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Analysis of landsliding caused by the February 2004 rainstorms in the Wanganui-Manawatu hill country, southern North Island, New Zealand

Science Report
2005/11

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July 2005

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Institute of Geological & Nuclear Sciences science report 2005/11

Institute of Geological & Nuclear Sciences Limited
Lower Hutt, New Zealand
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BIBLIOGRAPHIC REFERENCE

Hancox, G.T. and Wright, K., 2005. Analysis of landsliding caused by the 15-17 February 2004 rainstorm in the Wanganui-Manawatu hill country, southern North Island, New Zealand. *Institute of Geological & Nuclear Sciences science report* 2005/11. 64p.

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ISSN 1171-9184
ISBN 0-478-09888-X

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SUMMARY

The February 2004 rainstorm over the southern North Island caused extensive shallow landsliding over about 8000 km^2 of Manawatu–Wanganui hill country. The Mangawhero Valley was the area most damaged by landsliding, the Whangaehu, Turakina, and Pohangina Valleys were also badly affected. This study describes and compares the terrain characteristics (topography, vegetation cover, rocks, soils, slope angle, slope height and slope aspect) and the nature of the landslides in four study areas in the Mangawhero, Whangaehu, Turakina, and Pohangina Valleys where extensive landsliding occurred. The nature of the landsliding in these four areas can be attributed to terrain characteristics, with the most important factors affecting landslide susceptibility and distribution being: slope angle, slope height and aspect, the nature of the underlying rocks and soils, and the type of vegetation cover present. Variations in rainfall intensity also appear to have strongly influenced the location and magnitude of the landslide damage.

Landslides occurred on natural slopes ranging between 15º and 40°, but 56–86% of failures occurred on moderately rolling to steep slopes (16–25°). The average density of landsliding ranged from 32 to 43 slides per km^2, with the highest density recorded in the Mangawhero valley. Very few landslides formed on gentle slopes (<15°), but flatter areas in valley bottoms or below steep slopes were often overrun by landslide debris. There were also few landslides on very steep natural slopes (>36°). Most sub-vertical sides of river channels cut in mudstone bedrock were not affected by the rainstorm, but there were many failures of soil and colluvium at the tops of steep road cuts throughout the affected area. There was a clear preference for landsliding on slopes with a northerly (NE–NW) aspect, compared with generally wetter southerly (SE–SW) slopes, even though rainfall mainly came from the south during the storm. Regolith stripping by previous slope failures may have reduced the landslide susceptibility of south-facing slopes, and north-facing slopes appear to be more vulnerable to rainfall-induced landsliding because of thicker, weaker, and more porous soils on sunny slopes as a result of greater thermal weathering (wetting and drying cycles during which clay materials expand and contract).

Vegetation cover significantly affected the severity of the landsliding that occurred in steep hill country, with grassland areas clearly most affected by landslides in all four study areas. Total (scar and runout) landslide damage on hill-country areas in pasture ranged from 30–50%, compared with only about 8% for areas in native forest, scrub and pine forest. Mature pine forests and thick bush/scrub cover provides the most resistant land cover against landslide erosion. However, young trees less than about 10 years old offer little protection against landsliding possibly because they have insufficient canopy cover for effective interception of rainfall to reduce rapid runoff and soil saturation during severe rainstorms, or because root strength effects are less in younger trees. In some areas there was significant landsliding on scrub and bush-covered river banks, or on slopes planted with pine trees, that had been destabilised by fluvial undercutting, with up to 30% of such areas in the Pohangina valley affected by landsliding. Loading of fluvial systems with tree debris from riverbank collapses contributed to the destruction of several bridges during the flood.

Differences in terrain characteristics were partially responsible for variations in landslide distribution and density throughout the storm-affected area. However, in areas of similar terrain and vegetation cover, differences in landslide distribution are inferred to have been caused by local variations in rainfall intensity across a region. Areas of higher intensity rainfall may explain areas of greater landslide damage in similar terrain within and between the four study areas. Variations in landslide types and characteristics are related to slope angle, slope height, and rock and soil type, although the overall magnitude of the storm (amount and duration of rainfall) is also very important. Differences in landslide size are related to the nature of the terrain in which they occur, particularly the height of the slope on which the landslide occurs.

The majority of the geomorphic work (volume of material moved during the storm) was done by the larger landslides, which were numerically only a very small proportion of the total number of landslides that were formed. The larger landslides (>1000 m^3) formed only about 3 % of all landslides in the four study areas, but were responsible for about 48 % of the volume of landslide debris eroded from hillslopes. However, the visual impact of many small shallow landslides scarring large areas of hill country pastureland is often more striking than a few larger slides that erode deeper into bedrock. Larger landslides generally had longer debris tails (runout to scar length ratios of 5–10, compared with an average ratio of 2.9), and generally had higher (~75–95 %) fluvial connectivity compared to smaller slides and the 67% average for all landslides in all areas. In terms of sediment budget, larger landslides were also more important as they delivered much more sediment to streams and rivers than did smaller slides where much of the debris remained on slopes. The shallow scars and debris of smaller landslides also tend to regenerate grass cover more quickly than larger slides in mudstone bedrock, which therefore tend to be more permanent geomorphic features in the landscape.

KEYWORDS

Rainfall-triggered multiple landslide events, Wanganui-Manawatu hill country, landslide affected areas, densities, scar to runout length ratios, Feb 2004 rainstorm, Central North Island, New Zealand.

1. INTRODUCTION

A severe storm on 15–17 February 2004 caused widespread landsliding over about 16,000 km^2 of the southern North Island, affecting large areas of the Wanganui-Manawatu and eastern Wairarapa hill country, and the greater Wellington area (Hancox, 2004; Dymond *et al.*, 2004, Hancox and Wright, 2004). The Manawatu-Wanganui area was worst affected, with extensive, but mainly superficial, landsliding spread over about 8,000 km^2 of steep hill country extending from the Pohangina to Waitotara valleys (Figure 1).

Other publications have documented the extent and main areas affected by landsliding, and described the nature and effects of the landslides on the landscape, and extensive damage to roads and infrastructure in affected areas (Hancox, 2004; Dymond *et al.* in prep; Hancox and Wright, 2005). This report presents an analysis of terrain characteristics and landsliding caused by the 15—17 February 2004 storm in selected areas of the Wanganui-Manawatu hill country. It examines the types and characteristics of the landslides formed (landslide density, debris runout to scar length ratio, terrain damage, and sediment delivery to streams), and relates the findings to geological and geomorphic characteristics (lithology, soil, slope angles, slope aspect) of the affected areas and the storm that triggered the landsliding.

Four areas were identified for detailed studies (Figure 2) from examination of oblique and vertical aerial photographs of landslide damage resulting from the February 2004 storm (Hancox and Wright, 2005). These were the Mangawhero, Whangaehu, Turakina, and Pohangina areas (named for the main river that runs through them); four hill country areas in regions that experienced the severest damage to hill slopes during the storm. Detailed examination of the landslides (runout length as proportion of scar length, landslide density, and area affected) and nature of the terrain (lithology, soil, slope angles, slope aspect) in these areas was undertaken in order to determine why the landsliding was so severe in these areas, and to identify factors that controlled landslide distribution, relationships to vegetation and land use, and effectiveness of erosion-mitigation measures.

1.1 Background

Landslides are one type of geomorphic response to a trigger, or forcing factor (Crozier and Glade, 1999). In the case of the February 2004 storm the trigger was intense or prolonged rainfall over a three-day period (Figure 3), producing saturated slopes. Saturation reduces shear strength and increases shear stress. When shear stress exceeds shear strength, landslides occur. In the February 2004 storm, rainfall was estimated with return periods of greater than 150 years in the storm centre. and return periods between 100 to 150 year were estimated for the Mangawhero and Whangaehu Valleys. The most severe landslide damage occurred within the 100 year return period contour. Turakina and Pohangina Valleys lie within the 150 year return period, 72 hour rainfall contour (Figure 4) (Horizons Regional Council, 2004).

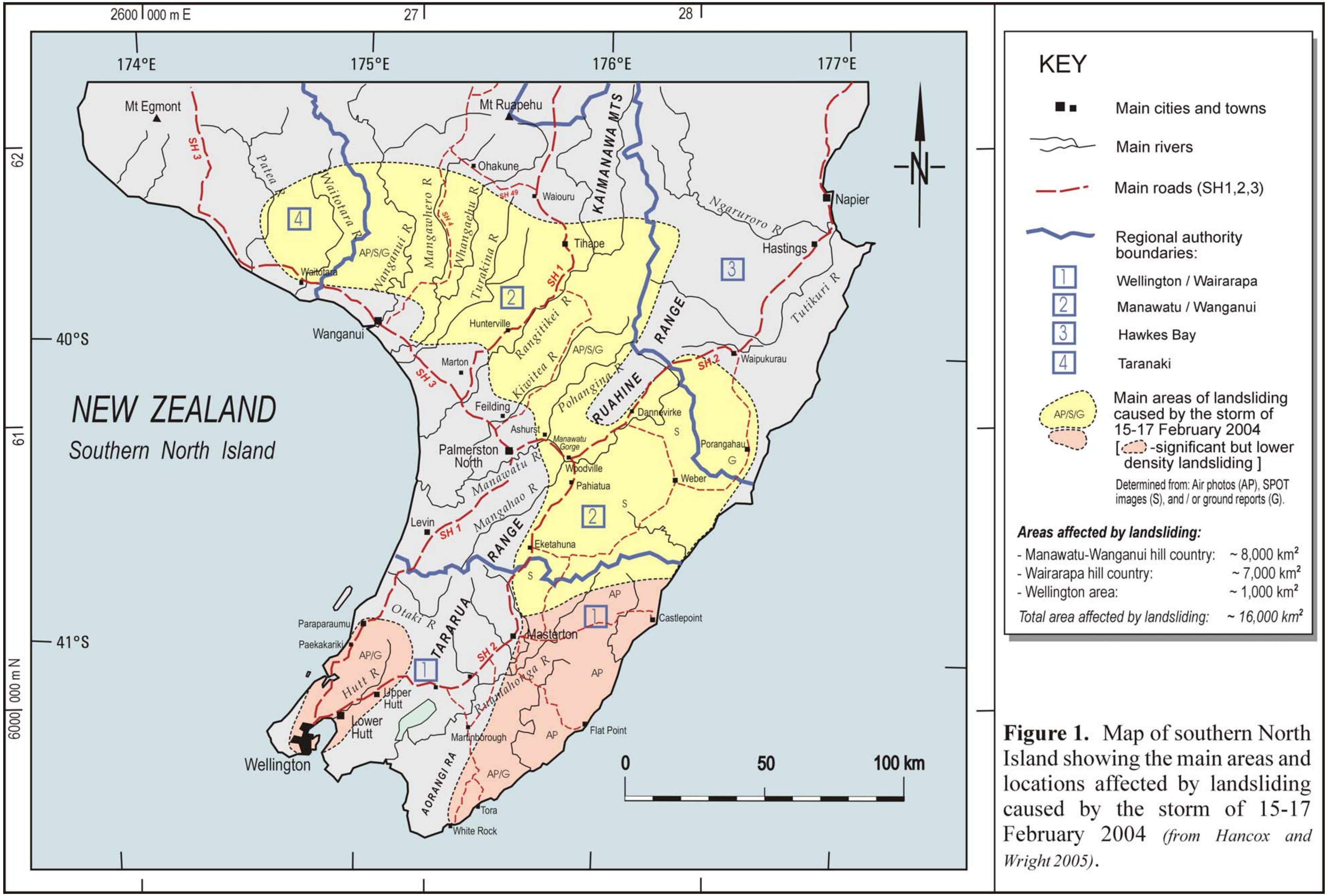


Figure 1. Map of southern North Island showing the main areas and locations affected by landsliding caused by the storm of 15-17 February 2004 *(from Hancox and Wright 2005)*.

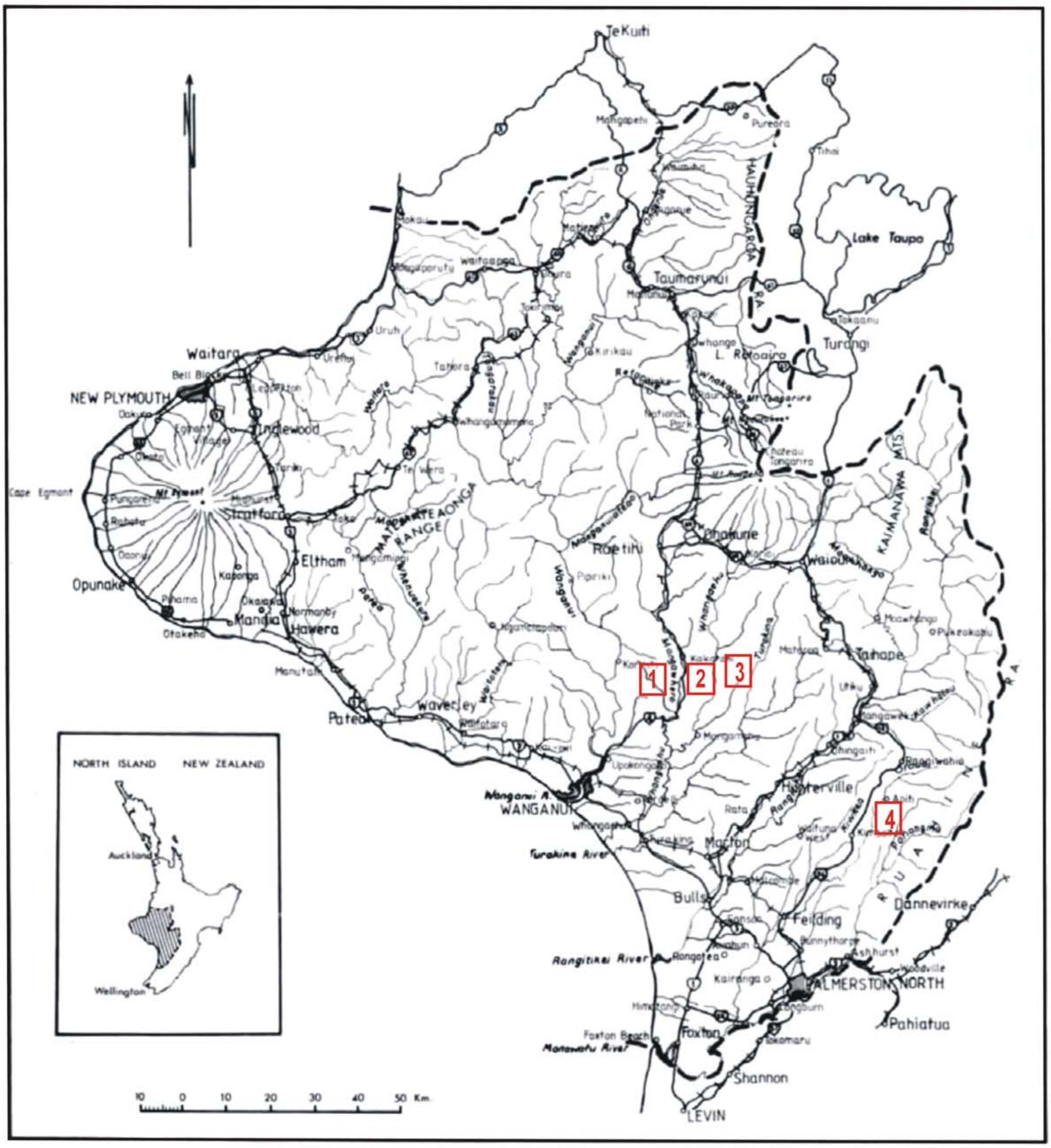


Figure 2. Locations of the four study areas described: 1 - Mangawhero, 2 - Whangaehu, 3 - Turakina, and 4 – Pohangina *(map adapted from Fletcher, 1987).*

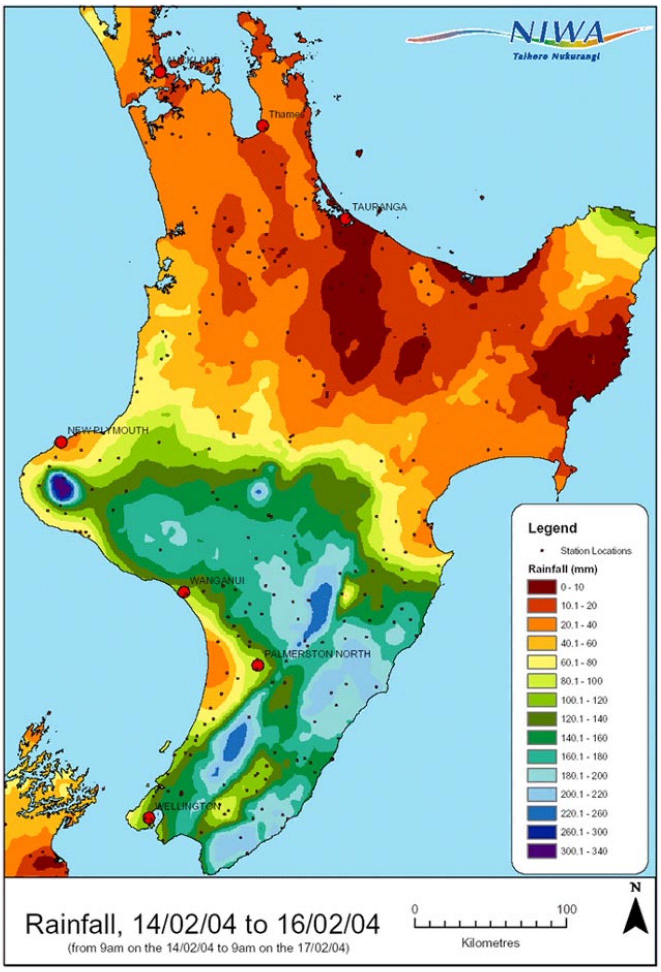


Figure 3. Rainfall totals for the February 2004 storm event, study areas fall within the light green band (160–180 mm in 72 hours) *(map from NIWA, 2004).*

The rainfall data shown in Figures 3 and 4 is generalised and the contours represent average values. Data collected by farmers within the study area indicate slightly higher rainfall than is shown by the contours in Figure 3. For example, in the Mangawhero region, 193 mm for the three day period was recorded at one farm (c.f. 160-180 mm in Figure 3 above), with 140 mm recorded in the 24 hour period to 9am, February 16th when one very large landslide (pers. comm., John Medlicott 2004). These extreme rainfalls produced widespread landsliding throughout the Wanganui-Manawatu region that was generally consistent with the rainfall distribution (Figure 4); if vegetation and land use are taken into account (Hancox, 2004; Dymond et. al. in prep; Hancox and Wright, 2005). However, since variations in the landslide response cannot be attributed entirely to variance in rainfall or unreservedly to variance in rainfall or vegetation, an examination of some of the worst affected areas was undertaken to see if terrain characteristics (e.g. rock and soil types, slope angle and aspect) contributed to differences in landslide density and damage.

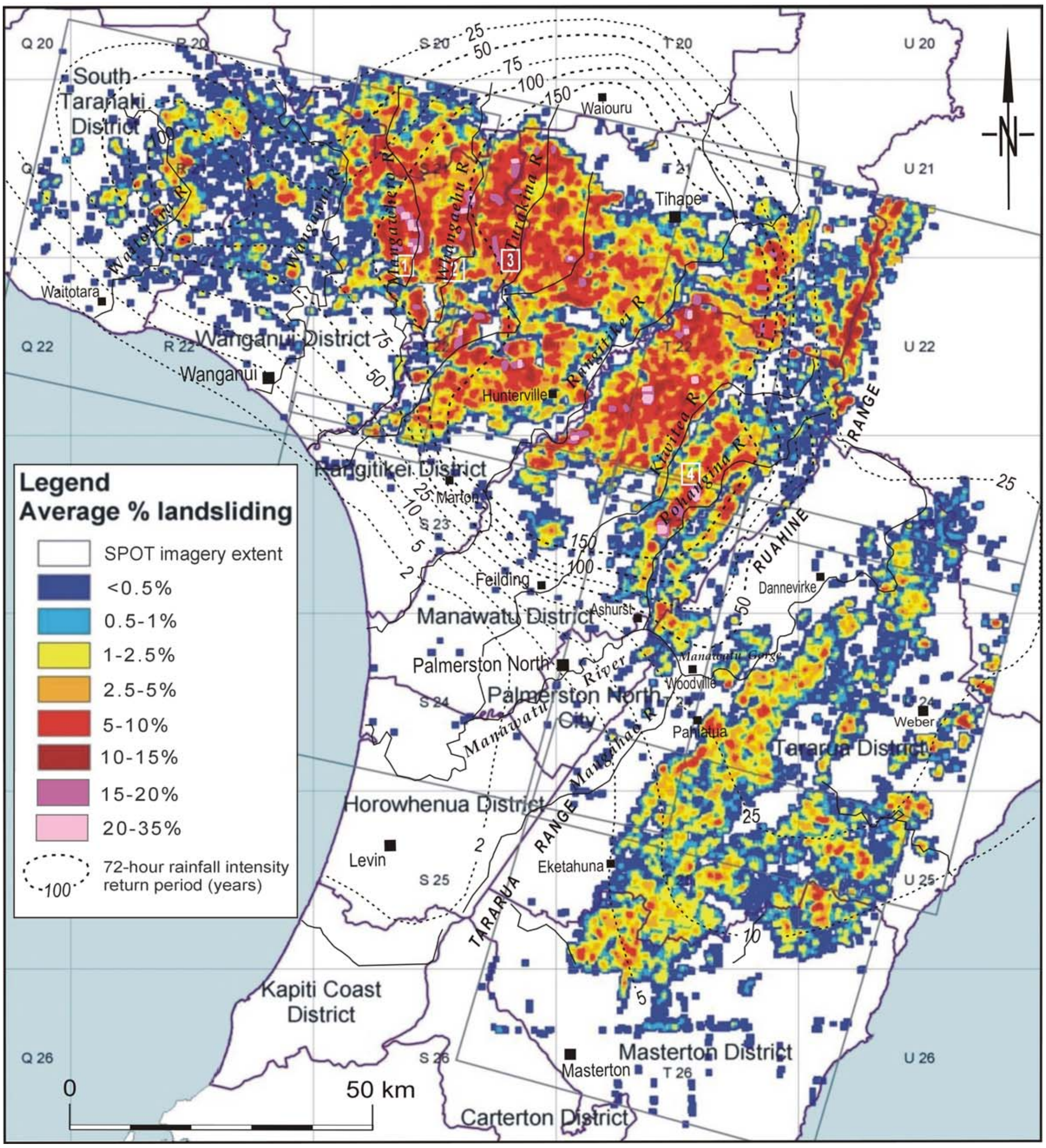


Figure 4. Summary map of landslides caused by the 15–17 February 2004 storm mapped from SPOT images (by Landcare Research). Colours show the percentage of land in one square km covered by landslides (source area scars and debris undifferentiated). 72-hour rainfall return period contours are also shown (from NIWA). *[Map adapted from Landcare Research, 2004]*. Note that the four study areas *(1-Mangawhero; 2-Whangaehu; 3-Turakina; and 4–Pohangina, show as white boxes and numbers)* are within the areas of heaviest landslide damage inside the 100-year–return-period, 72-hour rainfall contour.

In New Zealand, most pre-1990 studies of rainfall-triggered, multiple-landslide events investigated landslide damage as scar areas only. These earlier studies (e.g. Bell, 1976; Painter, 1981; Hicks, 1991) were primarily concerned with loss of pasture productivity, and focussed on scar areas, as scars have a much slower recovery than runouts. More recent studies have examined rainfall-triggering thresholds and antecedent soil moisture conditions (Crozier, 1999; Brooks *et al.* 2002; Crozier *et al.* 1995; Crozier and Preston, 1999), frequency-magnitude estimations (Crozier and Glade, 1999), the geomorphic impact of landsliding (Page *et al.* 1994; Kasai *et al.* 2001); modelling of landslide behaviour (Terlien *et al.* 1996; Morgan, 1996); and landslide hazard and risk (Luckman *et al.* 1999).

