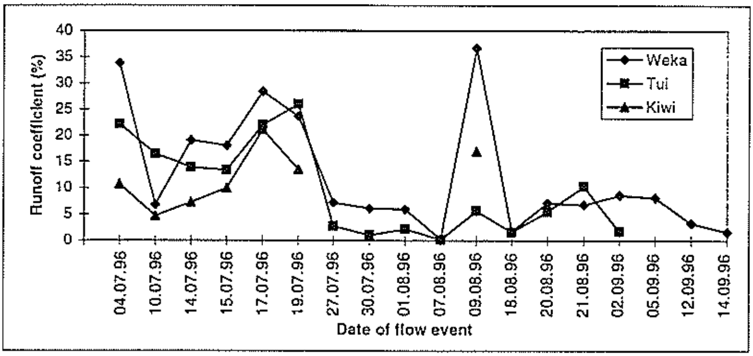


Table 3 – Approximate water balance, catchments Tui and Weka, July-August 1996

Component (mm)	Tui	Weka
Precipitation	343	343
Potential evapotranspiration	56	56
Streamflow	61	154
Change in soil moisture storage, 24 June-27 August	2	10
Total output and change in storage	119	220
Input not accounted for	224	123
(percent of input)	65%	36%

Processes and source areas of streamflow generation

Weka was the only catchment to have continuous baseflow during the study period, although the catchment is best classified as ephemeral, as there was zero flow in Weka in April and December 1996. Sustained seepage into and through the wetland near the head of the catchment is probably the principal reason for this baseflow (see the discussion of hydrograph shape, above). Weka also was more responsive to rainfall (in terms of the runoff coefficient and the quantity of rainfall needed to cause a hydrograph rise), again because of the presence of the wetland. Despite these distinctive characteristics of Weka, hydrographs in all three catchments responded in a very similar way to rainfall, which suggests that similar processes of streamflow generation are active. Differences can be observed in the hydrological characteristics and behaviour of the different land surface condition classes, but topographic position also influences hydrological behaviour of the catchments, in line with the variable/partial area concept of streamflow generation. Since land surface condition is partially related to topographic location, the hydrological effects of these two variables are difficult to isolate.

During rainfall, surface water is evident in many locations in the catchments. These include the axes of zero-order swales (Fig. 9), depressions in the ground surface, areas trampled by stock (especially in the valley bottom in Weka), along the farm track and its cut slope, on recent and Bola landslide scars, and on areas of recent and Bola landslide deposits, where frequent ponding of water indicates impeded drainage. Surface water was observed even on the upper parts of the catchments during the largest rainfall events during the study period.

Figure 9 – Surface water running down a zero-order swale during rain on 5 July 1996. Note the effect of stock trampling.

Infiltration-excess (Hortonian) overland flow was observed on recent and Bola landslide scars in the catchments; rainfall intensity exceeded the average infiltration capacity of recent landslide scars (3.7 mm/h) on six occasions during the three-month study period. The 10-minute, 1-hour, and 6-hour rainfall intensities with a recurrence interval of 5 years at Tutira are estimated to be 11 mm/10 minute, 28 mm/hour, and 80 mm/6 hours (Tomlinson, 1980), so that infiltration-excess overland flow also can be expected periodically on Bola landslide scars (with an average infiltration capacity of 27 mm/hour). However, the extent of landslide scars and their connection with the drainage system are insufficient to account for more than a small percentage of quickflow in flow events during the study period.

Pipes and collapsed pipes/gullies are evident in several places in the catchments, principally on undisturbed surfaces and in pre-Bola landslide deposits. In the latter, the pipes are usually at the contact between the buried soil and overlying deposit. Return flow is observed at landslide headwalls–and also at the cut slope along the farm track–during storms; the water then runs downslope across the landslide scars.

