Rotorua District Council Hazard Studies: Landslide hazards

G.D. Dellow

GNS Science Consultancy Report 2010/82
October 2010

DISCLAIMER

BIBLIOGRAPHIC REFERENCE

Dellow, G.D.; 2010. Rotorua District Council Hazard Studies: Landslide hazards *GNS Science Consultancy Report* 2010/82. 20 p.

CONTENTS

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

GNS Science (GNS) has been commissioned by Rotorua District Council (RDC) to describe landslide hazards within the Rotorua district. The project has assessed landslides throughout the district in order to differentiate areas where the landslide hazard is similar. The report and accompanying map explain and show the variation in relative landslide susceptibility throughout the district. This information will help RDC develop policies and rules for dealing with landslide hazards in the new district plan.

The landslide susceptibility map prepared using the methodology outlined in this report is in good agreement with the known landslide information in the Rotorua district. The agreement between the susceptibility model and historical landslide data provides confidence that the relative landslide susceptibility displayed on the map effectively discriminates relative landslide hazard.

Two rainfall events generated multiple landslides over a 14 year period between 1996 and 2010. Analysis of rainfall data indicates that 200 mm of rainfall in 24 hours is the threshold for causing multiple landslides. Given that the rainfall events were limited in their extent in the district and a threshold of 200 mm of rain in 24 hours (approximately a 1-in-20 year return period event based on HIRDS data), to have two multiple landslide generating rainstorms (greater than 20-year return period storms) in 14 years matches rainfall data (the rainfall and landslide datasets were collected independently).

The landslide damage caused by the 2004 Rotoehu earthquake is equivalent to MM8 in the epicentral area around Lakes Rotoehu and Rotoma. The 1987 Edgecumbe earthquake caused landslide damage equivalent to MM6 in the same area. In Rotorua City MM8 intensity has a return period of about 2500 years but for areas east of the city MM8 has a return period of 500 years. Thus the landslide distribution in the epicentral area of the Rotoehu earthquake is an analog for the type of landslide damage that might be expected during MM8 shaking in Rotorua city, which is expected to occur on average once every 2500 years.

Large pre-existing landslides have been searched for by systematically examining vertical aerial photographs. No pre-existing large landslides have been identified in the Rotorua district. Based on the lack of evidence for large landslides in these terrains nationally, there is no large, pre-existing landslide hazard in the Rotorua district.

First-time landslides not triggered by high-intensity rainfall or earthquake-shaking occur occasionally. Some of these occur in association with rainfall but there are often other contributing factors such as recent slope modification.

1.0 INTRODUCTION

1.1 Scope

GNS Science (GNS) has been commissioned by Rotorua District Council (RDC) to describe landslide hazards within the Rotorua district. This project will assess landslide hazards throughout the district, differentiating areas where landslide susceptibility is similar. Thus, for example, areas of low landslide susceptibility and areas of high landslide susceptibility will be differentiated using available data. This report will show RDC the variation in landslide susceptibility throughout the district and assist them to develop appropriate policies and rules for dealing with landslide hazards in the new district plan.

Landslide information is held within databases maintained by GNS who have been researching geology, soil, landslides and erosion as a part of their ongoing nationally funded research programmes. Consolidating this knowledge into a district specific landslide susceptibility assessment will provide a strong evidence base for decision making around policies and rules to be incorporated into the district plan to manage landslide hazard and risk. This project aims to transfer existing landslide hazard knowledge held by GNS to the Rotorua District Council.

1.2 Data

Data used in this report come from a variety of sources. The principal datasets used include geology, topography and landslide data. The geological data used comes from the newly compiled Rotorua sheet of the 1:250,000 geological map of New Zealand. The compilation scale of the geological data used in this map is 1:50,000. The topographic data is derived from the LINZ 30 m DEM derived from the 20 metre contour interval of the NZMS260 map series. This 30 m DEM has been interpolated to produce a 10 m DEM which is then used in the modelling process. Landslide data has been sourced from GNS and RDC records. GNS landslide data was obtained from the New Zealand national landslide database, maintained by GNS as a repository for all New Zealand landslide data. The New Zealand landslide database has been populated with data collected using two approaches. The two methods used to systematically collect landslide data in New Zealand are referred to for convenience as the ‘inventory’ and the ‘catalogue’. The landslide inventory records as accurately as possible the spatial location of landslides but has no information on time series. The landslide catalogue has less well defined spatial location but accurately records time series data.