This study is concerned mostly with the relationship between terrain characteristics and the landslide response to a large storm. Landslide response is described in terms of: landslide density, damage ratios, and ratios of scar length to runout length. These characteristics fall into the category of frequency-magnitude study as they are ways of describing the magnitude of the landslide event. Slope aspect preference in the distribution of landsliding damage is often be linked to triggering thresholds (sufficient rainfall), slope characteristics (e.g. sufficient material, differences in vegetation), and possibly directional aspects of the triggering agency, in this case intense and prolonged rainfall. These issues are examined in relation to the four study areas.

It is expected that the results of this study will be used in landslide-hazard studies, as runout damage provides a high proportion of the hazard associated with landslides runout of slide debris commonly blocks roads, destroys fencing, increases sediment loads in rivers, and less commonly destroys buildings, causes stock loss or loss of human life. For these reasons, both landslide scar and runout lengths were mapped in the four areas, and the ratio of landslide-runout length to scar length determined and compared in relation to terrain characteristics and resulting damage.

2. TERRAIN CHARACTERISTICS

The magnitude of a landsliding event (landslide volumes, density, and areal extent) is determined not only by the magnitude of the triggering force, but also by the nature of the terrain in which the event occurs. Terrain characteristics that are known to affect the geomorphic landslide response to triggers such as earthquakes (Keefer, 1984; Hancox *et al.* 2002) and rainstorms (Bell, 1976; Page and Reid, 1998; Crozier, 1999) include:

- Geology/lithology.
- Thickness and type of soil and regolith (weathered soil parent material).
- Slope.
- Hydrology; determined by soil, bedrock, slope angle, slope aspect, topography and climate.
- Topography; elevation, slope form (concave/convex), changes in slope form.
- Vegetation.
- The processes acting on and within the slope: weathering; mass wasting; soil creep; surface wash; subsurface piping.
- Whether a slope is undergoing *denudation* (losing material), *accumulation* (gaining material), or *transportation* (material losses equal gains).

Other factors affecting the hill-slope response include:

- The magnitude of the triggering event (rainfall duration and intensity, earthquake).
- Previous slope failures removing transportable material.
- Antecedent moisture conditions; saturated slopes are more likely to fail due to reduced shear strength and increase of increased shear stress (Young, 1972; Carson and Kirkby, 1972; Selby, 1982; Crozier *et al.* 1982).
- Position on slope profile – upper, middle or lower slope.

This study involved analysis of vertical aerial photographs, and a review of existing literature, with some field observations but few systematic field measurements. Therefore some slope characteristics were not included. The slope characteristics examined were those considered to be most important in landslide initiation on hills slopes (Crozier 1982) and were: geology/lithology; regolith and soil characteristics; slope; aspect and vegetation including: slope steepness, the underlying geology/lithology; regolith and soil characteristics; and slope aspect. Landslides were mapped and assessed on several vertical aerial photos (print scale ~1:18,000), while slope and aspect were determined from 1:50,000 topographic maps (NZMS 260-S22, T22, T21). Geology/lithology and soil information was obtained from published geological studies (Fleming 1978, Fletcher 1987, Stevens 1990) and soil maps (N.Z. Soil Bureau 1954, Campbell 1977, Rijkse 1977). Examined factors all contribute to hill-slope hydrological processes; how these factors interact determines the likelihood of hill-slope saturation under intense or prolonged rainfall. Saturation of slopes is a major source of landslide initiation in the New Zealand hill country (Crozier *et al.* 1982).

The following six sections (2.1 to 2.6) provide detailed descriptions of terrain characteristics examined in this report with respect to the four study areas, and their relationships with slope instability. Description of the four study areas and their susceptibility to hillslope failure as well as actual degree of failure is related to:

- Geology and rock types;
- Regolith and soils;
- Slope;
- Slope height and relief;
- Slope shape;
- Aspect;
- Vegetation.

2.1 Regional geology and rock types

The Mangawhero, Whangaehu and Turakina study areas are situated within the hill country northeast of Wanganui. The Pohangina study area is in the northeast of the Manawatu Region. The Wanganui and Manawatu regions have undergone similar processes of sediment deposition and tectonic uplift, but differences in types and ages of sediment exist. Ages and locations of major geological units for the lower North Island are shown in Figure 5. Descriptions of the regional geology of the Wanganui and Manawatu areas are given below in Sections 2.1.1 and 2.1.2.

2.1.1 Wanganui

The Wanganui region is dominated by Tertiary sediments laid down during Pliocene and Pleistocene marine transgression. A gravity anomaly situated near the lower west coast of the North Island is associated with local downwarping that created the Wanganui Basin and allowed marine transgression and sediment deposition onto basement rocks. During the Quaternary (last ~2 million years) uplift of older Mesozoic rock created the Ruahine and Tararua Ranges which form the eastern and southern boundaries of the Wanganui Basin; with the Taranaki, Ruapehu, Ngaurahoe, and Tongariro andesitic volcanoes along the northern boundary of the Basin. The soft Tertiary sediments within the Basin were also raised and folded during the Quaternary. Characteristic steep and sharp hillslopes were formed as the uplifted area was dissected by rivers and streams (Fleming, 1978).

The north-eastern Wanganui hill country, which includes the Mangawhero, Whangaehu and Turakina study areas, comprises very steep (25-40º), rectilinear slopes formed in weak, Tertiary-age sandstone and mudstone which dip gently (between 2º and 8º) to the southwest. Ridges are narrow, sharp, and fluted where sandstone caps the dominant mudstone (Neall 1982). Dendritic drainage patterns produce highly dissected topography in the soft Tertiary sediments (Figure 6) typical of (geomorphically) young terrain. River channels are deeply incised, with little or no flood-plain development in the narrow valleys. In the highest hills of erosion-resistant rocks, some sub-mature marine terraces remain (Figure 7) but the majority of ridges are sharp and narrow.

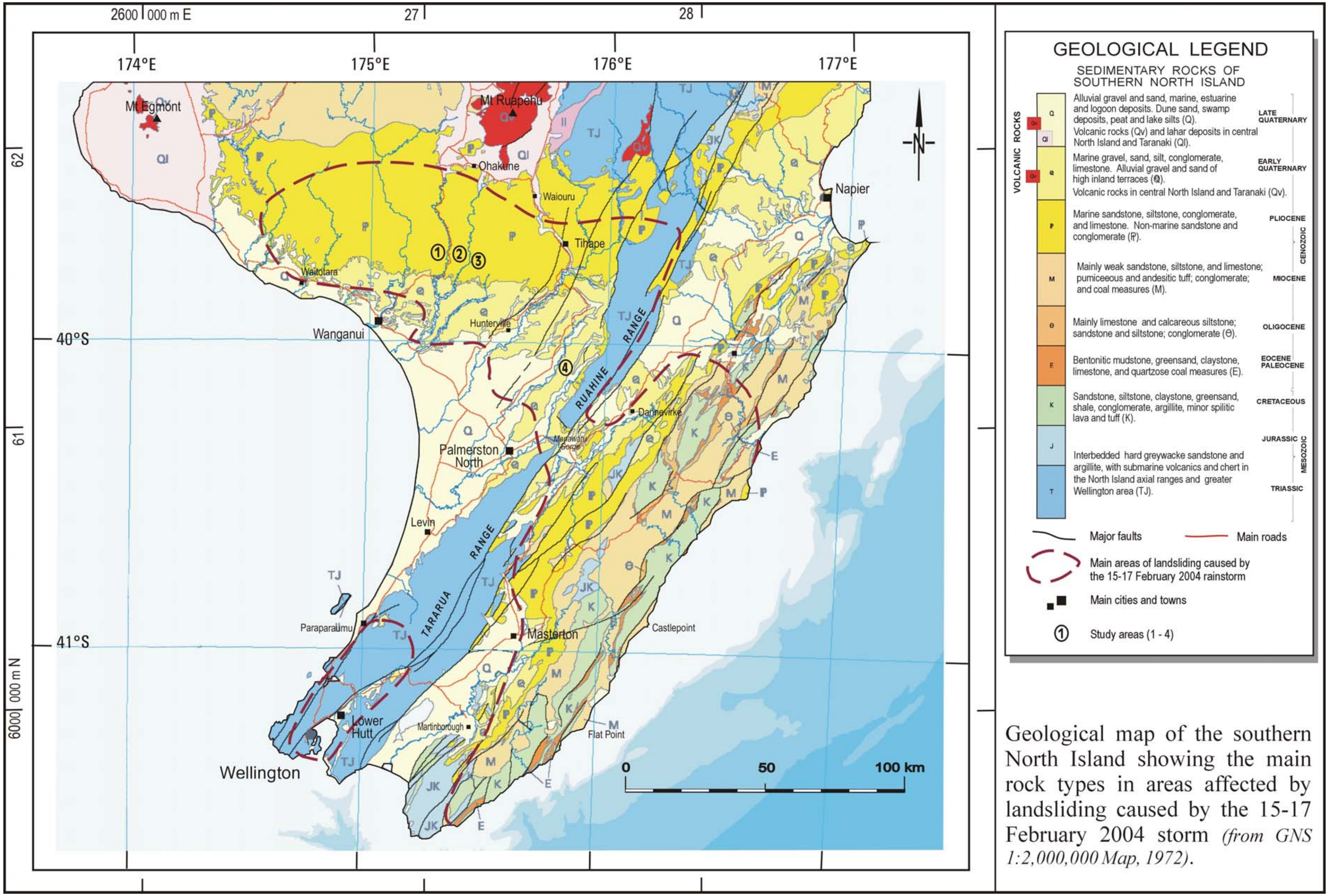


Figure 5. Map showing regional geology and rock types in relation to the four study areas and overall area affected by landsliding.

2.1.2 Manawatu

In the Manawatu hill country, uplift and sediment deposition also determined the form of hill-slopes. However source materials differ from those further north-west. The Manawatu region was entirely submerged until ~50 000 yrs BP. The underlying basement rocks consist of planed off argillite and greywacke sandstone of the Tararua and Ruahine ranges. This basement material was broken into blocks by faults. Blanketing by marine sediments resulted in the blocks never being an exposed unit at the land surface. As tectonic activity forced the underlying blocks up, the overlying sediments formed domes, and areas that went down formed sediment-filled depressions (Figure 8 and Figure 9). These domes prevent the Manawatu River from flowing directly to the coast, instead it flows southwest around them (Stevens, 1974).

The Manawatu and Pohangina hill country is less steep and less (dendritically) dissected than is the Wanganui hill country. Hill-slopes in the Pohangina study area exhibit a gentler, more rounded form with lower elevation than that of the study areas to the north. The Pohangina hill country does not exhibit rectilinear slopes meeting in deeply incised valleys of the Wanganui hill country. The Pohangina terrain appears less susceptible to hill-slope erosion in relation to topographic slope form.

Figure 6. Typical Tertiary hill country of north-east Wanganui region *(photo G. Hancox 2004).*

Figure 7. Photo showing typical hill country and preserved high level marine terrace in the Mangawhero valley – with Mt Ruapehu in the background. *(photo M. Crozier 2004)*

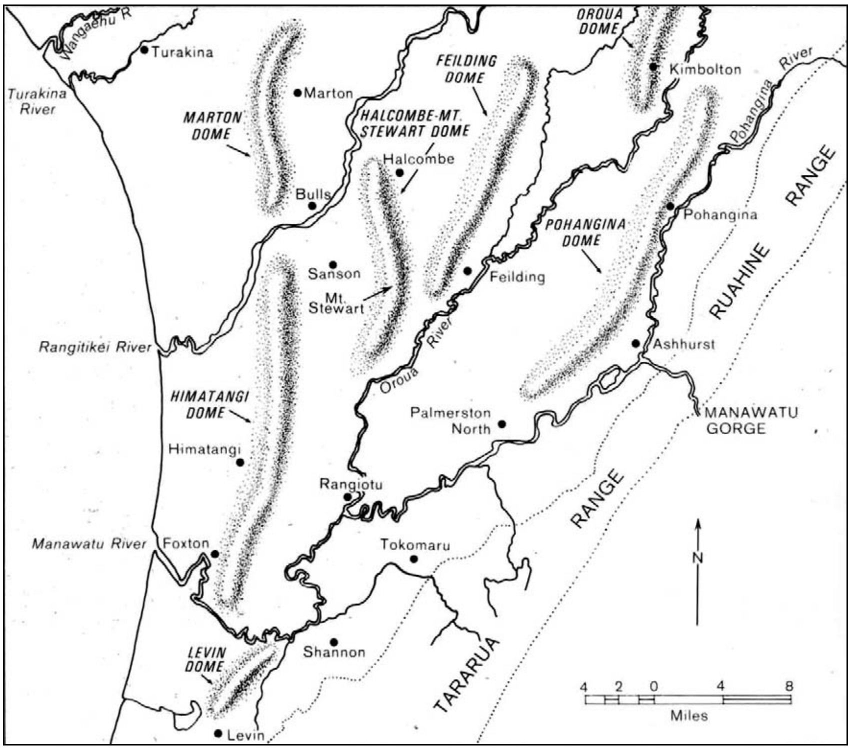


Figure 8. Domes in the Manawatu and lower Wanganui regions (*from Stevens, 1974*).

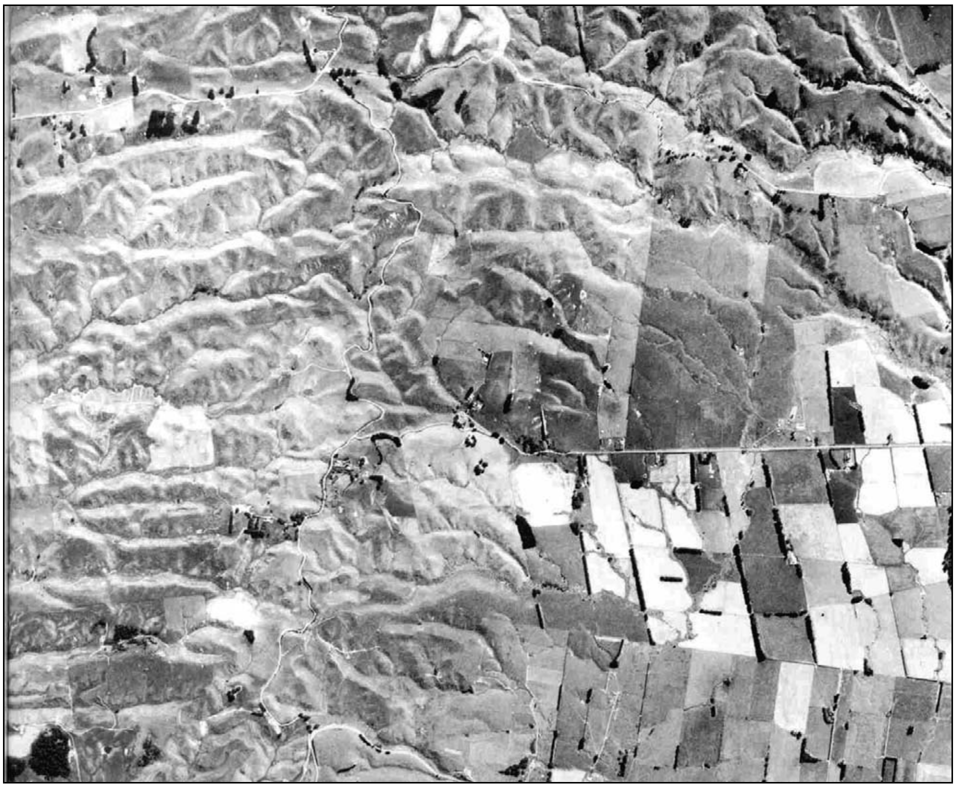


Figure 9. Aerial photo showing the crest of the Pohangina Dome - north is at the top of the photograph *(from Stevens, 1974)*.

2.1.3 Major geological units

All four study areas are dominated by sedimentary rocks with some variation in rock type and age. The Wanganui hill country has developed in weak Pliocene sedimentary rocks comprised of marine sandstone, siltstone, and conglomerate, whereas the Pohangina hill country consists of weak to extremely weak early Quaternary sediments comprising marine gravel, sand, and silt (Figure 5). The rock description nomenclature used in the terrain analysis is that of the New Zealand Geomechanics Society, where strength (resistance to breakage) and hardness (resistance to indentation or scratching) measures are used to provide the general rock description terms ranging between extremely weak (all soils) to extremely strong (Appendix 1).

The Mangawhero, Whangaehu and Turakina regions are dominated by the massive but weak Mangaweka Mudstone (Mm), a clayey siltstone. The Mangawhero and Whangaehu regions also contain a relatively compact and weak massive sandstone unit (Sm). In addition, the Whangaehu hill country contains another less compact, weaker form of the Sm unit. The Mm and Sm units are Pliocene in age. The Pohangina hill country is formed from younger rocks of Pleistocene age. In the Pohangina study area, bedrock generally consists of weaker (less compact) sandstone (Us), gravel, and minor beds of silts and clays.

2.1.4 Geological characteristics and erosion susceptibility

The dominant rock units occurring in the four study areas are all susceptible to erosion. The Mm unit is described as weak to very weak and typically massive (with little or no bedding). Soil/regolith slips are common, and shallow earthflows are likely to develop on footslopes. Deep-seated rotational slides may also occur in the Mudstone unit. In drier areas footslopes may be subject to tunnel gullying (this has been observed in the Mangawhero study area).

The Sm unit is also weak to very weak (strength is dependent on the degree of compaction resulting from its former depth of burial), is typically massive; and some bedding may be present. Surface erosion in the Sm unit takes the form of shallow soil/regolith slips or sheet erosion and tunnel gullying. In the moderately compacted Sm rock of the Upper Whangaehu area, slumps and earthflows also occur.

The weakest of the units is the Us unit, which consists of thickly to very thinly bedded sands and clays, varying from loose to very compact sediments. Gravel beds and pumice layers may also be present. The Us unit is subject to gullying, often severe, and also slip erosion and wind erosion (Lynn and Crippen, 1991). Examples of landslides and slip types formed during the February rainstorm in the various areas and hill-slope materials are shown in Figure 10. In geotechnical terms all units within the study areas fall into the category of ‘soft’ rocks (NZ Geomechanics Society 1988).

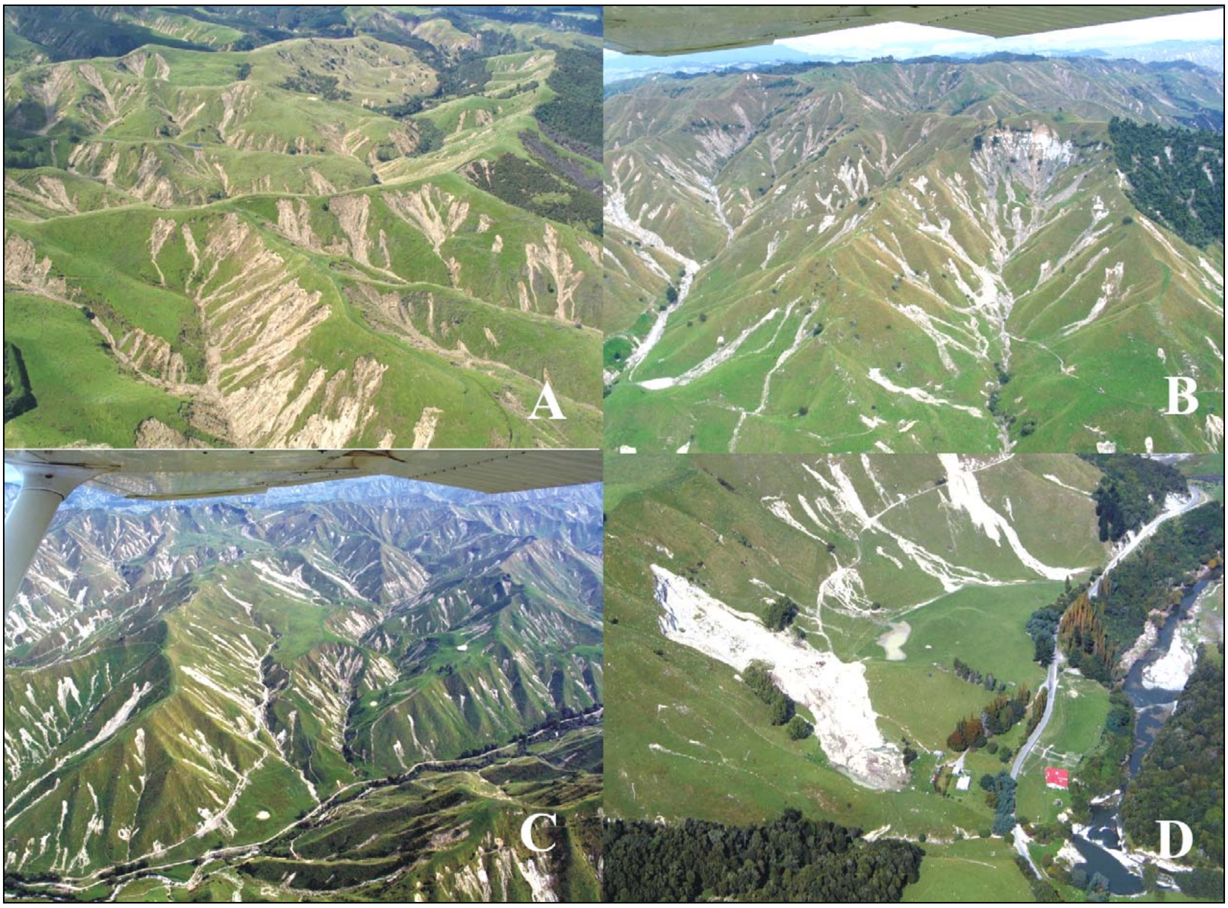


Figure 10. Typical landsliding caused by the February 2004 storm in different study areas.

A – Shallow slipping in the weak sandstone (Us) unit in the Pohangina hill country.

B – Shallow slipping on upper ridges of relatively strong (compact) sandstone (Sm) cap and soil flows in the underlying mudstone (Mm) slopes in the Whangaehu hill country.

C – Both shallow and deeper seated slipping and flows in Mudstone (Mm) in Mangawhero hill country.

D – Deep-seated rotational slide in mudstone in the Mangawhero River valley *(photos G. Hancox 2004).*

Recovery times (development of soil and revegetation) for bedrock, regolith, or soil landslides vary between the units. A summary of established recovery times for different damage types and materials is as follows (Fletcher, 1987):

Slip exposes soft rock - vegetation establishes quickly:

- *Mudstone(Mm) and sandstone (Sm)*

Slip exposes hard rock - vegetation establishes slowly:

- *Sandy mudstone(Mm), and sandstone(Sm),*

Slip exposes rock - erosion of bedrock follows:

- *Shattered greywacke (Gw), and less compacted (very weak) sandstone (Us)*

From this summary it can be seen that the Pohangina Us unit is particularly susceptible to further damage once landslides occur, often triggering gullying. The Sm unit is slow to recover, and the Mm unit recovers rapidly, unless a deep-seated slide occurs which exposes the massive bedrock.

Of the New Zealand Tertiary rocks, the mudstone is the most fertile soil parent material (with pasture producing the highest stock-carrying capacities), but also exhibits the most severe erosion hazards (Ministry of Works, 1969). This makes this unit both desirable and undesirable for pasture. For pastoral farming to be sustainable recovery rates must keep pace with soil erosion rates; the recovery rate for landslide-disturbed hillslopes is estimated to be 3.5 mm/yr for the first 50 years of recovery (if undisturbed by further slipping) and 1.2 mm/yr for the following 50 years (Pillans and Trustrum, 1991).