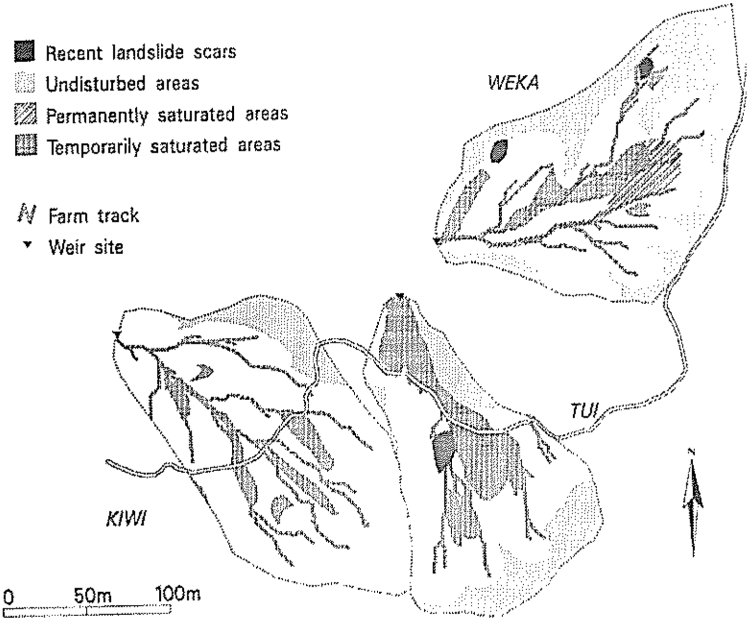
The combination of rapid subsurface flow through pipes and macropores in the well-structured undisturbed soils, return flow at landslide headwalls, and overland flow over a landslide scar, can rapidly deliver water from the upper slopes to landslide deposits in and adjacent to the saturated valley bottoms, and therefore contribute to streamflow during the hydrograph peak.

In summary, the full range of streamflow generating mechanisms appeared to operate in the catchments during the study period, with their relative importance varying among land surface condition classes. From direct observations during rain and the measurements of soil hydrology summarised in Table 2, the principal source areas for stormflow in the study catchments can be delineated (Fig. 10).

- A core area, comprising the channels and permanently saturated areas in the valley bottoms that are largely composed of landslide (colluvial) deposits, contributed to stormflow by direct precipitation during rainfall of more than one or two millimetres.
- Temporarily saturated areas in the valley bottoms and swales, which reach saturation during rainfalls, form variable source areas of saturation overland flow and return flow (Anderson and Burt, 1978; Dunne and Black, 1970; McColl *et al.*, 1985). Their locations reflected topography and landslide history–in particular, they include the scars, headscarps and deposits created during Cyclone Bola and more recent events.
- Infiltration-excess overland flow was generated during moderate rain on recent landslide scars (with a mean infiltration capacity of 3.7 mm/hour: Table 2), and would probably be observed on Bola scars (with a mean infiltration capacity of 27 mm/hour: Table 2) in heavy rain.
- Storm period pipeflow and macropore flow are characteristic of well-developed soils that are undisturbed by landsliding, and of older landslide deposits in which preferential flow pathways have been created by subsurface flow at the surface of the buried soils. No measurements were made of downslope rates of subsurface matrix

flow, but the near-saturated conditions of the valley bottoms and swales during periods without rain provide evidence for this process.

Figure 10 – Suggested source areas for stormflow during July-September 1996.



Discussion of hypotheses

The study provides evidence of hydrological differences between areas in the several land surface condition classes (undisturbed; landslide scars and deposits of recent, Bola, and pre-Bola age) in the catchments. There is considerable within-class variability in the hydrological characteristics of soils, and an impracticably large sampling programme would be needed to establish statistically significant differences between classes. There appeared to be no spatial pattern to this within-class variability. It is difficult to separate the hydrological effects of disturbance by landsliding from those associated with the distribution of topographically-controlled streamflow source areas.

(1) **Regolith depth** is reduced to an average of 2 cm on recent landslide scars and averages 120-130 cm where translated material is deposited, compared to an average depth of 111 cm on undisturbed areas. Available water-holding capacity is reduced almost to zero on fresh landslide scars, but recovers towards the average of 169 mm for undisturbed land as the scars age. There is no consistent pattern for available water holding capacity on landslide deposits, however, because of the varying regolith depth, porosity, and degree of saturation in the different sampling locations.