2.2 Regolith and soils of the four Study Areas

Soil characteristics affect landslide likelihood. The ability of a soil to drain freely, or hold large amounts of moisture influences hillslope hydrology. The strength of a soil is a function of its parent material, and is determined by porosity, cohesiveness, compaction, and Atterburg limits (e.g. the liquid limit; the likelihood of a soil behaving as a liquid when saturated). Variations in soils among the four study areas are closely linked to the underlying geology and parent materials of each of the four regions.

2.2.1 Regolith and parent material

Regolith is the soil mass plus the moderately to highly weathered (detached) bedrock (or soil parent material) from which the soil develops, and overlies the stronger unweathered or slightly weathered bedrock. Depending on the weathering agents and rates and duration of weathering, it is possible that more than one kind of regolith can be formed from one parent rock (Ministry of Works 1969). Regolith in the four study areas is controlled by the underlying rock types in those areas. In the Wanganui study areas little air-blown material such as loess or volcanic ash is present, and the type of parent rock (e.g. mudstone, sandstone) dominates regolith formation (Figure 11).

The soils that form in these parent materials are classed steepland or hill soils. Steepland and hill soils of the North Island are relatively unstable, and episodically rejuvenate by erosion (N. Z. Soil Bureau, 1954). These soils are mostly shallow (thin). Mudstone soils are typically thicker than sandstone-derived soils. The development of steepland soils is more strongly dominated by the parent material from which they form, than by variations in climate and vegetation compared with older soils on gentler slopes.

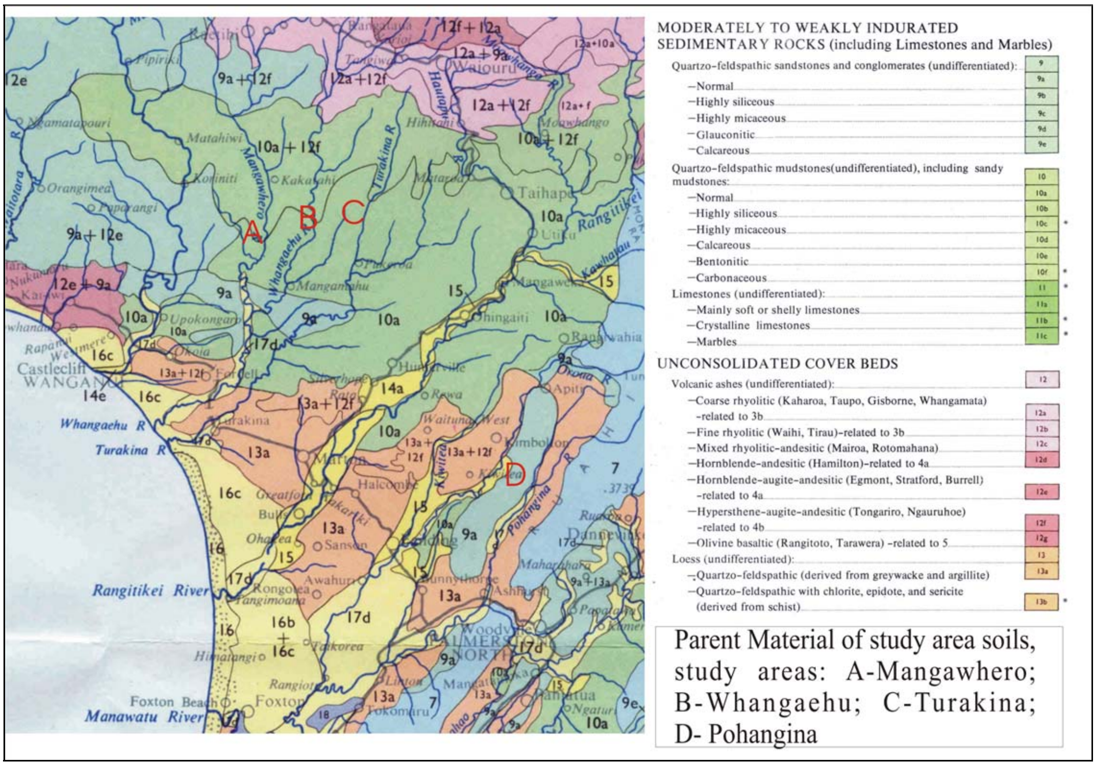


Figure 11. Map showing soil parent materials *(after N. Z. Soil Bureau, 1973)*

2.2.2 Soils of the four Study Areas

The three study areas north-east of Wanganui: Mangawhero, Whangaehu, and Turakina are all dominated by steepland soils although pockets of hill soils can be found. These steepland soils vary according to underlying parent material; with variation in soil type affecting susceptibility to landslides and the types of landslides that occur (Campbell, 1977). The degree of development and thickness of these steepland and hill soils are determined in part by the position on the slope where they form. Campbell (1977) identifies four distinct geomorphic settings for soil development and differentiates variants of soils formed on ridges, intermediate steep slopes, eroded slopes and accumulation slopes all from the same parent material.

Ridge soils typically show maximum profile development and occur on moderately steep slopes on ridges and spurs. Intermediate steep slope soils form on uneroded steep valley sides in areas where there is neither significant accumulation nor depletion of soil material. Intermediate steep slope soils have shallower profiles than ridge soils and less distinct horizon development; fragments of parent rock may also be present. The eroded slope variants develop on eroded surfaces, and are typically characterised by weak, shallow profile development. There is wide variation among the eroded slope variants depending on the degree of erosion and extent of soil re-development. Lastly, the accumulation slope soils develop on valley sides where slope debris has accumulated. These types of soils are generally deep but poorly drained (Campbell, 1977). Although four variants of steepland soils have been identified and characteristised, general mapping and classification is based on the intermediate steep slope soil as this is the most extensive of the four soil types.

Individual soil units for the Wanganui hill country study areas are all associated with yellow-brown earths; locations and descriptions are as follows:

- **Turakina Steepland Soil** (**TkS)** dominates the Mangawhero and Turakina study areas. TkS is a silt loam which ranges in depth (total of A and B horizons where horizons A, AB B_2, B_3 are present) from 1.09m to 1.9m. It is often found with Upukonui Steepland soil, and Mangatea Hill soil. Parent material of TkS is sandy mudstone. Prolonged or high-intensity rainfall can cause locally extensive erosion, including deep-seated slides and flows. Hillslope failure occurs when soils are at, or close to, saturation; this high moisture content leads to the development of highly mobile flows. Where shattered rock is exposed, revegetation can occur quickly; where massive parent rock is exposed revegetation occurs more slowly.
- **Mangatea Hill Soil (MtH)** is formed under similar elevation, climate and vegetation conditions as TkS, and from similar parent material, however the slopes it forms on are less steep and therefore soils show greater development MtH is a silt loam with depth ranges comparable to but slightly greater than TkS soils. Profile development is similar to TkS however B and C horizons are deeper. MtH is found on undulating and rounded hill country, and is common in the Whangaehu study area, with some pockets developed in the Turakina study area. Erosion in this soil type is mainly by slumps or earthflows.
- **Upukonui Steepland Soil (UpS)** occurs in the Mangawhero study area and in small pockets in the Whangaehu study area. UpS is a sandy loam which ranges in depth from 0.94m to 1.66m where all possible A and B horizons (as for TkS) are represented. UpS is formed from moderately strong (compacted) silty sandstone in areas of higher (1250-1525mm p.a.) rainfall where there is a change in parent material from sandstone to silty-sandstone formations. The depth of the soil profile decreases as the strength of the underlying sandstone unit increases. This soil is moderately susceptible to landslide erosion. However, landslides stabilise and revegetate quickly as the parent rock weathers relatively rapidly.
- **Mangamahu Steepland Soil (MhS)** occurs on very steep slopes in deep valleys, up to an altitude of about 525 m. MhS is a silt loam to fine sandy loam with a depth range between 1.21m and 2.28m when all possible horizons (A, AB, B_{21} and B_{22}) are present. MhS soils occur mostly on long valley slopes that are only slightly concave. Parent material is predominantly weak sandy siltstone. However MhS can form on sandstones and siltstones of varying strengths. Where MhS forms on sharp ridges of sandstone the ridges take on a fluted appearance. MhS soils are found only in the lower reaches of the Whangaehu study area. These soils are prone to landslides and very slow to heal due to the parent rock’s resistance to weathering (Campbell 1977).

The Pohangina soils are formed in weaker parent material, and all are prone to erosion (Rijkse, 1977). The soil types and erosion/slip characteristics (Rijkse, 1977) are as follows:

- **Pohangina Steepland Soils (PhS)** form on loosely banded sandstone with greywacke gravels and pumice bands. PhS is comprised of horizons of sandy loam and loamy sand, and varies in depth between 0.05 m and 0.25 m; horizons may include O_1, A_1, and Bg. These soils dominate the Pohangina hill-country west of the Pohangina River. The parent material renders these soils susceptible to severe erosion and gullying often associated with landslide scars and because of this scars in PhS heal very slowly. On slopes over 40º a very steep phase (PhvS) of this soil forms which is highly susceptible to landsliding.

- **Opawa Steepland Soils (OaS)** are common in the north west of the Pohangina Valley hill country. As with PhS, these soils include horizons of sandy loam and loamy sand, with depth ranges of 0.18m to 0.58m (horizons A_1, and B). Formed from the same parent material as PhS, these soils are also subject to moderate to severe landslide erosion, but landslides do not progress to gullies and scars heal rapidly in the easily weathered parent rock.

All soil units in the four study areas are susceptible to landslide erosion; the main differences between units lie in the type of landslides that will occur and the recovery time.

2.3 Slope angle

Slope angle strongly affects the stability of slopes and controls how far landslide debris travels. It also plays a role in slope hydrology, influencing overland runoff and infiltration rates, and hence groundwater levels within the slope. Other factors such as soil type, rainfall intensity and slope form (concavity/convexity) also influence hillslope drainage (Kirkby 1978).

Slope angle classes and descriptions for hill country terrain in this report are based on those defined in the Land-Use Capability Survey Handbook (Ministry of Works, 1969) as follows:

Land Use Capability Slope Classes		Slope Classes used for this study	
• 0º – 3º	*- Flat to gently undulating*	0º – 15º	*- Flat to Rolling*
• 4º – 7º	*- Undulating*		
• 8º – 15º	*- Rolling*		
• 16º – 20º	*- Strongly rolling*	16º – 25º	*- Strongly Rolling to Moderately Steep*
• 21º – 25º	*- Moderately Steep*		
• 26º – 35º	*- Steep*	26º – 35º	*- Steep*
• > 35º	*- Very steep*	> 35º	*- Very steep*

Slope angles and average slope angles of landslide-affected hills in the four study areas were calculated manually from the 20 m contours on the 1: 50 000 NZMS260 maps. The angles of slopes containing a total of approximately 700 landslides were measured in each study. The corresponding values for all slopes within the four study areas were derived from 20m digital elevation models.

Slope classes and the average and range of slope angles on which landslides occurred as well as corresponding values for all slopes (whether landslide affected or not) in the four study areas are shown in Table 1. This shows that failures on natural slopes in the four areas occurred on slopes ranging from 15–40°, but the average angles of landslide affected slopes varied by only 2º. Almost all landslide-affected slopes were in the *strongly rolling to steep range (16º–35º).* When considered in comparison with the total number of slopes in each class, the *gentle to rolling* and *very steep* classes are under-represented in terms of landslide occurrence. The *strongly rolling to moderately steep* class is over-represented with percentages of landslide affected slopes in this class in relation to all slopes in this class of between 156 % and 287 %.

As expected, few landslides formed on flat to rolling slopes *(0–15°)*, but these gently sloping areas were often affected by runout of debris from landslides formed on steeper slopes above. It is somewhat surprising that the *steep* class is not as affected as the *strongly rolling to moderately steep* class. Reasons for this may be related to availability of vulnerable material (regolith and soil thickness, usually thinner on higher steeper slopes), or that better drainage on steeper slopes produces lowers soil moisture levels in comparison with lower angle slopes where drainage (overland and throughflow) is slower. There were also relatively few landslides formed on *very steep slopes (>36°)*. Although steep road cuts were affected, sub-vertical sides of river channels cut in mudstone were not. While slope angle clearly influences landslide occurrence in that there is a threshold angle below which no landslides occur, it is not the case that the steepest slopes provide the most landslides (in proportion to their overall representation within the study areas).

Table 1. Comparison of landslide affected slopes and slope angles in the four study areas.

Slope Angle Class	Slope Range	Mangawhero		Whangaehu		Turakina		Pohangina	
		Landslide affected	All slopes	Landslide affected	All slopes	Landslide affected	All slopes	Landslide affected	All slopes
Gentle to rolling	0 – 15°	1 %	30 %	3 %	24 %	–	25 %	1%	47 %
Strongly rolling to moderately steep	16 – 25°	56 %	36 %	69 %	36 %	75 %	31 %	86 %	30 %
Steep	26 – 35°	41 %	31%	28 %	33 %	25 %	34 %	13 %	18 %
Very steep	> 36°	2 %	7%	–	8 %	–	10 %	–	5 %
Average Slope		25 º	22º	24º	23³	24º	23º	23º	18º
Slope Angle Range		15º – 40º	0º-52º	15º –30º	0º-55º	16º –34º	0º-54º	18º –32º	0º-54º
Notes: Average and range of slope angles on which landslides occurred and for all slopes within study areas									

2.4 Slope height (relief)

Relief (slope height) are important terrain characteristics for landslide development as they influence the maximum potential size and runout of landslides. Relief factors such as drainage density, slope angle and slope length, in combination with storm energy, control *terrain coupling* (the potential linkages between hillslopes and fluvial systems) and therefore *fluvial (or event) coupling* (where landslide material connects with active drainage channels). In general, the shorter and steeper the slope the more likely it is that a landslide will reach the drainage channel at the slope bottom. Average slope heights for landslide-affected slopes in the four study areas were derived from topographic map analyses, the results are shown inTable 2, and a summary of the data used is presented in Appendix 2.

Table 2. Average slope heights for landslide-affected slopes of the four study areas

	Mangawhero	Whangaehu	Turakina	Pohangina
Average slope height	144 m	148 m	138 m	64 m

The Pohangina terrain is less than half the average slope height of the others whereas slope heights in the three Wanganui study are within 10 % of one another. A comparison of slope height in relation to slope form was also made; this is shown in Figures 12 and 13.

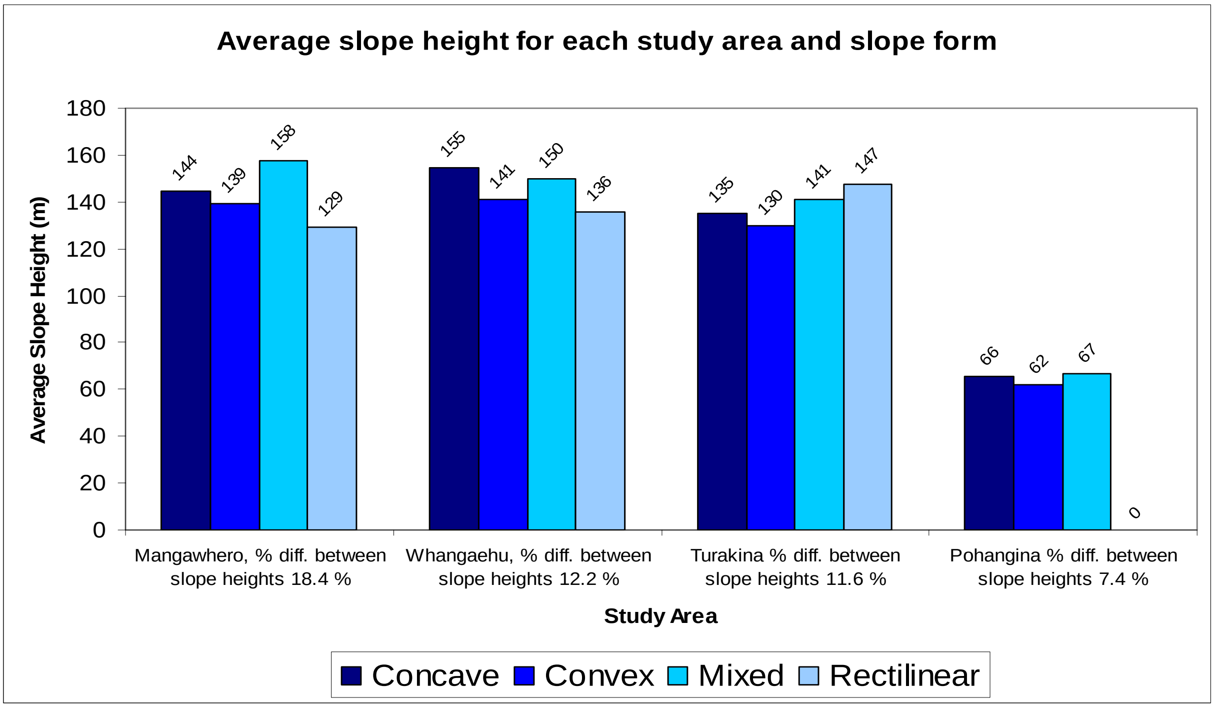


Figure 12. Classed by study area, the average heights are shown for slopes of different types present in each study area.

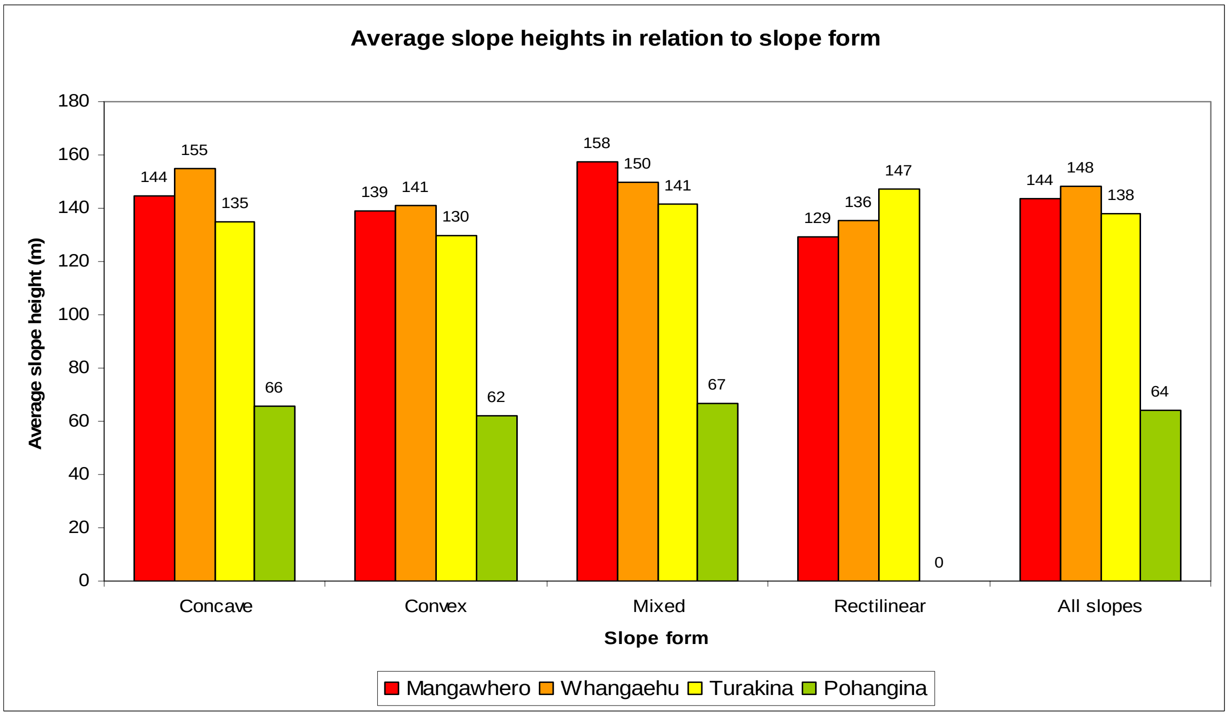


Figure 13. Average heights, classed by slope form in relation to the four study areas.

It can be seen that there is no apparent trend across study areas in terms of the highest slopes being related to particular slope forms. Pohangina shows little variation in slope height between slope forms (Figure 12), implying the terrain is far more regular in form.

2.5 Slope form

Landslides can change slope form by over-steepening scar slopes and creating shallow runout slopes of debris material (Young 1972, Crozier and Glade 1999). The long-term net geomorphological effect of landslides is to reduce slopes to angles at which they possess long-term stability. Changes to slope form due to landsliding require detailed pre-and post event field measurements. For the February 2004 landslide event detailed pre-event measurements are not available.

The effects of slope form (whether a slope is concave, convex, rectilinear, or a mixture of forms) and slope height on landsliding are able to be interpreted from vertical aerial photographs when referenced to topographic maps. Theoretically concave slopes are more susceptible to landsliding as they concentrate drainage. Convex slopes conversely, are shaped so that surface water is dispersed, meaning saturation occurs more slowly; this is also the case with rectilinear slopes. Mixed slopes may disperse water in some parts and accumulate it in others, they exhibit irregular terrain; often the cause of this irregularity is previous landsliding.

Slopes that had been affected by landsliding within the four study areas are separated into four classes: concave, convex, rectilinear, and mixed. Figures 14 and 15 show the data classed primarily by study area (Figure 14) and for comparison primarily by slope form (Figure 15). The slope-form data are summarised in Appendix 3.

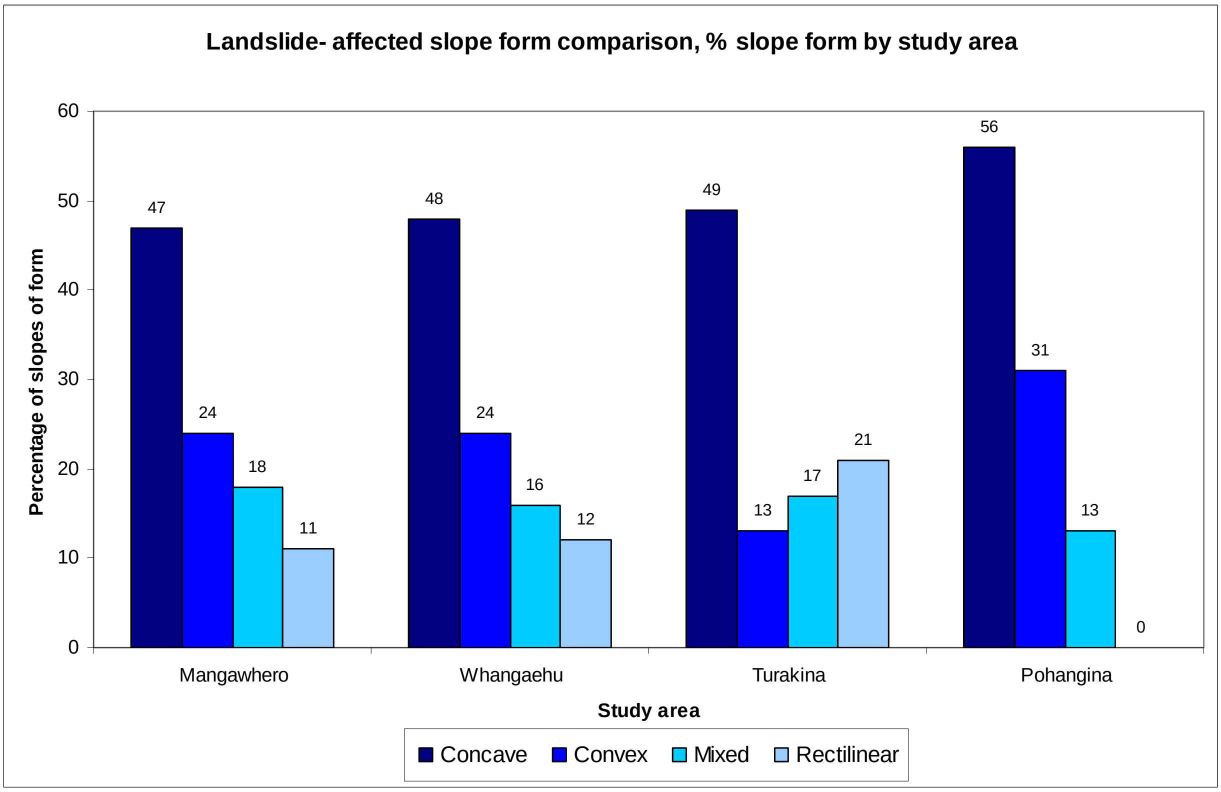


Figure 14. Percentage of slopes of each form by study area.

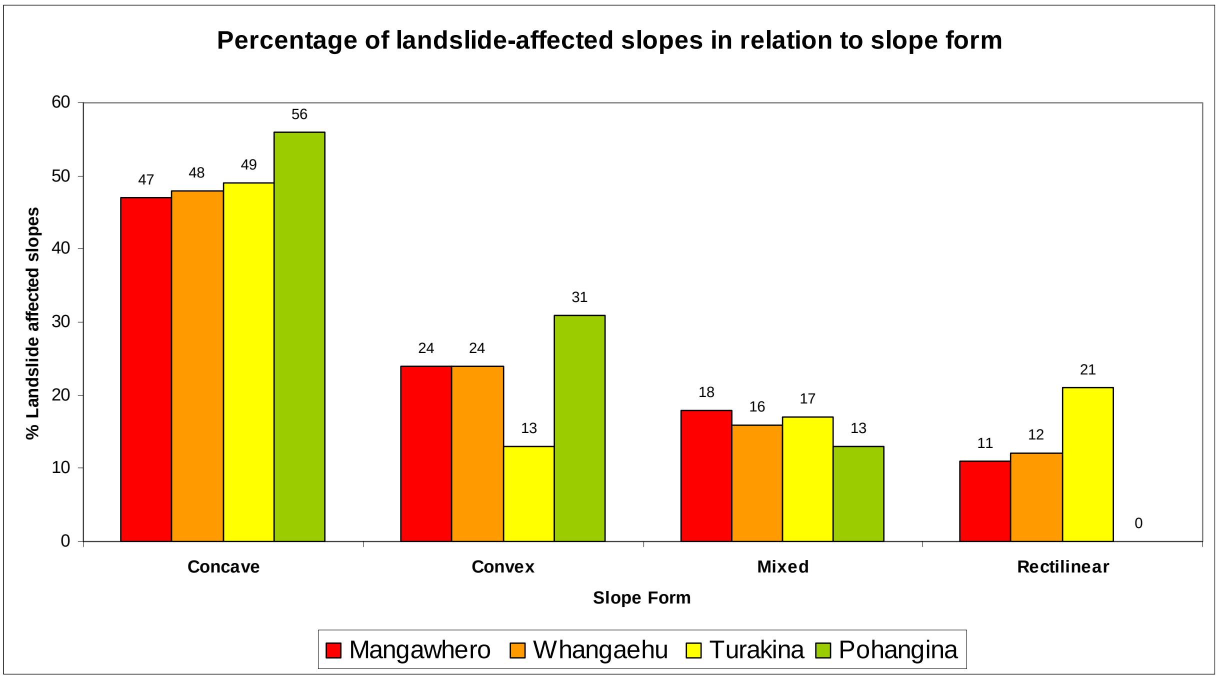
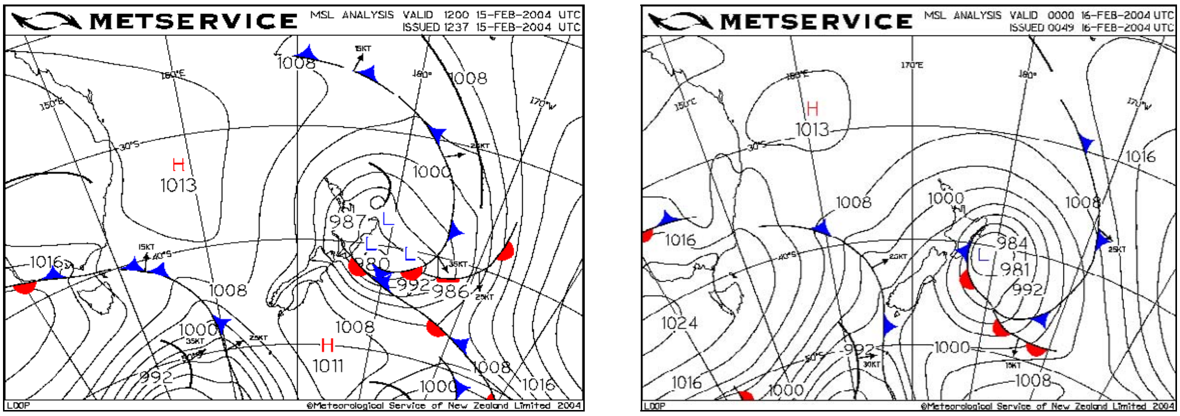


Figure 15. The percentage of landslide affected in each slope form class, the data are the same as in Figure 14 however, data are now grouped by slope form class. Clearly the majority of landslides in all study areas occurred on concave slopes..

A similar ratio of slope forms occurs in the Mangawhero and Whangaehu study areas. Turakina is similar to the other Wanganui study areas in terms of the proportion of concave slopes. However, unlike Mangawhero and Whangaehu it has a higher proportion of rectilinear slopes and a lower proportion of convex slopes. Pohangina has no rectilinear slopes and shows similarity to Mangawhero and Whangaehu in distribution shape of slope forms for concave, convex and mixed slopes. The data show that concave slopes produced approximately half of the landslides in all four study areas.

2.6 Slope aspect

Slope aspect affects hillslope hydrology because southern facing slopes are generally wetter, with lower evapotranspiration rates than north facing slopes. Aspect may also be a strong controller on hillslope hydrology during a localised storm which impacts from a given direction directly onto hillslopes (orographic rainfall). The February 2004 storm centre was located off the east coast of the North Island (Figure 16) with rainfall peaking between 9am February 15th and 9am February 16th. During the height of the storm the main airflow and rainfall over the lower North Island came from a southerly direction, with the air flow going around to the west in the final day of the event (February 16th to February 17th).



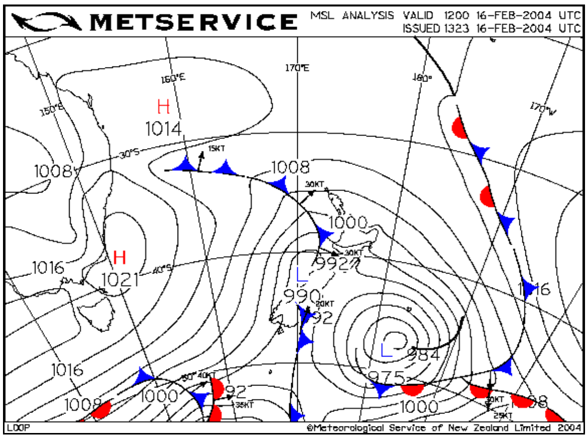


Figure 16. Maps showing the progression of the February storm during the peak rainfall period. Cyclonic (clockwise) airflows produce rain from the south for most of the storm event. *(MetService, 2004).*

Eight classes of slope aspect (West, Northwest, North, Northeast, East, Southeast, South, and Southwest) were used for the analysis, in which each of the landslide affected slopes measured for slope angle was placed in one of the eight aspect classes. To eliminate any bias caused by local topography the aspect of all slopes within each of the four defined study areas was also measured and compared against the aspect of slope on which landslides occurred. All slope aspect data are presented in Appendix 4 and graphic summaries are shown in Figures 17-19. Figure 17 shows "aspect roses" for all slopes in the four study areas, while the aspect preference for landslide affected slopes are shown in Figure 18. A summary of landslide aspect preference data is presented in Figure 19, which shows the aspect of landslide affected slopes as a percentage of all slopes of that aspect. For example, if for one study area the percentage of *east-facing* slopes (in relation to over all slopes) is 12.5%, and the percentage of *east-facing* slopes affected by landslides is 25%, the percentage of landslide affected *east-facing* slopes in relation to all *east-facing* slopes within the study area would be 200%).

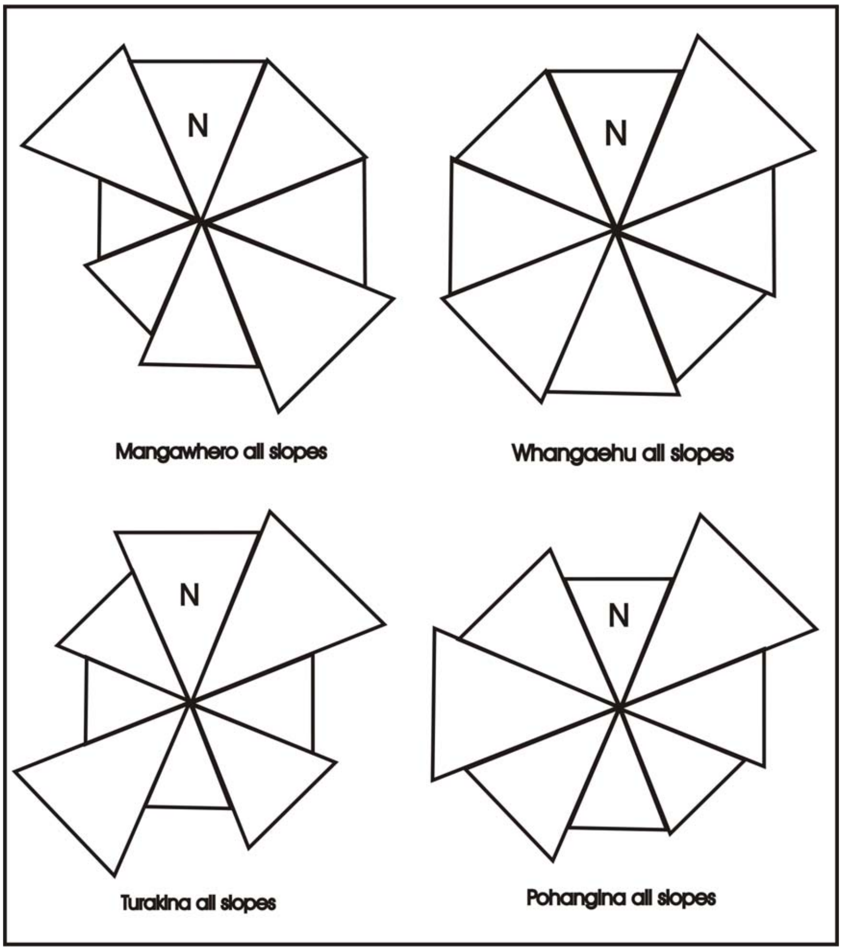


Figure 17. Aspect roses for all slopes within the four study areas. These show some variation between the 8 aspect classes (from average of 12.5% for each) but within areas the variations are not great.

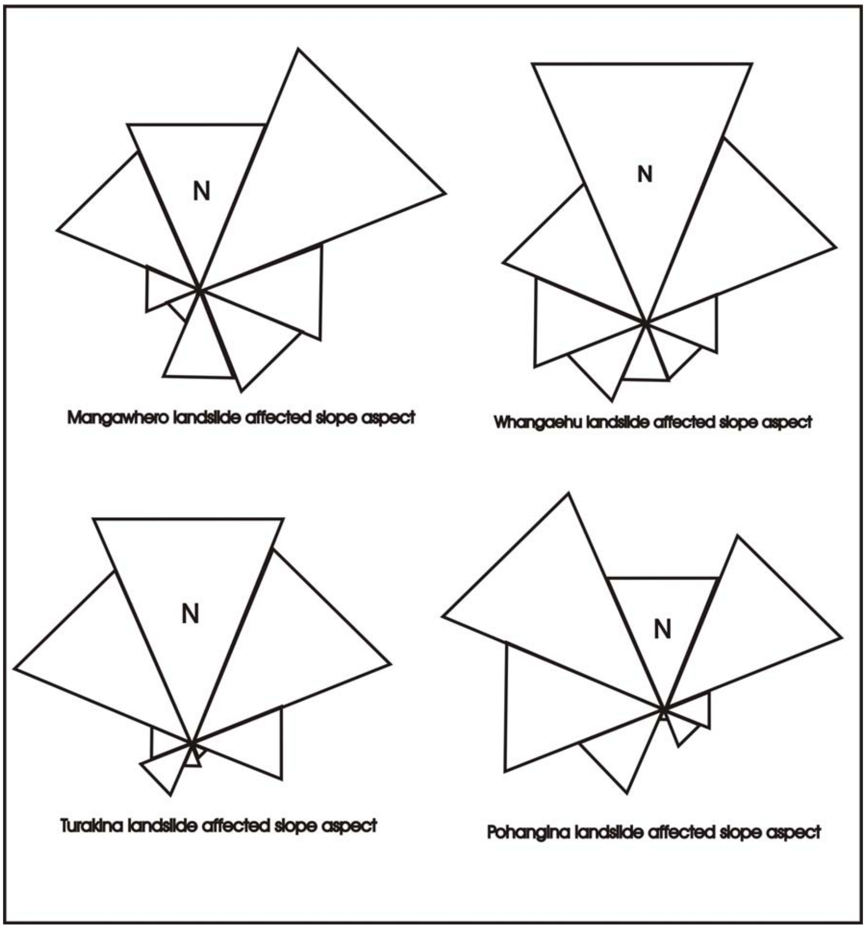


Figure 18. Aspect roses showing slopes affected by landsliding in the four study areas. Theoretically for an "ideal" landslide event landsliding preference would match all slope aspect classes for a given area, but all areas generally show landsliding preference on north-facing slopes (NW, N, and NE).

From Figure 17 and Figure 18 it can be seen that landsliding aspect ratios do not correlate with aspect ratios for all slopes. It is also apparent that generally wetter south-facing (SW, S, SE) slopes appear least affected for all study areas. Antecedent rainfall conditions prior to the event suggest slopes were not close to saturation (pers. comm., John Medlicott 2004); for these areas January and February are the driest months of the year with maximum evapotranspiration. The storm approached from a southerly direction for most of its duration; this would perhaps be expected to provide greater saturation, and hence greater landsliding on south-facing slopes. However, the ratio of landslide affected slopes as percentages of all slopes suggest that there is another control on preferential location of landsliding in the affected areas.

A study of a similar rainfall-induced, multiple landslide event in the Wairarapa hill country (Crozier *et al.* 1980) found similar aspect preference of landsliding on north (NW, N, NE) facing slopes. Similarly for that earlier study, aspect preference could not be attributed to the directional impact of rainfall, and concluded that previous landsliding on the wetter south facing hillslopes had rendered them less susceptible to landsliding during the 1977 Wairarapa storm.

Crozier *et al.* (1980) theorised that the removal of regolith and soil from south facing slopes in previous storms had left less material able to be saturated, and mobilised during the 1977 event. However, Owen (1981) studies of 1977 landslides in the Wairarapa found that shady slopes were generally stronger than sunny slopes, which were drier and more desiccated. Sunny slopes would therefore absorb water more quickly during intense rainfall, which also might make them more vulnerable to rainfall-induced slope failure.

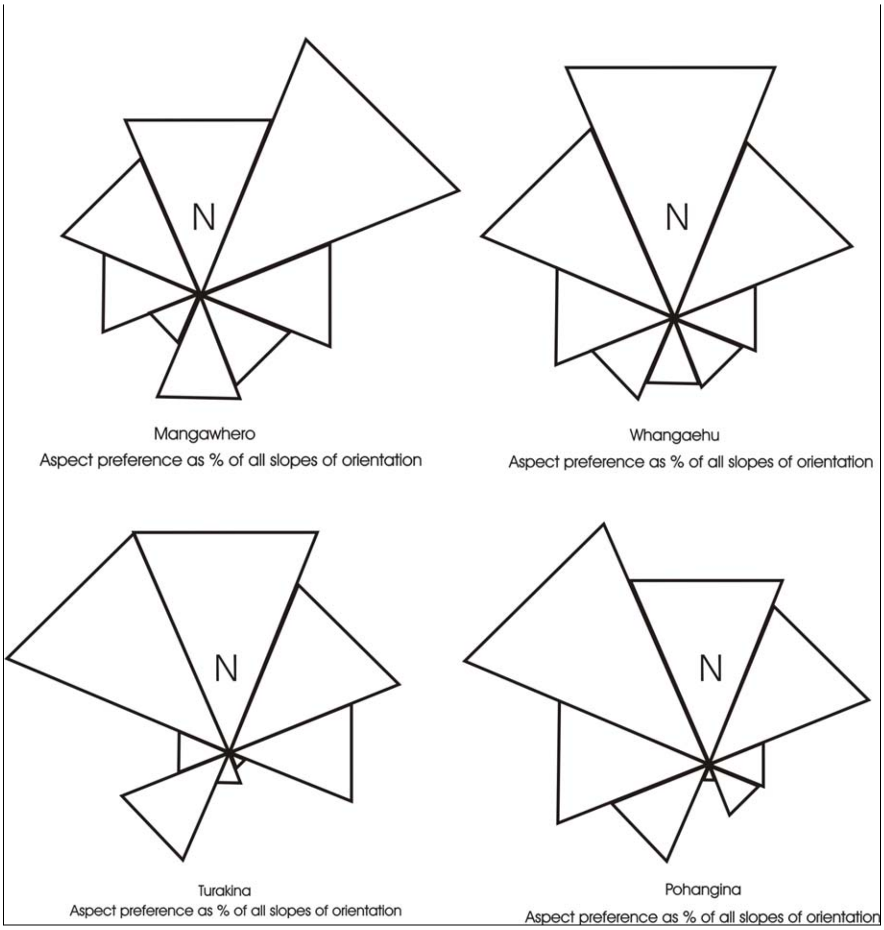


Figure 19. Summary of landslide aspect preference data with aspect ratios of landslide affected slope shown as a percentage of the aspect ratios of all slopes. Some variations in slope aspect is evident, but there is clearly a preference for north-facing (NW, N, NE) slopes in all study areas.

As all of the study areas have lithologies and soil properties which render them vulnerable to landsliding, and there are many scars from previous landslide events visible on the hills in the affected areas at the present time; it seems possible that aspect preference for the February 2004 event may be attributed to previous failures on south facing slopes. However, other factors such as greater thermal expansion and weathering on north-facing slopes, and possibly differences in soil thickness, moisture content, and lower strength (as found by Owen 1981) are also likely to have contributed to the preference for landsliding on north-facing slopes seen in the study areas. Further studies of soil thickness and previous landsliding on slopes with southerly aspect need to be carried out to clarify these unresolved issues of landsliding in relation to slope aspect.

3. LANDSLIDE CHARACTERISTICS

3.1 Landslides in relation to vegetation

Other studies of damage caused by February 2004 rainstorms have suggested that landslide occurrence was correlated with land use and vegetation type, with hill slopes covered with native bush or exotic forest much less affected by landsliding than grassland areas (Hancox and Wright 2004, 2005, Dymond in prep). In an attempt to quantify this relationship, typical vertical photos from the four study areas were selected for analysis of vegetation cover effects on landsliding. Four photographs with a variety of vegetation types were chosen from each study area. Therefore photos with at least 50% vegetation cover other than pasture in the four study areas were used.

Four classes of vegetation type were recognised: pasture, bush/scrub, pine, and poplar/willow. For each of the photographs, 1 km grid squares were overlaid on photos, referenced from the 1:50,000 NZMS 260 map. Each of these 1 km grid squares were then divided into 100 smaller grids, each one hectare in area. For each 1 km grid square the number of hectare grids of each vegetation class was counted, as well as the number of grids of each vegetation class that contained some landslide damage. These numbers were converted to percentages to reflect the density of landsliding in each vegetation class in the four study area (Figures 20 and 21).

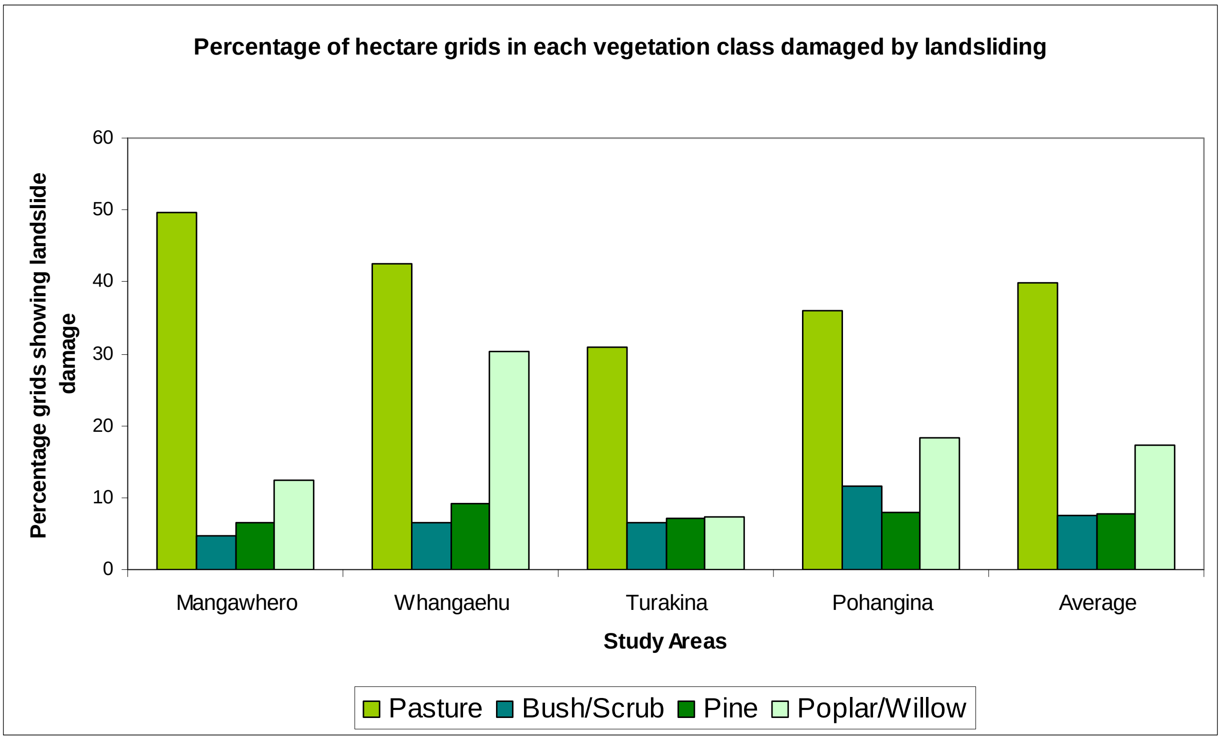


Figure 20. Proportion of vegetation class occupied by landslides for each of the four study areas.