(2) **Soil structure** and texture are modified substantially, with a near-total loss of regolith on many scars, and loss of structure in the translated material. On fresh scars, infiltration capacity and water-holding capacity are reduced to almost zero (Table 2). In landslide deposits, porosity tends to be below that of undisturbed sites, but macroporosity appears to increase, at least initially, due to the formation of fissures during mass movement. On the other hand, the presence of standing water in places on recent and Bola landslide deposits, and their high percent saturation, indicate that drainage of water is reduced, so that the average available water-holding capacity is less than that of undisturbed sites. This is presumably because of the loss of soil structure, and the disruption of macropores (root channels, worm holes etc.) that could rapidly convey water away from an undisturbed surface. Pre-Bola landslide deposits, on the other hand, have had time to re-develop characteristics more like those of undisturbed sites, so that the moisture storage capacity of these soils is in some places greater than on undisturbed sites (Table 2).

(3) The observations on **infiltration capacity** are inconclusive, except that on recent and Bola scars it is below that of undisturbed sites. Both pre-Bola scars and deposits have higher infiltration capacities than undisturbed sites. Observations of stock grazing preferences indicate that compaction by stock trampling may be greater on the undisturbed sites on the spurs than on the midslopes. Measurements, preferably using a spray infiltrometer, are required to investigate this further.

(4) **Runoff generation** in the three catchments strongly reflects the presence of permanently and near-saturated areas in valley bottoms and swales, and particularly of seepage through a wetland at the head of Weka. Hydrograph shapes and the timing of runoff are similar in all catchments, and are consistent with a combination of saturation overland flow, rapid subsurface stormflow through preferred

pathways, and infiltration excess overland flow (Selby, 1993). The importance of these processes is indicated by both direct observation during rainfall and measurements of soil characteristics. The same mechanisms of streamflow generation appear to be operating in all catchments, despite differences in the extent and spatial distribution of the various land surface condition classes within the catchments.

(5) **Hydrograph attributes** related to the volume of runoff differ between catchments and reflect the relative extent and importance of partial source areas in valley bottoms, swales, and the wetland in Weka. Weka normally generated most runoff in response to rainfall, and seepage through the wetland is thought to be the source of sustained baseflow. Kiwi normally generated the least runoff in a rainfall event (Figs. 7, 8), which we attribute to the limited area (16%) of disturbance by Bola and recent landslides (Table 1), and the large area (76%) of pre-Bola deposits and scars, which have an intermediate to high ability to store water (Table 2). Tui, which is the smallest catchment but which has been most affected by Bola and recent landsliding, normally has the second highest volume of runoff. The lack in Tui of a valley-bottom wetland, like that in Weka, is believed to be compensated for by the extent of highly disturbed areas, and their proximity to the drainage network.

Conclusions

Virtually the full range of streamflow generating mechanisms that have been described in the literature can be observed in the study catchments; the variable/partial source area model can be used as the basis of their description (Beven and Kirkby, 1979; Woods *et al.*, 1997). However, the influence of mass movement on these mechanisms also is clear. Because of the complex distribution of areas in different land surface condition classes, with different landslide histories, soils and hydrological characteristics, and of saturated and near-saturated partial source areas partly controlled by topography, streamflow generation in the study area cannot be described simply in terms of topography and location on a hillside. The work of Woods *et al.* might suggest a way to tackle streamflow generation in hill country, if factors related to landslide disturbance can be included in the analysis. Characteristics which this study indicates are significant include the spatial variations in soil depth and horizon development, the nature of the soil surface and vegetation cover, the presence of features such as landslide scar headwalls, the porosity, infiltration characteristics, and location on the hillside of spurs and swales.

In terms of identifying source areas for contaminant runoff, to plan mitigatory measures, the study permits some tentative conclusions. Source areas for rapid runoff are, in particular, saturated and near-saturated areas in valley bottoms and swales, recent (Cyclone Bola and subsequent) landslide scars, areas trampled and pugged by livestock, and farm tracks from which water can run directly to the drainage system. To the extent that these locations are favoured by livestock–and many of them appear to be–runoff could be expected to have particularly high levels of contaminants.

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