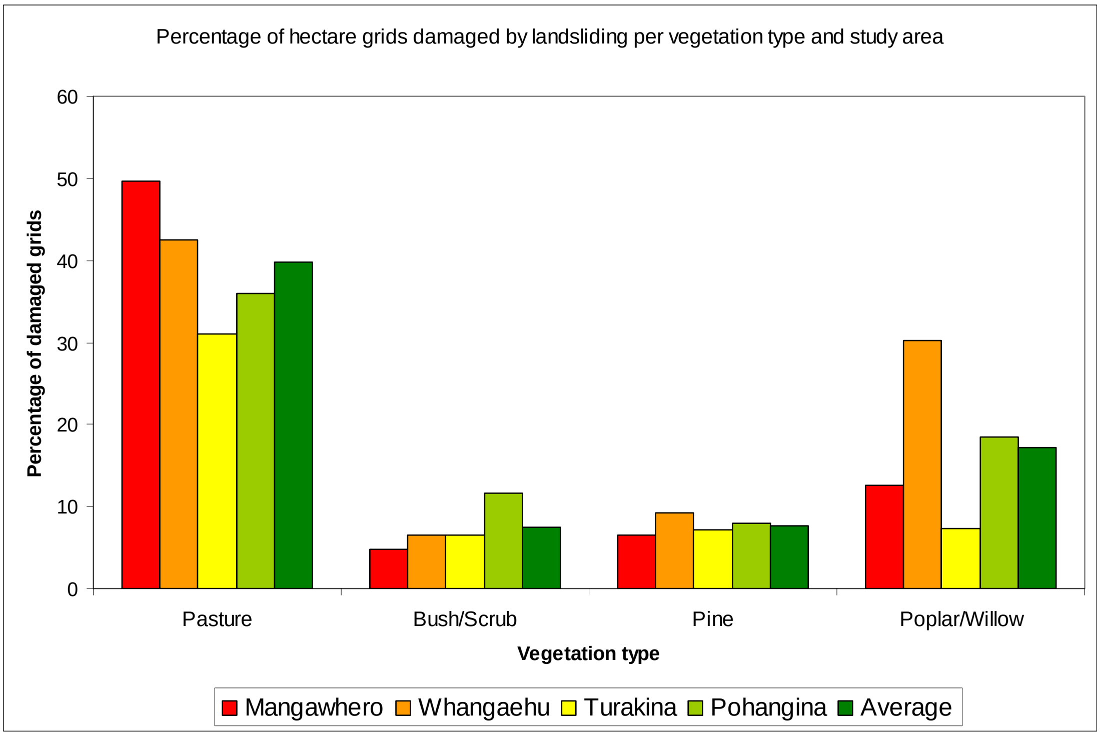


Figure 21. Percentages of grids occupied by landslides in study areas for each vegetation type.

A summary of vegetation and landslide data used for the analysis is presented in Appendix 5. Of the four main vegetation types, pasture (grassland) was clearly most affected by landslides in all four study areas. The percentage of landslide damage on pasture ranged from 31–49.6%, with an average of about 40%. Areas in native bush or scrub and pine forest had levels of landsliding averaging 7.5 % and 7.7 % respectively. However, in the Pohangina study area the percentage of landsliding in native bush and scrub was greater than other study areas, as there was considerable landsliding on river banks steepened by fluvial undercutting. Collapse of bush-covered riverbanks in the upper Pohangina valley probably was the source of the water-borne tree debris that contributed to the destruction of the road bridge at Ashhurst (Figure 22).

Figure 22. Loading of tree debris on bridge supports of the road bridge over the Pohangina River at Ashhurst contributed to its collapse during the flood. *[GNS Photo: GH 1189].*

Poplar and willow plantings appear to have some influence on reducing landsliding as the landslide densities are lower than for bare pasture, however as these trees are mostly planted on vulnerable slopes and along drainage channels, the proportions of landslide damage are higher than for areas of pines or bush/scrub. Pine forests and bush/scrub covered areas have dense vegetation than sparsely planted poplars and willows, and appear to provide greater protection against landsliding.

Pine forests areas with higher than average levels of landslide damage coincided with areas of young trees. The younger age of the trees could be inferred because the ground surface was visible (canopy closure had not yet occurred) and individual rows of trees were easier to discern. Low occurrence of landslides was generally most noticeable in areas of mature pine forest and native bush and scrub, where the canopy layer was complete and uniform in appearance, even though in dense forest landslide scars were easier to identify than on bare ground between young trees.

Summary of relationship between vegetation type and landsliding

During rainfall-induced landslide events where the terrain has common physical characteristics (slope height, form, angle, geology, regolith, and soil type) but varying vegetation types are present, it is clear that mature trees can significantly reduce the severity of the landsliding. This is apparent from the lower densities of landslides on forested hills in all study areas.

Steep hill country areas with pasture cover provides the most susceptible condition for landsliding. Of the tree-covered areas, sparsely-distributed plantings of poplar or willow were most affected by landslides. These trees are often planted in an attempt to reduce hillslope erosion. Areas of mature pine forest and thick bush/scrub cover provides the best protection against landslide erosion. Where pine trees are young (less than about 10 years) and do not provide a full canopy cover, or significant root reinforcement of soil, landslide erosion rates are much higher than for areas of mature trees. Native bush and scrub-covered slopes that are most vulnerable to landslide erosion are those on riverbanks steepened by fluvial undercutting. Bush, scrub, and pine trees are ineffective in protecting these slopes, and often enhance downstream damage through debris loading of fluvial systems.

3.2 Landslide density

For each of the four study areas a selected sample area of severe landslide damage was examined to determine maximum *landslide density (number of landslides per km^2)*. Some of the vertical aerial photographs used for this analysis are shown in Figure 23 (grids superimposed on photos for landslide counts not shown).

The extent of the area examined was dependent on the density of landslides within it as a sample population of approximately 700 landslides *(n =~700)* for each study area was considered desirable (Appendix 6). Depending on the density of landsliding in each area, the size of the areas studied ranged from 16.61 km^2 (Mangawhero) to 22.73 km^2 (Turakina). A kilometre square grid was overlaid on selected vertical aerial photos and aligned to match those on NZMS 260 maps. To improve counting accuracy, the km^2 grid squares were then further divided into 100 smaller grids of one hectare in area. The grid square overlays were also used for measuring affected area (proportion of landslide affected terrain including scar and runout damage - Section 3.4). This method avoided double counting of individual landslides when measuring scar length to debris runout length ratios (Section 3.5).

Landslide density describes the number of landslides (Ls) per km^2, but gives no indication of the volume of landslide debris involved. As shown in Table 3, landslide densities ranged from 43.4 Ls/km^2 in the Mangawhero valley to 32.1 Ls/km^2 in the Turakina valley.

Table 3. Landslide densities in the four study areas.

Landslide Data	Study Areas			
	Mangawhero	Whangaehu	Turakina	Pohangina
Total landslides (Ls)	721	723	730	748
Total area (km^2)	16.6	20.2	22.7	19.9
Landslide Density (Ls/km^2)	43.4	35.8	32.1	37.7
Rainfall return periods	100-150yrs	100-150yrs	>150yrs	>150yrs
Rainfall amount (absolute)	160-180 mm	160-180 mm	160-180 mm	180-200 mm

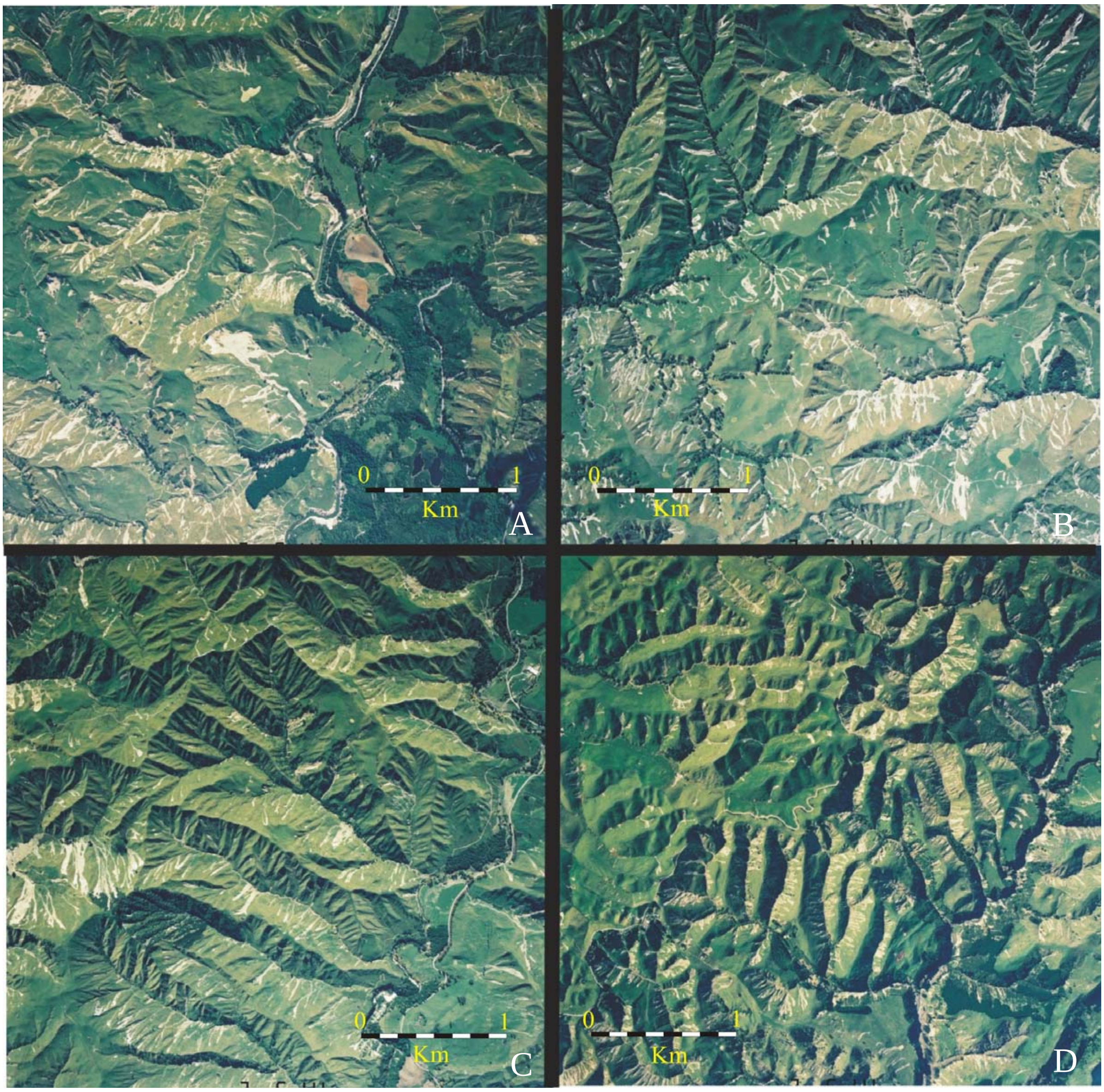


Figure 23. Four vertical aerial photos used for landslide counts in different study areas: A - Mangawhero, B - Whangaehu, C - Turakina, D – Pohangina *(original print scale 1:18 000)*. These photos clearly show the differing landslide densities and styles of landsliding in the four areas. Note that the very large (~100 million m3) prehistoric Otoko Lakes landslide (bottom right, A) was unaffected by the rainstorm, as were many other very large prehistoric landslides in the region.

The data shown in Table 3 (displayed as a graph in Appendix 7) show that landslides were more numerous in the severely affected hill country of the Mangawhero Valley than in other areas, with the Pohangina area having the second highest density of landsliding. There is little variation in landslide density between the four study areas despite terrain characteristics such as geology, soils slope height and slope form showing considerable variation especially when comparing the Pohangina study area with the three Wanganui areas.

3.3 Landslide size (scar area and volume) and fluvial connectivity

3.3.1 Theoretical background

Accepted geomorphic theory on the frequency and magnitude of landslide events suggests that the majority of work (volume of material moved a given distance, in a given time) is done during large infrequent events, rather than frequent small-scale events (Rapp 1960, Selby 1982, Crozier and Glade 1999). The February 2004 landslide damage was triggered by an extreme rainfall event that triggered landslides over an area of about 16,000 km² (Hancox and Wright 2005). It is expected, therefore, that the volume of material removed from hillslopes will be geomorphically significant. It is not possible to produce a sediment budget for the entire event, given the size of the area affected and wide areal distribution of an estimated 80,000 landslides. However, geomorphic frequency/magnitude theory also applies at smaller scales, and so it is possible to compare the amount of material transported by landslides of various sizes.

Given that a triggering event of a certain magnitude is required (e.g. a large earthquake or severe rainstorm) for multiple landslide initiation, it follows that the larger the trigger the larger the geomorphic response will be in terms of landslide size and areal extent (Crozier 1999). The February 2004 rainstorm was of sufficient magnitude to produce tens of thousands of landslides of varying sizes, therefore a comparison of the work done by varying sizes of landslides is possible. If magnitude/frequency theory for landsliding is transferable from the event scale to the scale of individual landslides, data from the February 2004 event should show that most hillslope material was removed by the larger landslides.

3.3.2 Data analysis

Landslide sizes ware measured in representative areas of between 5.5 km² and 6.5 km² in each of the four study areas. This provided a dataset of at least 250 landslides for each study area, depending on landslide density. Approximate landslide sizes were determined by firstly measuring scar areas on highly magnified digital aerial photographs (using bar-scales with 10 m divisions to determine scar widths and lengths). Landslide scar volumes were then calculated using a default average depth of 0.5 m for most landslides; although for slides that appeared to be deep-seated a scar depth of 1.5 m was used. Landslide scar volumes were then calculated by multiplying measured areas by an inferred average depth (except where depths were known from field measurements, Wright 2005). A comparison of all data is shown in Figure 24. Proportional landslide cumulative volumes are shown compared with proportional number of landslides measured. Clear differences can be seen between the four study areas; for example the three Wanganui areas have curves that rise steeply indicating a high proportion of landslide erosion volume is produced by a low proportion of landslides (e.g. for Mangawhero approximately 5 % of landslides produce approximately 80 % of erosion for the landslides measured). The Pohangina data show a different relationship between cumulative scar volume and landslide number; the curve is gentler, showing a more even distribution of landslide sizes contributing to overall scar erosion volume.

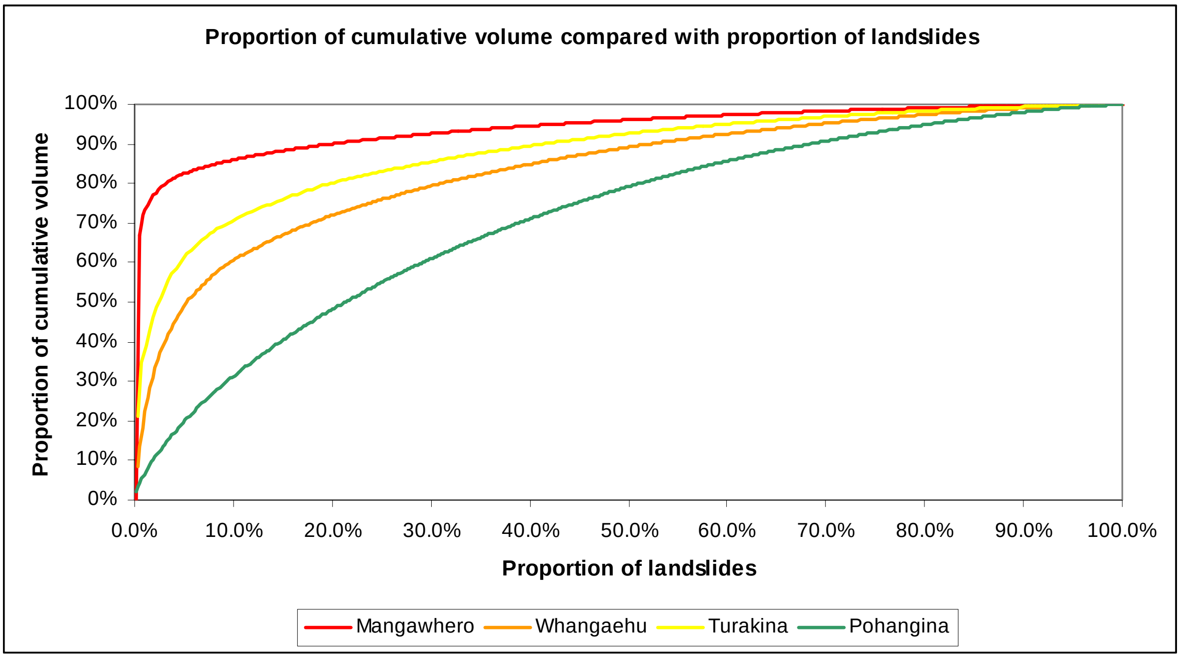
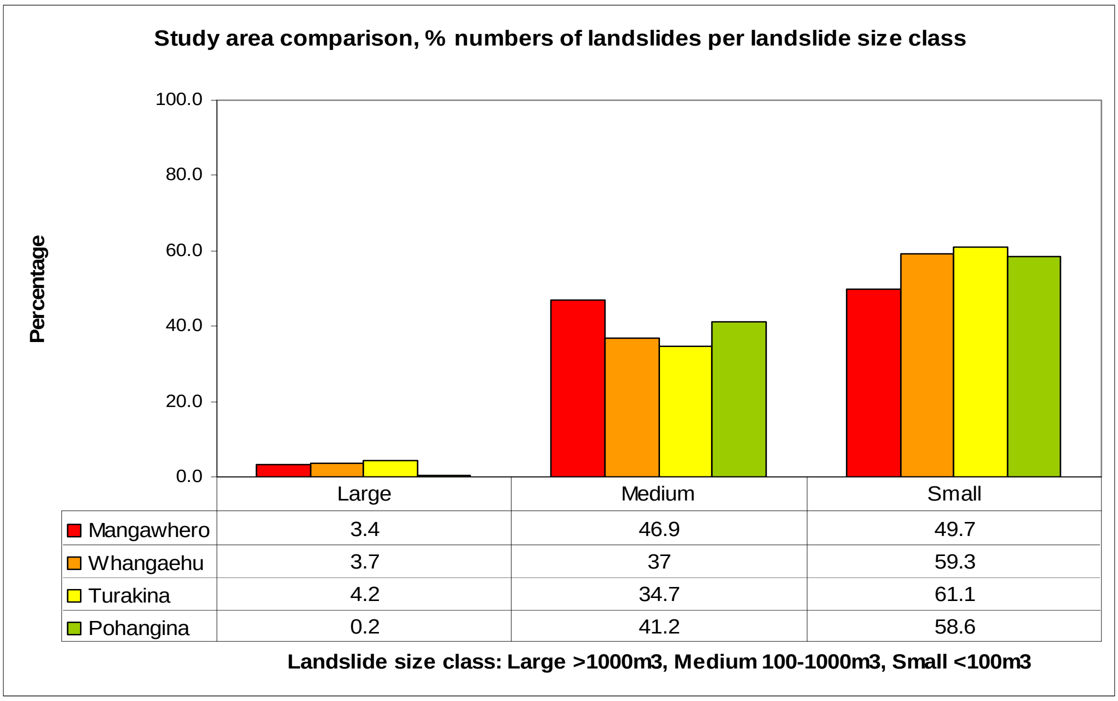


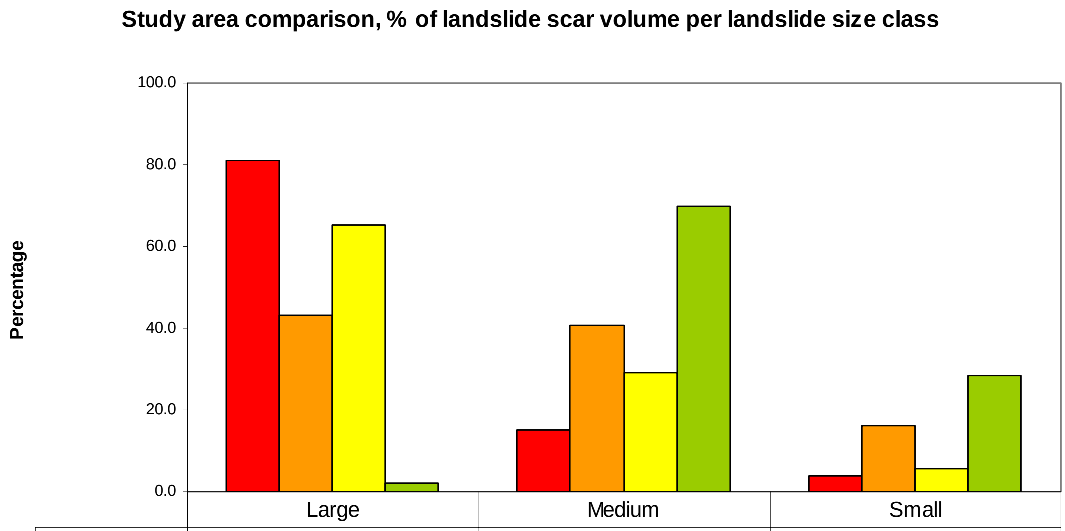
Figure 24. Proportional cumulative scar volume in relation to the proportion of landslides measured for each of the four study areas.

A further analysis of the distribution of scar volumes and amount of material eroded was undertaken by assigning landslides measured one of three size classes as follows: *Large:* > 1000 m³; *Medium:* 100-1000 m³; and *Small:* < 100 m³. The landslide size data derived from this process was then analysed and plotted to show the proportion (numbers) of landslides (l/s) within each size class (Figure 25) and the proportion of landslide scar volume within each size class (Figure 26) for each of the study areas.



	Large	Medium	Small
Mangawhero	3.4	46.9	49.7
Whangaehu	3.7	37	59.3
Turakina	4.2	34.7	61.1
Pohangina	0.2	41.2	58.6

Figure 25. Graphs showing the number (%) of landslides in each size class.



	Large	Medium	Small
Mangawhero	81.0	15.1	3.9
Whangaehu	43.3	40.6	16.1
Turakina	65.4	29.1	5.5
Pohangina	1.95	69.67	28.37

Figure 26. Comparison of the percentage contribution to total scar volume for each landslide size class, and for each study area shows greater variation between study areas than seen in Figure 24. The data table differentiates percentages that appear similar on the graph (particularly those of the Whangaehu study area).

There was some variation between the proportion of landslides in each size class in the Wanganui study areas (Mangawhero, Whangaehu and Turakina), but there was greater variance between those study areas and the Pohangina study area. For example, the proportion of large landslides for the three Wanganui study areas was found to be (east to west) 3.7 %, 3.4 %, and 4.2 %, while the percentage of large landslides in the Pohangina study area was only 0.19 % (these data in graphic format are presented in Appendix 8). Greater variation was found for the proportion of scar volume per size class. Only in the Pohangina area was it found that the large landslides did not contribute the greatest volume of landslide debris, where slides of medium size were of most significance in slide debris mobilisation.

The causes of variations between study areas for landslides in each size (scar volume) class can be seen from the photographs used for the scar volume analysis (Figure 27). In each of the three Wanganui study areas (A, B, and C) several large deep-seated slides are apparent, whereas in the Pohangina photograph there are few large slips but more medium-size slips. In the Pohangina photograph (Figure 27D) of more than 500 landslides measured only one large landslide (volume >1000 m³) was found (on a bluff over-steepened by river undercutting). Why such a large percentage of scar erosion volume was contributed by smaller landslides in Pohangina is also made clear by the photographs. The ridges and valleys of the Pohangina hill country are more closely spaced, with lower relief and high fluvial connectivity. Hillslopes in that area are generally not of sufficient height and steepness to produce large deep-seated landslides.

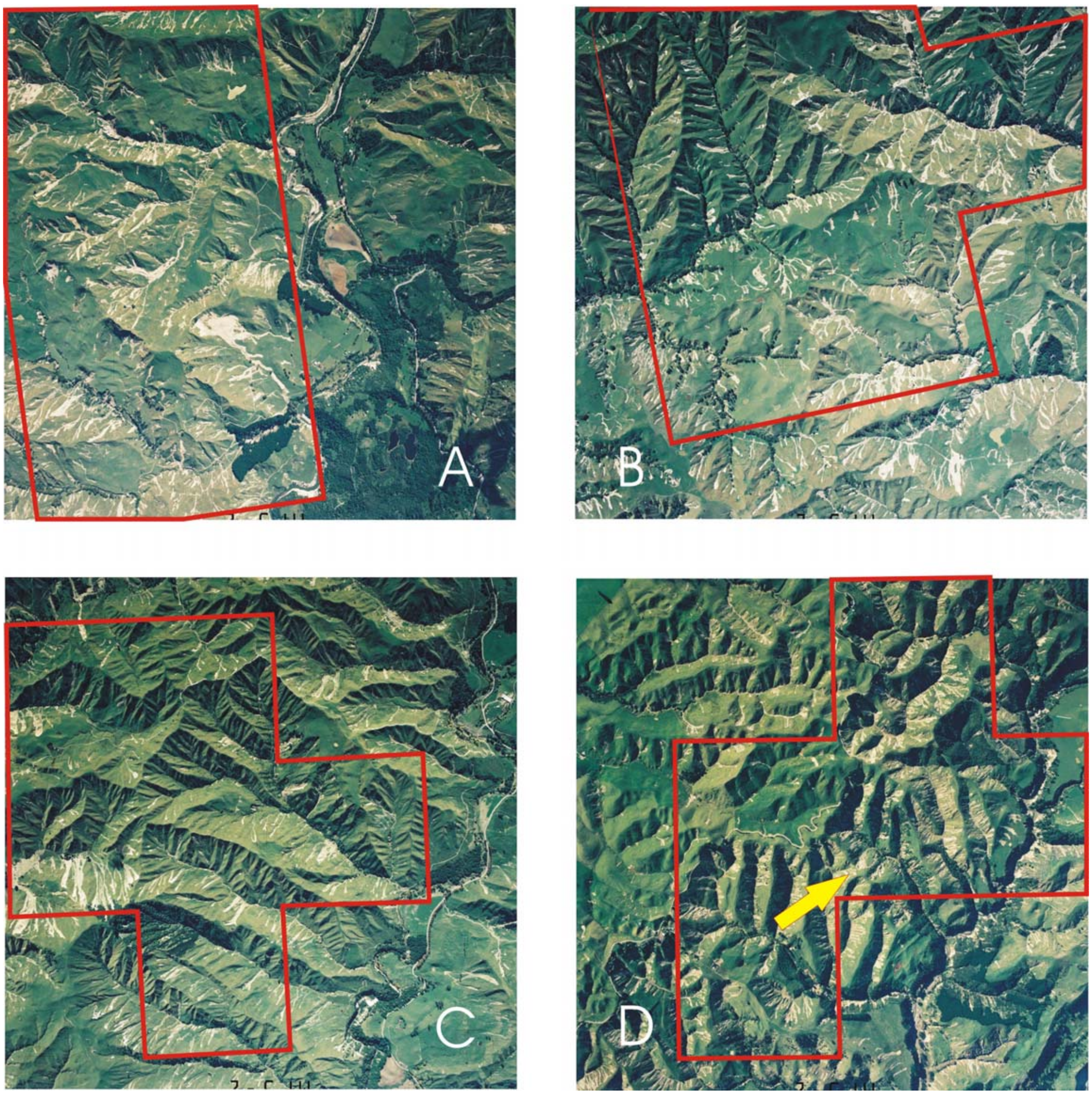


Figure 27. Vertical aerial photographs used for scar volume analysis: A – Mangawhero (Run K/photo 6); B – Whangaehu (M/9); C – Turakina (P/10); D – Pohangina (Y/22). The arrow in photograph D indicates the one large (1225 m³) landslide within the Pohangina sample area; red lines indicate the areas of photos analysed.

The Whangaehu data also show variance from the other Wanganui study areas. From Figure 27 it can be seen that landsliding is denser than in the Turakina study area, but there are less obviously large, deep-seated landslides. The largest landslide in the Mangawhero photograph (A), probably the largest landslide in the hill country, has strongly influenced the overall percentage of scar volume for the large landslide class in the Mangawhero study area.

The data from the four study areas generally support frequency-magnitude landslide theory. For areas of terrain such as that in the Pohangina Valley, the landslide scale relationships shown in the other three study areas are not apparent. Despite this it is clear that large landslides have the capacity to dominate sediment budgets even when they occur at low frequencies.

The fluvial connectivity of landslides was also examined as part of the landslide size analysis. Landslides were classed as fluvially-connected when they either connected physically with active drainage systems, or fed into fluvially-connected landslides. Landslides feeding into fluvially-connected landslides had to have the appearance of having flowed freely with sediment having had the possibility of entering the drainage system directly if it had not first encountered another landslide. A summary of data on landslide connectivity are presented in Table 6, in the row summarising landslide scar volumes, and detailed data are included as Appendix 8b. Note that the fluvial connectivity averages were derived from the all raw data, and not the by averaging the values of the three size classes. This provides an average in proportion to the number of landslides (regardless of size class) rather than an average weighted by the number of size classes. This part of the analysis showed larger landslides generally had higher fluvial connectivity (~75–95 %) compared to smaller slides and the average for all landslides in all four study areas (67%). Landslide connectivity was highest in the Pohangina area (~81% for small slides, 92% for medium slides, and an overall average of 85%). However in terms of sediment budget, the larger landslides were clearly more important as they delivered much more sediment to streams and rivers than did the smaller slides where much of the debris remained on the slopes.

3.4 Percentages of hillslopes affected by landslide damage

Within each of the four study areas any part of a hillslope affected by landslide scarring or runout (debris deposit) was classed as 'affected area'. Affected area percentage classes of heavy, moderate, and slight to zero were assigned for each 1km² grid overlain on the study area photographs. Each km² grid was divided into 100 one hectare sub-grids and these smaller grids were used to produce the percentage affected values. Exceptions to this system were km² grids overlying the edges of photographs, in these cases the larger grids would contain some fraction of 1km² divided into hectares. None of the aerial photograph runs were aligned exactly north-south so there were always some partial 1km² grids on each photograph. Each hectare grid was assigned to one of the three affected area classes, heavy, moderate, or slight to zero damage. For each of the large grids, the number of hectare grids contained within it falling into each damage class, was then converted to a proportion for that large grid (i.e. an edge 1 km by 1 km overlay produces a large grid of 0.8 km² or 80 hectare grids, and 20 of these hectare grids show heavy damage (> 20% affected area), the heavy landsliding ratio for that 0.8 km² grid is 25%). The km² (or part thereof) grids were then assigned to the following classes (Table 4):

- Heavy> 20% damage
- Moderate5 – 20% damage
- Zero to slight 0 – 5% damage

The value of the km by km grid (or part thereof on photograph edges) showing maximum area affected is also included in Table 4. The combined affected areas of heavy, moderate and slight produce a total affected area percentage for each larger grid and this value and the actual area of the grid are shown.

Table 4. Percentage of affected area for sampled parts of study areas

Study Area	Heavy > 20%	Moderate 5 - 20%	Slight – zero 5 – 0 %	Average %	Area Sampled	Max. Damage 1 grid %	Area of max. damage grid
Mangawhero	12.9	23.7	63.4	12.3	18 km²	20.1	1 km²
Whangaehu	7.1	23.6	69.3	8.9	23 km²	14.7	0.5 km²
Turakina	4.1	19.1	76.8	6.8	24 km²	16.1	0.85 km²
Pohangina	7.8	20.9	71.3	9.1	22 km²	16.5	1 km²

From Table 4 it can be seen that the highest (average) landslide-affected area percentage was found in the Mangawhero study area, followed by Whangaehu and Pohangina. Turakina had the lowest overall damage as well as the lowest landslide density. Larger landslides, such as those seen in Figure 23 and Figure 26 clearly have a strong influence on overall damage ratios. No large deep-seated landslides were present in the Pohangina sample area; however the high-density shallow landsliding in the area results in affected area proportions similar to those in the Whangaehu sample area. Although there were some large deep-seated slides in the Turakina study area, in this analysis they were not of sufficient quantity to produce heavy affected area percentages values comparable to the Whangaehu or Pohangina areas.

The average affected area percentage of each sample area was determined by taking the midpoint value in each damage class (i.e. 2.5%, 12.5%, and 60%), and multiplying that value by the proportion of grids represented by that class. These values were then summed produce an average percentage for each area.

When these values are compared with the SPOT imagery damage classes (Figure 4) all four study areas fall within the 5-10% (light red) and 10-15% (dark red) classes on the map. However, these study-area averages are produced from relatively large sample areas (18-22km^2) and therefore maximum grid damage values are included in Table 4 to show that isolated patches of the study areas experienced landsliding which would place them in the 10-15% (dark red), 15-20 % (dark pink) and 20-35% (light pink) classes on the SPOT image map (Figure 4). Again these values are an average, as on a hectare level individual grids may have up to 100% damage, however, to obtain more detailed damage ratios would require analysis of 8700 individual hectare grids, and the results would be of little use for comparison with the SPOT image map due to scale differences.

Also, because the km^2 grid squares are based on the NZMS260 map grid squares, not all of the sampled area is terrain of a type that is susceptible to landsliding, however the majority of grid squares selected cover hill country areas. The use of areal grid squares to provide densities of landslides per square kilometre does not provide information on the proportion of hillslopes affected for a given area. The number of hillslopes affected ranges between 119 (Whangaehu) and 173 (Pohangina) for sample areas, and this value is dependent on the areal extent of individual hillslopes and the density of landsliding. Areal measurements of each slope were not undertaken for this study. Also, because the sample is focussed upon the most heavily affected hillslopes within each of the four study areas a value for proportion of hillslopes affected would not be valid from this sample. However, despite using different sampling and analytical methods, the affected area ratios determined in this study are generally comparable (of the same order) to those determined by Dymond *et al.* (in prep).

3.5 Landslide runout length to scar length ratios

The distance of landslide debris runout (material eroded from the scar area including un-evacuated material and material that has travelled from its original location) can have a major influence on the damage caused by an individual landslide. Greater runout distances (usually in the form of soil flows) increases the likelihood of *landslide-fluvial* coupling during rainstorms (landslide debris entering streams and rivers and contributing to overall sediment transportation during floods). Landslide debris that enters river channels increases sedimentation loads, raises river bed levels, contributes to bridge damage (through build up of large woody debris on bridge supports, and increased force of debris laden waters upon supports), and lowers water quality. The ratio of landslide runout length to scar length also gives an indication of the nature of landsliding, especially the type of movement. A higher ratio suggests material that easily forms or is incorporated into flows, whereas a lower ratio is indicative of material that stays intact and fails as a block or slump. When the propensity for hillslope material to travel far as a flow is identified, it assists with the design of mitigations measures and future hazard and risk planning, particularly where buildings or other infrastructure may be at risk.

The landslides sampled (~ 700) for each of the sample areas were measured on enlarged copies of vertical aerial photographs overlain with hectare grid squares visually referenced to the NZMS 260 map grid to prevent double counting of landslides that appear on adjacent photographs. Scar areas appear brighter and “cleaner” on the photographs and were reasonably easy to identify on enlarged photographs. Landslide debris in the runout zone was generally geomorphologically distinct, with a more textured appearance and “murkier” colour which assisted in distinguishing between the two landslide components.

The maximum scar length and maximum runout length for each landslide were then measured manually and the ratio of runout length to scar length calculated. For multiple-headed slides (where more than one scar contributes to debris runout tail) the combined length of all scars contributing to the runout material were summed to produce an overall scar length for that landslide. Average runout length to scar length ratios are shown in Table 5. As the number of landslides measured in each study area varies slightly, the data have been converted from slide numbers to percentages for better comparison of the four study areas and to produce an average. Figure 28 shows the spread of the data, which is also listed as a table in Appendix 9.

Table 5. Average ratios for landslide debris runout length to scar length in the four study areas.

	Mangawhero	Whangaehu	Turakina	Pohangina	Average
Average ratios of slide debris runout length to scar length	3.48: 1	2.62: 1	2.71: 1	2.69: 1	2.88:1

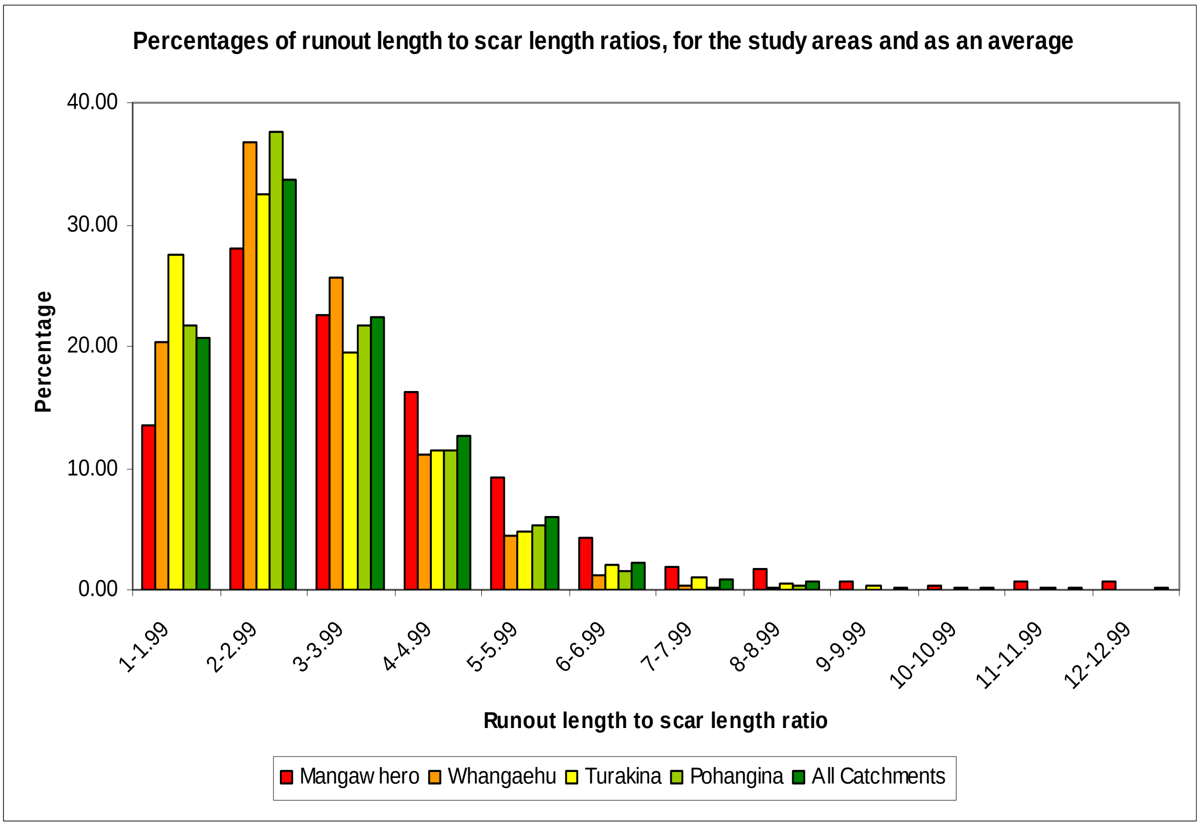


Figure 28. Graph showing the spread of landslide runout length to scar length data for the four sample areas. The Mangawhero area has very high ratios (>10: 1), and fewer low ratios (< 2: 1). In general a similar spread of data and predominance of higher ratios applies to all four sample areas.

The average values shown are considerably higher than landslide scar to debris runout ratios calculated by Dymond *et al.* (in prep) who determined average values of *runout area* to *scar area* of between 1: 1 and 2:1. The Dymond *et al.* (in prep) study focussed on *area* rather than *length*, which may account for some difference in the ratios determined in the two studies. The vertical aerial photographs show that most of the landslides have a relatively regular, linear form, meaning that length is in proportion to area. The measuring methods used in the differed from this study (digitised aerial photographs and manual digitisation of scar and landslide areas of a total of 440 landslides).

A different sampling method was used in this study from that of Dymond *et al.* (in prep). This study was concerned with sample areas of greatest damage, while the Dymond *et al.* (in prep) study chose a more random sampling method (selecting landslides nearest 300m x 300m grid intersection points) within similar areas of landslide damage. The numerous large, long-runout landslides (with high runout to scar length ratios) clearly affected landslide debris distribution on slopes and sediment delivery to streams in all the study areas (see Figures 10 and 23). They also affect the calculated scar to runout ratios, which are regarded as appropriate for the areas studied. Because of the larger sample size and the total landslide count methodology used in this study, and confirmation by field observations of many individual landslides, it is believed that the results of this study are valid for the areas sampled (with a minor component of error due to the use of non-rectified photographs, see Section 3.5.1).

The debris runout length to scar length ratio measurements calculated for this study indicate average ratios of between 2.5:1 and 3:1, which is considerably higher than the debris runout area to scar area values (between 1.14:1 and 1.61:1) determined by Dymond *et al.* (in prep).

Different methods were also used to identify landslide scar and debris (runout) areas in the two studies. In this study, scar and runout areas were identified using enlarged vertical aerial photographs. Differentiation between the two landslide components (scar and runout) was based mainly on variations in colour and texture on the photos, and supported by field and aerial observations of many landslides formed during the event. Although Dymond *et al.* (in prep) also used vertical aerial photographs for landslide measurements, the photos were digitised and pixel shade used to differentiate between the landslide components. This method may be efficient in terms of the amount of data that can be quickly processed, but lacks the judgement of an observer able to identify terrain types from first-hand experience.

A field study of one landslide-affected catchment (area 0.7 km^2), undertaken in the Mangawhero area, used hand-held GPS units to map scar and runout areas for the 26 landslides within the catchment (Wright 2005). In that study, ground measurements of landslide debris runout area to landslide scar area ratios ranged from 1:1 to 8.1:1, with an average value of 3:1 (Wright 2005). Although fewer landslides were sampled in the field study than in either of the aerial photo studies, the field catchment contained landslides of all sizes, and was within one of the four areas used for this study. The field measurements also have a greater level of precision than those produced by photographic analysis. The field measurements are consistent with those determined in this study using aerial photos.

It is likely, therefore, that the sampling method used for selecting which landslides were measured was mainly responsible for the marked difference in the scar to debris ratios determined in the two photograph-analysis studies. In this study, all landslides within the four study areas were measured, however in the Dymond et al (in prep) study, the landslides measured were selected on a semi-random basis by choosing landslides closest to grid intersection points. Because there are far more small landslides in all study areas (and in all other areas inspected) it is reasonable to assume that the method used by Dymond *et al.* had a lower likelihood of sampling the larger landslides with much longer debris runout compared to scar length (Figure 10). The larger landslides, while fewer in number, are more likely to have very long debris tails (ratios of 5:1–10:1 are common, Appendix 9), which increase the overall average ratio of scar to runout length or area. However, in terms of sediment budget, long-runout large landslides are probably most important as they deliver much more sediment to streams and rivers than do smaller slides where much of the debris remains on slopes.

3.5.1 Calculation of error from use of non-rectified photos

The non-rectified vertical aerial photographs used in this study have an increasing degree of distortion from the centre of the photograph towards the edges, which could lead to error in the landslide data derived from them. The magnitude of this error was calculated by examining adjacent (and therefore overlapping) photographs, and then measuring the dimensions of landslides appearing in the centre (non-distorted) of one photograph, and comparing it with the dimensions of the same landslide as it appears on the edge of the adjacent photograph. Distortion between adjacent east-west photographs was examined as well as adjacent north-south photographs. Measurements of total lengths (scar and runout) were compared (Appendix 10) and the average east-west error was found to be 4 %. For adjacent north south photographs (as they are taken in each image run, either flying north to south, or south to north) the error was found to be 2 %. The average error values seem low, however errors of up to 25 % were found for a few individual landslides. It must also be noted, however, that while the error measured is for the entire length of the landslide, it is expected that both scar and runout contain similar degrees of distortion, as they are in similar positions on the photograph, and as this study uses ratios, the error due to the use of non-rectified photos does not significantly effect the overall results.

Table 6. Summary of terrain and landslide characteristics for four study areas in the Wanganui-Manawatu hill country.

Attribute	Mangawhero	Whangaehu	Turakina	Pohangina
Bedrock	Mudstone; weak and massive, Sandstone Consolidated (strong) (Pliocene)	Mudstone; weak and massive, Sandstone Consolidated (strong) and moderately consolidated (mod. strong) (Pliocene)	Mudstone; weak and massive (Pliocene)	Sandstone; unconsolidated (weak), containing thinly bedded clays and limestones, some gravel and pumice layers (Pleistocene)
Soil Parent Material	Quartzo-feldspathic Mudstones, including sandy mudstones	Quartzo-feldspathic Mudstones, including sandy mudstones	Quartzo-feldspathic Mudstones, including sandy mudstones	Quartzo-feldspathic Sandstone and conglomerates
Soil characteristics	Turakina steepland soil (TkS) dominant, Upokoni steepland (UpS) soil at mudstone-sandstone boundary. TkS generally stable, but can develop deep seated slides and earthflows, heals slowly on bedrock rapidly on regolith. UpS moderately susceptible to slipping, heals reasonably rapidly.	TkS in north with areas of Mangatea hill soils (MtH). Mth on shallower slopes prone to slumps and earthflows. Mangamahu steepland soils (MhS) in the south. MhS prone to slipping and heals slowly. Some UpS present.	TkS dominates, Small regions of Mth where slopes are less steep.	Pohangina steepland soils (PhS), Opawa steepland soils (OhS), both prone to slip erosion, Phs slow to heal, OhS more rapid
Average Slope Angle and class	24.85°- Moderately steep. Range of affected slopes: 15°- 40°	23.60°- Moderately steep. Range of affected slopes: 15° - 30°	24.03°- Moderately steep. Range of affected slopes: 16 ° - 34°	22.54°- Moderately steep. Range of affected slopes: 18° - 32°
Slope form and height	Mostly concave average height 144 m Height range 80 m – 220 m	Mostly concave average height 148 m Height range 60 m – 280 m	Mostly concave average height 138 m Height range 80 m – 240 m	Mostly concave average height 64 m Height range 20 m –140 m
Vegetation and landsliding	Landsliding occurs on 49.6 % of pasture, 4.7 % of bush/scrub, 6.5 % of pine and 12.5 % of poplar/willow	Landsliding occurs on 42.5 % of pasture, 6.6 % of bush/scrub, 9.2 % of pine and 30.3 % of poplar/willow	Landsliding occurs on 31 % of pasture, 6.5 % of bush/scrub, 7.1 % of pine and 7.4 % of poplar/willow	Landsliding occurs on 35.9 % of pasture, 11.6 % of bush/scrub, 7.9 % of pine and 18.4 % of poplar/willow
Landslide (l/s) Density (ls/km²)	43.31	35.81	32.12	37.66
Damage Ratio %	Heavy 12.9 Moderate 23.7 0-slight 63.5	Heavy 7.1 Moderate 23.6 0-slight 69.3	Heavy 4.1 Moderate 19.1 0-slight 76.8	Heavy 7.8 Moderate 20.9 0-slight 71.3
All slopes aspect preference*	Range 7.9% - 15.8% Ideal topography: all slopes 12.5%	Range 12.0% - 14.7% Ideal topography all slopes 12.5%	Range 9.2% - 16.6% Ideal topography all slopes 12.5%	Range 10.0% - 15.9% Ideal topography all slopes 12.5%
Landslide (ls)-affected slope aspect preference*	Range 3.5 % (SW) - 26.1 % (NE) Preference: Northeast l/s affected slopes as % of NE slopes: 190.2%	Range 5.0 % (S) – 23.5 % (N) Preference: North l/s affected slopes as % of N slopes: 196.9%	Range 1.6 % (SE) – 28.8 % (N) Preference: North l/s affected slopes as % of N slopes: 190.4%	Range 1.2 % (S) – 25.4 % (NW) Preference: Northwest l/s affected slopes as % of NW slopes: 196.0%
Scar volume % Large > 1000 m³ Med. 100-1000m³ Small < 100 m³	% of total landslides / % total scar volume / Fluvial connectivity (%) 3.4 / 81.0 / 75 46.9 / 15.1 / 57 49.7 / 3.9 / 59 Fluvial connectivity average 59	% of total landslides / % total scar volumeFl / conn 3.7 / 43.3 / 93 37.0 / 40.6 / 76 59.3 / 16.1 / 58 Fluvial connectivity average: 66	% of total landslides / % total sc/ vol / Fl/conn 4.2 / 65.4 / 100 34.7 / 29.1 / 78 61.1 / 5.5 / 48 Fluvial connectivity average: 60	% of total landslides / % total sc vol / Fl/conn 0.2 / 2.0 / 100 41.2 / 69.6 / 92 58.6 / 28.4 / 81 Fluvial connectivity average: 85

4. DISCUSSION

This section provides a summary and discussion of the main findings on terrain and landslide characteristics determined in this study. To facilitate this, a summary of terrain attributes of each of the four study/sample areas as well as the main conclusions relating to landslides is presented in Table 6. This table provides a quick reference for all terrain attributes and landslide characteristics presented in the report. The most significant findings from this study are discussed below.

Slope angle, slope height and slope form: Slope angles, slope form distributions and average slope heights were similar in all three Wanganui study areas. The Pohangina study area differed from the Wanganui study areas. Average slope angles and heights were less for Pohangina; and unlike the Wanganui study areas, no rectilinear slopes were present. While there was some variation in slope-form distribution between the three Wanganui study areas (for example Turakina study area has a greater proportion of rectilinear slopes than Mangawhero or Turakina). However, variations in slope form did not translate into differences in landsliding severity or size.

Landslides occurred on natural slopes ranging from 15–40°, but most of the landslide-affected slopes were in the moderately rolling to steep range (16–35°) with 56-86% of slopes in the strongly rolling to moderately steep class (16–25°). There were very few landslides formed on flat to gentle slopes (0–15°), but such areas in valley bottoms or below steep slopes were often overrun by landslide debris from above. There were few landslides on very steep natural slopes (>36°), and most sub-vertical sides of river channels cut in mudstone bedrock were not affected by the storm. However, there were many failures of soil and colluvium at the tops of steep road cuts throughout the affected area.

Slope aspect: There was a preference in all study areas for landsliding to occur on north-facing slopes (slopes with northerly aspect). This preference cannot be attributed to the direction of the prevailing wind and therefore incident rainfall during the storm, which was mainly from the south. One possible explanation for this preference is many of the south-facing slopes had lost susceptible hillslope material in previous events making them less susceptible to failure in February 2004. In other words, north-facing slopes may also be more vulnerable to landsliding because of thicker, weaker, and more porous soils on sunny slopes as a result of greater thermal weathering.

Effect of vegetation on landsliding: Vegetation type influences landslide occurrence on hillslopes. Slopes covered in pasture are most likely to fail, followed by poplar and willow tree plantings, while pine forests and areas of native bush and scrub are most strongly protective against landsliding. The protection provided by poplar and willow trees is difficult to judge, as often plantings of these trees were along drainage channels, but not of sufficient number or density to be effective in preventing landslide initiation, especially where river banks are undercut.

Poplars and willow trees were also more often planted on very steep pasture slopes that were already vulnerable to landsliding. Where pine trees were not sufficiently mature (less than about 8-10 years old) to produce full canopy cover, landsliding was significantly greater than under mature pines or bush/scrub. However, the number of landslides per unit area in areas of young pines trees was still lower than for grass-covered slopes. Native bush and scrub was generally associated with fewer landslides, although not in steep gullies and along steep riverbanks, particularly in the Pohangina study area.

Landslide density and proportions of affected areas: The intensity of landslide damage (affected areas and landslide density) is remarkably similar in the four study areas. The Mangawhero study area has the highest density of landsliding and the highest runout length to scar length ratios. The Whangaehu and Turakina areas have similar slope angles and rock and soil types, but only minor differences are apparent for the magnitude (landslide density and landslide volumes) of the landslide event between these three areas. The presence of the Upukonui Steepland Soil (UpS) may be linked to increased damage in the Mangawhero area; however this soil type is also found to a lesser degree in Whangaehu and is described by Campbell (1977) as only "moderately susceptible to slipping". The Turakina area suffered the least damage of all four study areas, while having similar terrain attributes to the Mangawhero and Whangaehu areas. The Pohangina area has differences in both lithology and soil characteristics from the Wanganui study areas, yet its weaker, more erosion-prone terrain shows similar damage ratios to Whangaehu, and to some degree the Turakina area. The density of landsliding in the Pohangina study area (37.7 ls/km^2) was greater than both Whangaehu and, Turakina (35.8 ls/km^2 and 32.1 ls/km^2 respectively), of the Wanganui study areas only Mangawhero had a density greater (43.4 ls/km^2) than Pohangina. The minor differences in landslide density may also reflect variations in rainfall intensity but the lack of detailed rainfall data means that this could not be investigated.

Differences in landslide density and amount of landslide affected area between the four study areas cannot be attributed solely to differences in terrain characteristics. It is considered more likely that differences in landslide density are caused by differences in rainfall, with areas of dense landsliding caused by local cells of more intense rainfall. Although there is insufficient recoded rainfall data from these areas to prove this hypothesis, it is an effect that has been observed elsewhere during other storms (e.g. Hancox 2004). There may also be a link between previous landslides on hill slopes and the amount of landslide damage during this event in the four study areas. All the study areas have experienced rainfall-triggered landslide events prior to February 2004, and these past events probably affected the response of slopes during February 2004.

Slope height and landslide size: Slope height is probably the factor that exerts most control over landslide size (scar volume) variations in the four study areas. The average height of slopes in the Pohangina area is 64 m, compared to average slope heights of 144 m in the Mangawhero, 148 m in the Whangaehu, and 138 m in the Turakina, more than twice the height of the Pohangina slopes. Compared to the Pohangina area, average landslide scar volumes were also >200 % larger in the Mangawhero and Turakina and 170% larger in the Whangaehu area. The proportion of landslides in each size class also differs, for example in the Pohangina there are far fewer (only 0.2%) large landslides (> 1000 m^3), whereas there are considerably more in the three Wanganui study areas (between 3.4% and 4.2 %). Although the number (%) of large landslides in all areas are relatively low; large landslides generally contribute most to overall hillslope erosion. However, in the Pohangina area the majority of erosion is produced by medium sized landslides, as there are very few large landslides but the second highest number (after Mangawhero) of medium sized (100-1000 m^3) landslides of all four study areas.

Landslide runout and damage: Landslide debris runout is important for assessing the hazard from landsliding during future storm events, and also the contribution of landslide debris (sediment) to fluvial systems. Identification of potential landslide runout zones on susceptible hillslopes would influence the location and construction of new buildings and infrastructure. Planning and site or route investigation should consider vulnerability to erosional undercutting, and inundation from debris from the slopes above. The February 2004 event was extreme in the extent and amount of landslide damage that occurred. It was largely a matter of chance that no lives were lost to landslides. Although the worst landslide damage occurred in sparsely populated farmland, some landslides came close to houses and closed roads, but did little significant long-term infrastructural damage.

Landslide analysis methods: Manual measurement and comparison of over 2800 landslides is time-consuming and contains considerable judgement and some degree of error. For future landslide events of similar magnitude, manual digitisation of rectified vertical aerial photographs, followed by analysis in GIS would improve the capacity to undertake a similar study to a greater level of detail in less time. Digitisation does not remove the potential for error, however, as identifying landslide scar and runout material based on pixel shade only (Dymond *et al.* in prep) removes the capacity for human experience of actual landslides to assist with identification. It is suggested, therefore, that a combination of manual digitising, followed by analysis in GIS be used for quicker assessment of terrain characteristics and more accurate measurement and analysis of landslides.

5. CONCLUSIONS

(1) The February 2004 storm over the southern North Island caused extensive shallow landsliding over about 8000 km^2 of Manawatu–Wanganui hill country. The Mangawhero valley area was most affected by landsliding, and hills bordering the Whangaehu, Turakina, and Pohangina valleys were also strongly affected. This study has determined and compared the terrain characteristics (topography, vegetation cover, rocks and soils, and slope angle, aspect and height) and the nature of the landslides in four study areas in the Mangawhero, Whangaehu, Turakina, and Pohangina valleys where extensive landsliding occurred. The nature of the landsliding in these four areas can be attributed mainly to terrain characteristics, with the most important factors affecting landslide susceptibility and distribution being: vegetation cover and slope aspect. Variations in rainfall intensity also strongly influenced the location and magnitude of the landslides.

(2) Landslides on natural slopes occurred on slopes ranging from about 15–40°, but 56-86% of those failures occurred on moderately rolling to steep slopes (16–25°). The average density of landsliding ranged from 32 to 43 slides per km^2, with the highest density recorded in the Mangawhero valley. Very few landslides formed on gentle slopes (<15°), but flatter areas in valley bottoms or below steep slopes were often overrun by landslide debris from above. There were also few landslides on very steep natural slopes (>36°). Most sub-vertical sides of river channels cut in mudstone bedrock were not affected by the rain, but there were many failures of soil and colluvium at the tops of steep road cuts throughout the affected area.

(3) There was a preference for landsliding on slopes with a northerly (NE–NW) aspect, compared with southerly (SE–SW) slopes, even though rainfall mainly came from the south during the storm. Regolith stripping by previous slope failures may have reduced the landslide susceptibility of south-facing slopes, and conversely north-facing slopes appear to be more vulnerable to rainfall-induced landsliding because of thicker, weaker, and more porous soils on sunny slopes as a result of greater thermal weathering.

(4) Vegetation cover is significantly correlated with the severity of the landsliding that occurred in steep hill country. Grassland areas were most affected by landslides in all four study areas. Landslide affected area ratios on hill country areas in pasture ranged from 30–50 %, compared with only about 8 % for areas in native forest, scrub and pine forest. Mature pine forests and thick bush/scrub cover provides the most resistance against landslide erosion. However, areas with young trees less than about 10 years old were associated with much landsliding. In some areas, there was significant landsliding of scrub and bush-covered river banks, and those planted with pine trees that had been destabilised by fluvial undercutting, with up to 30% of such areas in the Pohangina valley affected by landsliding. Loading of fluvial systems with tree debris from river-bank collapse contributed to the destruction of several bridges during the flood.

(5) In areas of similar terrain and vegetation cover, differences in landslide distribution are inferred to have been caused by local variations in rainfall intensity across a region. Areas of higher intensity rainfall may explain areas of greater landslide damage in similar terrain within and between the four study areas.

(6) Variations in landslide size are clearly related to the nature of the terrain in which they occur, particularly the height of the slope on which the landslide occurs.

(7) The majority of geomorphic work (volume of material moved during the storm) was done by the larger landslides, which were numerically a very small proportion of the total number of landslides that were formed. Landslides >1000 m^3 formed only about 3 % of all landslides in the four study areas, but were responsible for about 48 % of the volume of landslide debris eroded from hillslopes. This relationship was not surprising as it tends to be a typical geomorphic effect of landslides, although the impact of many small shallow landslides scarring large areas of hill country pastureland is often visually more striking than a few larger slides that erode deeper into bedrock.

(8) Larger landslides generally had longer debris tails (runout to scar length ratios of 5–10, compared with an average ratio of 2.9), and generally had higher (~75–95 %) fluvial connectivity compared to smaller slides and the 67% average for all landslides in all areas. In terms of sediment budget, larger landslides were also more important as they delivered much more sediment to streams and rivers than did smaller slides where much of the debris remained on slopes. The shallow scars and debris of smaller landslides also tend to regenerate grass cover more quickly than larger slides in mudstone bedrock, which therefore tend to be more permanent geomorphic features in the landscape.

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7. ACKNOWLEDGEMENTS

The authors wish to thank GNS colleagues Grant Dellow, Mauri McSaveney, and Mike Crozier (VUW) for their valuable reviews of this report. This study was initiated through the GeoNet Project, funded by the Earthquake Commission and the Foundation for Research Science and Technology. Support of FRST contract RIWRH (C01X0401) is also acknowledged.

Appendix 1. Rock and soil strength classification
(from New Zealand Geomachnics Society 1988)

<table>
<tr><th>GeneralTerm</th><th>Class</th><th>Approx. uniaxial Strength (MPa)</th><th colspan="3">Field Characteristics</th></tr>
<tr><td colspan="3" rowspan="2"></td><td colspan="2">COHESIVE MATERIAL</td><td>NON-COHESIVE MATERIAL*</td></tr>
<tr><td colspan="2">Class RO sub-divisible into classes S1-S6
Fine grained soils such as clay, sandy clay, silt etc</td><td>Class RO
Coarse grained soils such as sand, silt & grave and various mixtures of these</td></tr>
<tr><td rowspan="6">EXTREMELY WEAK</td><td>S1</td><td>< 0.025</td><td>VERY SOFT</td><td>Exudes between fingers when squeezed</td><td rowspan="3">Loosely packed – can be removed from exposure by hand or removed easily by shovel</td></tr>
<tr><td>S2</td><td>0.025 – 0.05</td><td>SOFT</td><td>Easily indented by fingers when squeezed</td></tr>
<tr><td>S3</td><td>0.05 – 0.10</td><td>FIRM</td><td>Indented only by strong finger pressure</td></tr>
<tr><td>S4</td><td>0.10 – 0.20</td><td>STIFF</td><td>Indented by thumb pressure</td><td rowspan="3">Tightly packed- requires pick for removal, either as lumps or as disaggregated material</td></tr>
<tr><td>S5</td><td>0.220 – 0.40</td><td>VERY STIFF</td><td>Indented by thumb nail</td></tr>
<tr><td>S6</td><td>0.40 - 1.0</td><td>HARD</td><td>Difficult to indent by thumb nail</td></tr>
<tr><td colspan="6">*Strength correlation with cohesive material not implied</td></tr>
<tr><td colspan="6">………………………………………………Approximate Soil/Rock Boundary……………………………………………………</td></tr>
<tr><td colspan="6">STRENGTH(1) AND HARDNESS(2) CRITERIA</td></tr>
<tr><td>VERY WEAK</td><td>R1</td><td>1 – 5</td><td colspan="2">Crumbles under firm blow with point of geological hammer. Can be gouged with a pocket knife</td><td rowspan="2">‘Soft’ rocks</td></tr>
<tr><td>WEAK</td><td>R2</td><td>5 - 20</td><td colspan="2">Breaks readily with light hammer blow. Shallow identifications made by firm blow with point of geological hammer, can be scraped and peeled by a pocket knife with difficulty</td></tr>
<tr><td>MODERATELY STRONG</td><td>R3</td><td>20 – 50</td><td colspan="2">Specimen can be fractured with a single firm blow of geological hammer. Can be scratched but not scraped or peeled with knife.</td><td rowspan="4">‘Hard’ rocks</td></tr>
<tr><td>STRONG</td><td>R4</td><td>50 – 100</td><td colspan="2">Specimen requires more than one blow of hammer to fracture it. Scratched with knife or hammer point only with difficulty</td></tr>
<tr><td>VERY STRONG</td><td>R5</td><td>100 – 250</td><td colspan="2">Specimen requires many blows of geological hammer to fracture it. Cannot be scratched with knife or hammer point</td></tr>
<tr><td>EXTREMELY STRONG</td><td>R6</td><td>> 250</td><td colspan="2">Specimen can only be chipped with a geological hammer</td></tr>
</table>

(1) Strength criteria – resistance to breakage (2) Hardness criteria – resistance to indentation or scratching

Appendix 2. Summary of slope height data (in relation to slope form)

		Height Range (m)	Average Height (m)
Mangawhero	Concave	80-220	144
	Convex	80-200	139
	Mixed	120-200	158
	Rectilinear	80-200	129
	All slopes	**80-220**	**144**
Whangaehu	Concave	80-280	155
	Convex	100-260	141
	Mixed	100-180	150
	Rectilinear	60-200	136
	All slopes	**60-280**	**148**
Turakina	Concave	80-200	135
	Convex	100-180	130
	Mixed	80-200	141
	Rectilinear	100-240	147
	All slopes	**80-240**	**138**
Pohangina	Concave	20-140	66
	Convex	20-120	62
	Mixed	40-100	67
	Rectilinear	0	0
	All slopes	**20-140**	**64**
NB: no rectilinear slopes in Pohangina			

Appendix 3. Summary of slope form analysis data

	Percentage of landslide affected slope forms	**%**
Mangawhero	Concave	47
	Convex	24
	Mixed	18
	Rectilinear	11
Whangaehu	Concave	48
	Convex	24
	Mixed	16
	Rectilinear	12
Turakina	Concave	49
	Convex	13
	Mixed	17
	Rectilinear	21
Pohangina	Concave	56
	Convex	31
	Mixed	13
	Rectilinear	0
		%
Concave	Mangawhero	47
	Whangaehu	48
	Turakina	49
	Pohangina	56
Convex	Mangawhero	24
	Whangaehu	24
	Turakina	13
	Pohangina	31
Mixed	Mangawhero	18
	Whangaehu	16
	Turakina	17
	Pohangina	13
Rectilinear	Mangawhero	11
	Whangaehu	12
	Turakina	21
	Pohangina	0

Appendix 4. Slope aspect data.

		Mangawhero			landslide aspect as % of all slopes of orientation
	L/S Slopes	%	All Slopes	%	
West	8.0	**5.6**	23.0	**7.9**	71.5
North	25.0	**17.6**	39.0	**13.4**	131.8
Northeast	37.0	**26.1**	40.0	**13.7**	190.2
East	18.0	**12.7**	39.0	**13.4**	94.9
Southeast	15.0	**10.6**	46.0	**15.8**	67.1
South	13.0	**9.2**	35.0	**12.0**	76.4
Southwest	5.0	**3.5**	28.0	**9.6**	36.7
Total	142.0	100.0	292.0	100.0	
		Whangaehu			landslide aspect as % of all slopes of orientation
	L/S Slopes	%	All Slopes	%	
West	14	**11.8**	32.0	**12.7**	92.3
Northwest	21	**17.6**	30.0	**12.0**	147.6
North	28	**23.5**	30.0	**12.0**	196.9
Northeast	24	**20.2**	37.0	**14.7**	136.8
East	9	**7.6**	30.0	**12.0**	63.3
Southeast	7	**5.9**	28.0	**11.2**	52.7
South	6	**5.0**	31.0	**12.4**	40.8
Southwest	10	**8.4**	33.0	**13.1**	63.9
Total	119	100.0	251.0	100.0	
		Turakina			landslide aspect as % of all slopes of orientation
	L/S Slopes	%	All slopes	%	
West	5.0	**4.0**	25.0	**9.2**	43.4
Northwest	27.0	**21.6**	31.0	**11.4**	188.8
North	36.0	**28.8**	41.0	**15.1**	190.4
Northeast	30.0	**24.0**	45.0	**16.6**	144.5
East	14.0	**11.2**	29.0	**10.7**	104.7
Southeast	2.0	**1.6**	34.0	**12.5**	12.8
South	3.0	**2.4**	25.0	**9.2**	26.0
Southwest	8.0	**6.4**	41.0	**15.1**	42.3
Total	125.0	100.0	271.0	100.0	
		Pohangina			landslide aspect as % of all slopes of orientation
	L/S Slopes	%	All slopes	%	
West	32	**18.5**	52	**15.3**	120.6
Northwest	44	**25.4**	44	**13.0**	196.0
North	27	**15.6**	36	**10.6**	147.0
Northeast	35	**20.2**	54	**15.9**	127.0
East	9	**5.2**	41	**12.1**	43.0
Southeast	7	**4.0**	35	**10.3**	39.2
South	2	**1.2**	34	**10.0**	11.5
Southwest	17	**9.8**	43	**12.7**	77.5
	173.0	100.0	339.0	100.0	

Appendix 5. Summary of data used to analyse relationship of landsliding to vegetation

Percentage of area of each vegetation type affected by landsliding

Classed by Area

	Pasture	Bush/Scrub	Pine	Poplar/Willow
Mangawhero	49.6	4.7	6.5	12.5
Whangaehu	42.5	6.6	9.2	30.3
Turakina	31	6.5	7.1	7.4
Pohangina	35.9	11.6	7.9	18.4
Average	39.8	7.5	7.7	17.2

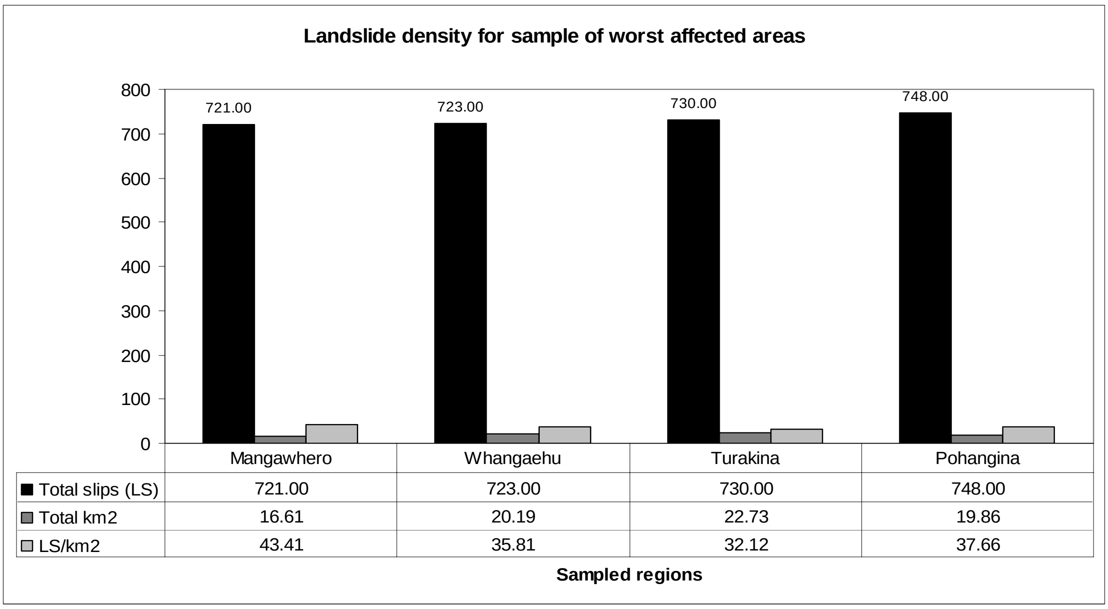
Classed by Vegetation Type

	Mangawhero	Whangaehu	Turakina	Pohangina	Average
Pasture	49.6	42.5	31	35.9	39.8
Bush/Scrub	4.7	6.6	6.5	11.6	7.5
Pine	6.5	9.2	7.1	7.9	7.7
Poplar/Willow	12.5	30.3	7.4	18.4	17.2

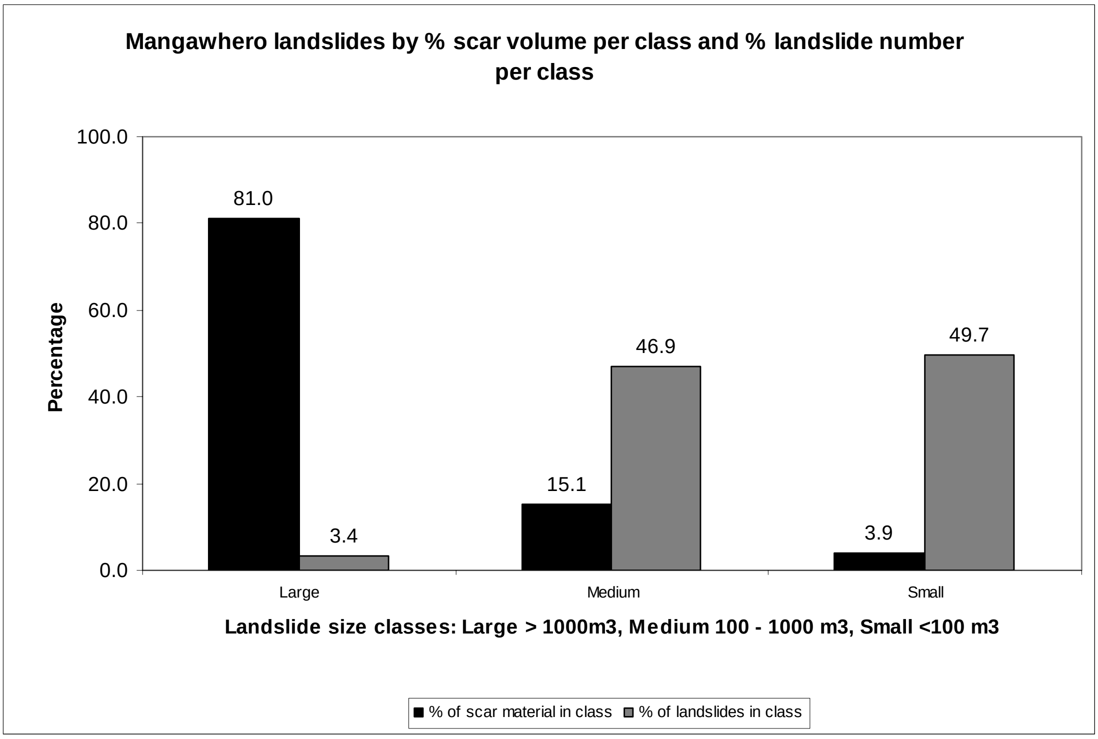
Appendix 6. Landslide density data

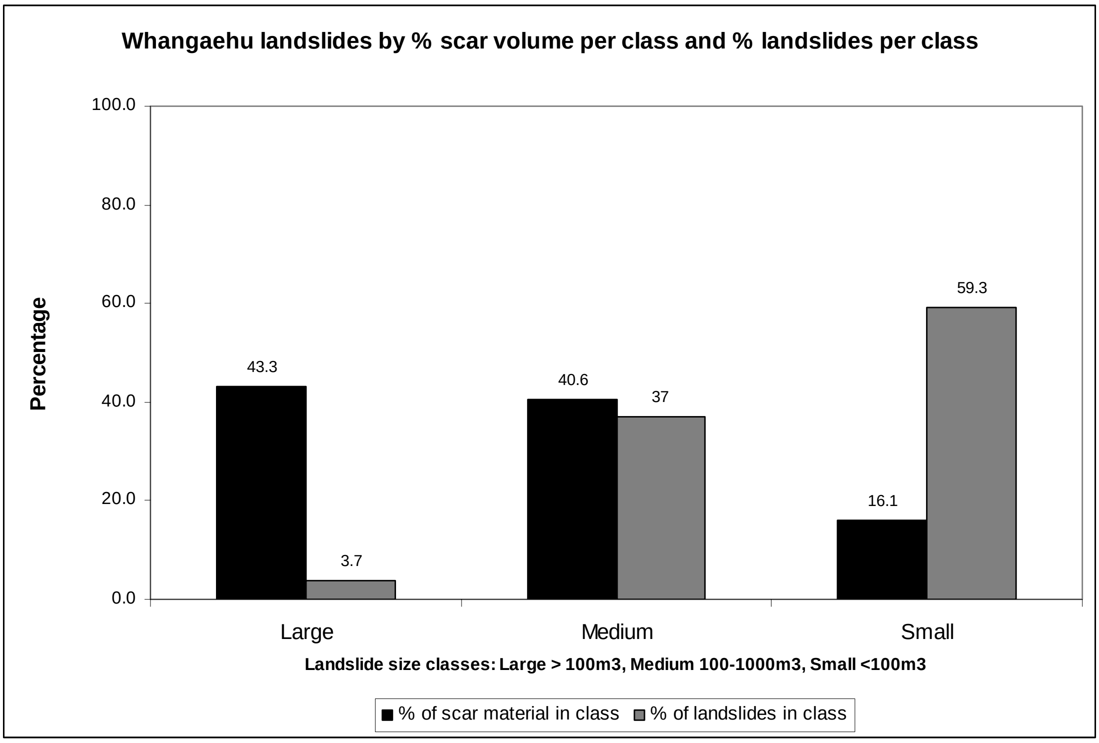
		Area of grids (km2)		
	Mangawhero	**Whangaehu**	**Turakina**	**Pohangina**
	0.90	0.67	0.76	0.82
	1.00	0.89	1.00	0.87
	0.69	0.78	1.00	0.72
	0.80	1.00	1.00	1.00
	0.84	1.00	1.00	0.85
	0.98	0.97	1.00	0.55
	1.00	1.00	1.00	0.66
	1.00	1.00	1.00	1.00
	1.00	0.67	0.79	1.00
	0.77	1.00	0.85	0.93
	1.00	0.92	0.88	0.58
	0.92	0.46	1.00	1.00
	1.00	0.82	1.00	0.70
	0.96	1.00	1.00	0.58
	1.00	0.95	1.00	0.80
	0.82	1.00	1.00	0.80
	0.93	1.00	0.97	1.00
	1.00	1.00	1.00	1.00
		1.00	1.00	1.00
		1.00	0.81	1.00
		0.84	0.80	1.00
		0.72	1.00	1.00
		0.50	0.90	1.00
			0.97	
Density Values	**Mangawhero**	**Whangaehu**	**Turakina**	**Pohangina**
Total slips (LS)	721.00	723.00	730.00	748.00
Total km2	16.61	20.19	22.73	19.86
LS/km2	43.41	35.81	32.12	37.66

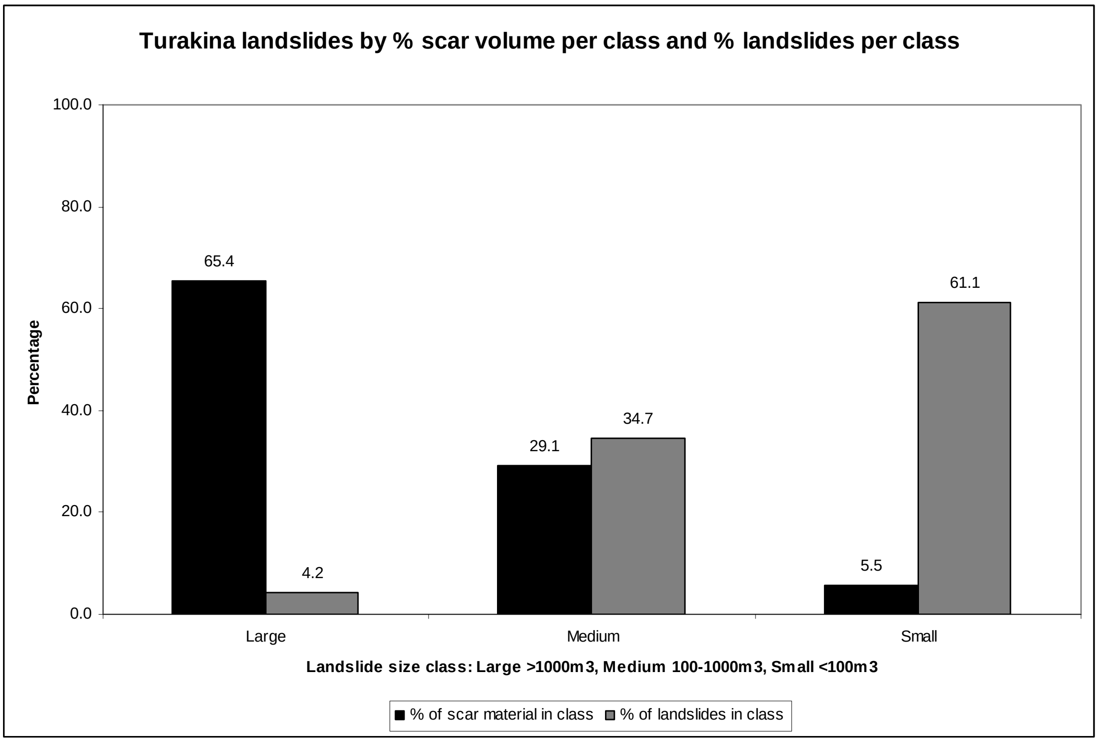
Appendix 7. Landslide density data



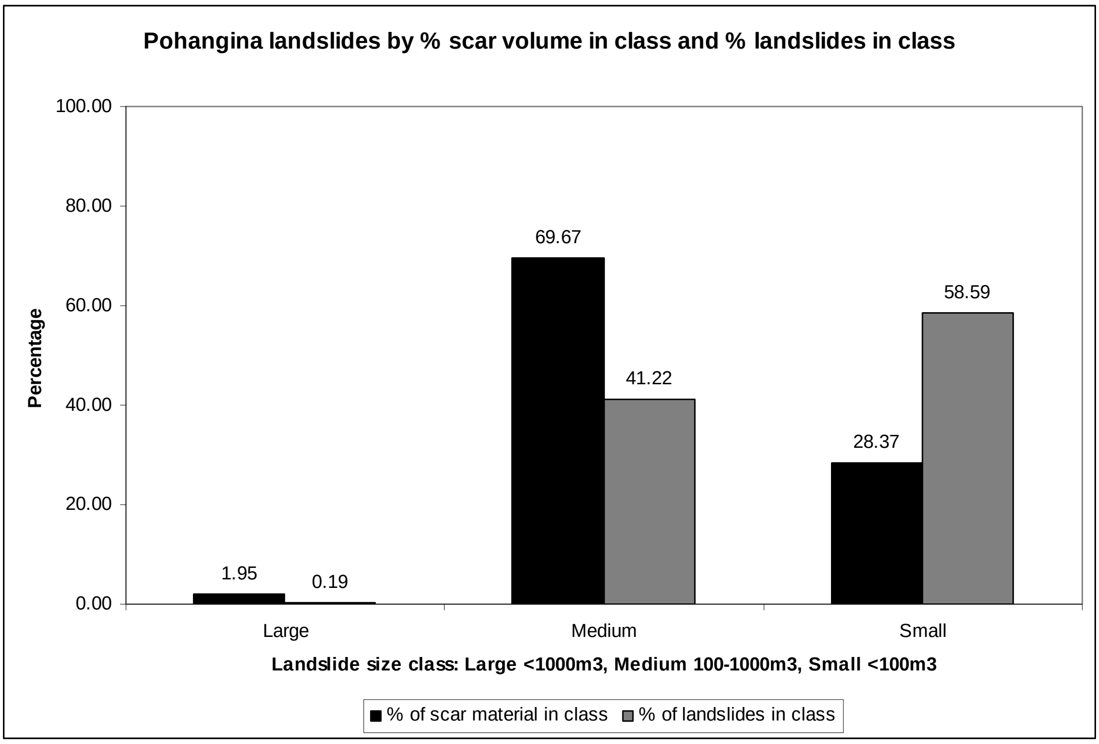
Appendix 8. (a) Landslide size analysis (by scar area and volume)







Turakina landslides by % scar volume per class and % landslides per class
100.0
80.0
60.0
40.0
20.0
0.0
Percentage
65.4
4.2
29.1
34.7
5.5
61.1
Large
Medium
Small
Landslide size class: Large >1000m3, Medium 100-1000m3, Small <100m3
% of scar material in class
% of landslides in class



Pohangina landslides by % scar volume in class and % landslides in class
100.00
80.00
60.00
40.00
20.00
0.00
Percentage
1.95
0.19
69.67
41.22
28.37
58.59
Large
Medium
Small
Landslide size class: Large <1000m3, Medium 100-1000m3, Small <100m3
% of scar material in class
% of landslides in class

Appendix 8: (b) Landslide size and fluvial-connectivity data

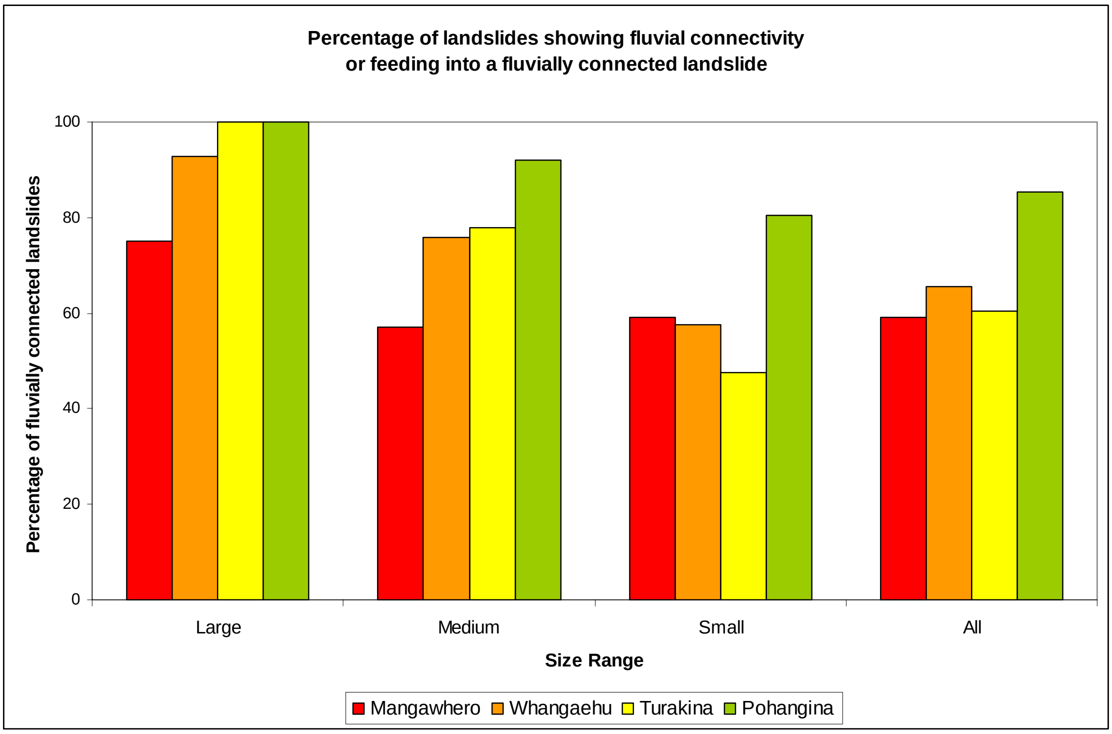
Landslide size (m^3)	Mangawhero study area					
	Size class	**Scar Volume (m3)**	**Volume %**	**Class %**	**Fluvially Connected (%)**	**Number in Class**
x > 1000	Large	262107.5	81.0	3.4	75	16
100< x <1000	Medium	48866.8	15.1	46.9	57	218
x < 100	Small	12459.0	3.9	49.7	59	231
Total (Average*)		323433.3	100.0	100.0	59*	465

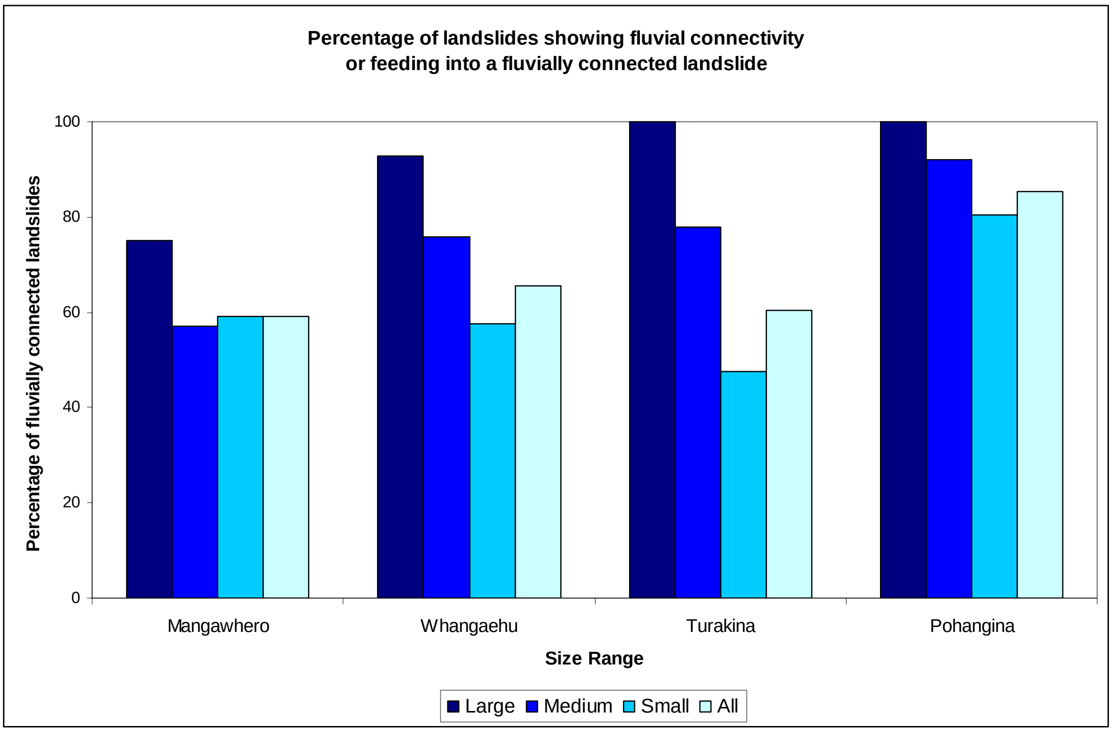
Landslide size (m^3)	Whangaehu study area					
	Size class	**Scar Volume (m3)**	**Volume %**	**Class %**	**Fluvially Connected (%)**	**Number in Class**
x > 1000	Large	31110	43.3	3.7	93	14
100< x <1000	Medium	29201	40.6	37	76	141
x < 100	Small	11561	16.1	59.3	58	226
Total (Average*)		71872	100.0	100	66*	381

Landslide size (m^3)	Turakina study area					
	Size class	**Scar Volume (m3)**	**Volume %**	**Class %**	**Fluvially Connected (%)**	**Number in Class**
x > 1000	Large	40762.5	65.4	4.2	100	14
100< x <1000	Medium	18114.5	29.1	34.7	78	141
x < 100	Small	3456.5	5.5	61.1	48	226
Total (Average*)		62333.5	100.0	100	60*	381

Landslide size (m^3)	Pohangina study area					
	Size class	**Scar Volume (m3)**	**Volume %**	**Class %**	**Fluvially Connected (%)**	**Number in Class**
x > 1000	Large	1125	1.95	0.19	100	1
100< x <1000	Medium	40122.5	69.67	41.22	92	216
x < 100	Small	16338.5	28.37	58.59	81	307
Total (Average*)		57586	100.00	100.00	85*	524

Note: Average values relate to fluvial connectivity (averages of all landslide data, not the different size classes)


Percentage of landslides showing fluvial connectivity
or feeding into a fluvially connected landslide
Percentage of fluvially connected landslides
100
80
60
40
20
0
Large
Medium
Small
All
Size Range
Mangawhero
Whangaehu
Turakina
Pohangina


Percentage of landslides showing fluvial connectivity
or feeding into a fluvially connected landslide
Percentage of fluvially connected landslides
100
80
60
40
20
0
Mangawhero
Whangaehu
Turakina
Pohangina
Size Range
Large
Medium
Small
All

Appendix 9. Summary of landslide scar/runout length ratio data

Data presented by number of landslides (n)

Runout length: scar length ratio	**Mangawhero**	**Whangaehu**	**Turakina**	**Pohangina**
1-1.99	97	147	201	163
2-2.99	202	267	237	281
3-3.99	163	186	142	162
4-4.99	117	80	84	86
5-5.99	67	32	35	40
6-6.99	31	9	15	12
7-7.99	14	3	8	1
8-8.99	12	1	4	3
9-9.99	5	0	2	0
10-10.99	3	0	1	0
11-11.99	5	0	1	0
12-12.99	5	0	0	0
Total	721	725	730	748

Data presented as percentages

	%	**%**	**%**	**%**	**%**
Runout length: scar length ratio	**Mangawhero**	**Whangaehu**	**Turakina**	**Pohangina**	**All Catchments**
1-1.99	13.45	20.28	27.53	21.79	83
2-2.99	28.02	36.83	32.47	37.57	135
3-3.99	22.61	25.66	19.45	21.66	89
4-4.99	16.23	11.03	11.51	11.50	50
5-5.99	9.29	4.41	4.79	5.35	24
6-6.99	4.30	1.24	2.05	1.60	9
7-7.99	1.94	0.41	1.10	0.13	4
8-8.99	1.66	0.14	0.55	0.40	3
9-9.99	0.69	0.00	0.27	0.00	1
10-10.99	0.42	0.00	0.14	0.00	1
11-11.99	0.69	0.00	0.14	0.00	1
12-12.99	0.69	0.00	0.00	0.00	1

Appendix 10. Non-rectified photos, error calculations

J5 length	K5 length	Difference	% change		K5 length	K6 length	Difference	% change
15.00	18.50	-3.50	23.33		21.50	22.00	-0.50	2.33
13.00	12.00	1.00	7.69		13.00	13.00	0.00	0.00
25.00	31.00	-6.00	24.00		4.50	4.50	0.00	0.00
9.00	10.00	-1.00	11.11		8.50	8.50	0.00	0.00
15.00	16.00	-1.00	6.67		12.00	9.00	3.00	25.00
15.00	16.50	-1.50	10.00		6.00	6.00	0.00	0.00
8.50	9.00	-0.50	5.88		9.50	9.00	0.50	5.26
7.50	7.50	0.00	0.00		12.50	13.50	-1.00	8.00
18.00	24.00	-6.00	33.33		10.00	8.50	1.50	15.00
7.00	7.00	0.00	0.00		15.00	15.00	0.00	0.00
8.50	8.50	0.00	0.00		18.00	18.00	0.00	0.00
9.00	10.00	-1.00	11.11		15.50	15.50	0.00	0.00
10.00	11.00	-1.00	10.00		31.00	29.00	2.00	6.45
15.00	15.00	0.00	0.00		21.00	22.00	-1.00	4.76
12.00	12.00	0.00	0.00		13.00	12.00	1.00	7.69
12.00	14.00	-2.00	16.67		26.00	28.00	-2.00	7.69
5.00	5.00	0.00	0.00		43.00	43.00	0.00	0.00
11.00	12.00	-1.00	9.09		13.00	12.00	1.00	7.69
14.00	14.00	0.00	0.00		18.50	18.50	0.00	0.00
4.00	4.00	0.00	0.00		24.50	22.00	2.50	10.20
7.50	8.00	-0.50	6.67		27.00	27.50	-0.50	1.85
10.00	10.00	0.00	0.00		15.00	16.50	-1.50	10.00
4.50	4.50	0.00	0.00		19.50	17.00	2.50	12.82
19.00	17.00	2.00	10.53		12.00	13.00	-1.00	8.33
5.00	5.00	0.00	0.00		7.00	7.00	0.00	0.00
6.50	7.00	-0.50	7.69		15.50	15.00	0.50	3.23
5.50	5.00	0.50	9.09		15.00	14.00	1.00	6.67
9.00	9.00	0.00	0.00		21.00	17.00	4.00	19.05
17.00	21.00	-4.00	23.53		10.00	10.00	0.00	0.00
22.00	23.00	-1.00	4.55		7.50	7.00	0.50	6.67
4.50	4.50	0.00	0.00		17.00	15.00	2.00	11.76
6.50	6.00	0.50	7.69		21.00	18.00	3.00	14.29
6.00	5.00	1.00	16.67		13.50	15.00	-1.50	11.11
16.00	12.00	4.00	25.00		10.00	10.00	0.00	0.00
8.00	10.00	-2.00	25.00		11.00	11.00	0.00	0.00
12.00	13.00	-1.00	8.33		6.50	6.50	0.00	0.00
13.00	13.00	0.00	0.00		33.50	34.00	-0.50	1.49
12.00	12.00	0.00	0.00		42.00	40.00	2.00	4.76
5.00	5.50	-0.50	10.00		13.00	12.50	0.50	3.85
5.00	5.00	0.00	0.00		29.00	27.50	1.50	5.17
4.50	4.50	0.00	0.00		10.50	10.50	0.00	0.00
16.00	15.00	1.00	6.25		10.00	12.00	-2.00	20.00
7.00	7.00	0.00	0.00		7.00	7.00	0.00	0.00
5.00	6.00	-1.00	20.00		23.00	19.00	4.00	17.39
16.50	14.00	2.50	15.15		20.00	17.00	3.00	15.00
3.50	4.00	-0.50	14.29		12.50	12.50	0.00	0.00
14.00	15.00	-1.00	7.14		10.00	10.00	0.00	0.00
6.00	6.50	-0.50	8.33		20.50	20.50	0.00	0.00
7.00	7.00	0.00	0.00		20.00	20.00	0.00	0.00
6.50	7.00	-0.50	7.69		13.50	14.00	-0.50	3.70
		Total	206.35				Total	118.68
		Average	4.13				Average	2.37