1.3 Terminology

It is necessary to clarify the terminology being used because there are different meanings attributed to the same terms in the literature (i.e. “hazard” is sometimes treated as synonymous with “risk”). This will in turn help identify the next steps required to improve the quantification of landslide hazard and consequently the management and mitigation of landslide hazards within Rotorua District. Additional definitions for landslide related terms used in this report are given in a glossary at the end of the report (Appendix 1).

A landslide is defined as the down-slope movement of rock or soil. This can be a purely gravitational process (very rare) but is most commonly triggered by rainfall or strong ground shaking at susceptible sites (often where slope modification or undercutting of a slope has occurred). This definition is deliberately very broad and encompasses the many different landslide processes. These include (but are not limited to) debris flows, earth flows, block slides and rock avalanches.

This report covers all landslide hazards. Four different landslide hazards are described, primarily because the methods used to calculate the hazard (or probability of occurrence) vary. The four landslide hazards, ranked in order of landslide frequency, that combined comprise the total landslide hazard are:

1. First-time rainfall-induced landslides (probability or hazard calculated from rainfall intensity probabilities);
2. First-time earthquake-induced landslides (probability or hazard calculated from strong ground shaking intensity probabilities)
3. Pre-existing landslides (probability or hazard calculated from site specific information); and
4. First-time landslides triggered by other processes or causes (probability or hazard calculated from landslide data).

Landslide hazard, in order to be measurable, is defined as the probability of a landslide of a certain size (magnitude) occurring within a certain time-frame (frequency). Different methodologies can be used to calculate the hazard for the four landslide hazards described above. This report outlines existing landslide data and the current methodologies used to determine landslide hazard in Rotorua District. Future improvements in the quality of the landslide data available for the district will allow better constrained quantitative methodologies to be applied.

This report does not assess landslide risk. The primary aim of this report is to describe landslide hazard in the Rotorua District this brief discussion of risk is included to demonstrate the connection between landslide hazard and landslide risk. Landslide risk is obtained by combining landslide hazard information with vulnerability information (building and infrastructure locations and the exposure of people based on their time spent at different locations in a community) held by RDC. By combining current vulnerability (or future potential vulnerability such as a proposed new subdivision site) and landslide hazard, variations in landslide risk across the Rotorua District can be identified. Understanding the variation in the distribution of landslide hazard across the district will enable RDC to identify low landslide risk areas as potential sites for future development and prioritise the highest landslide risk areas for landslide risk reduction work (mitigation).

2.0 METHODOLOGY

This report aims to develop a landslide hazard model for the RDC area based on available data. The currently available landslide data is insufficient to develop a fully probabilistic landslide hazard model. Based on the available data the selected methodology for portraying landslide hazard in the Rotorua district is a landslide susceptibility map, portraying differences in relative hazard. The susceptibility model is tested using data obtained in the review above. The spatial basis for the landslide susceptibility model is the LINZ NZMS260 derived digital elevation model (DEM) with supporting data supplied from the new geological map of the Bay of Plenty (Wilson and Leonard, in prep)and that includes the RDC area.

Rainfall data will be compared against landslide events to establish the rainfall threshold for causing multiple landslides. This will allow climate change information to be incorporated into the model as it becomes available – i.e. if the rainstorm frequency changes the landslide hazard changes.

Historical earthquake data (Franks et al, 1989; Dellow and Hancox, 2005 and Johnson et al, 2002) are used to describe the landslides that can be expected for a range of shaking intensities. This will be compared against the return periods expected for the different shaking intensities to describe the likely earthquake-induced landslide hazard in the Rotorua district.

The pre-existing landslide hazard and the hazard from other landslides will be addressed based on the information supplied by RDC and from GNS records. Based on experience both these components of the landslide hazard in the RDC area will be minor and will probably represent less than 1% of the total landslide population.

3.0 LANDSLIDE DATA

3.1 Landslide inventory

The New Zealand landslide inventory has been compiled using vertical aerial photographs to identify significant historic and prehistoric landslides in the landscape. The inventory mapping started in 1992 with the intention of locating all landslides with a volume greater than 1,000,000 m^3. No inventory landslides have been identified within the Rotorua district. The reasons for this are discussed below under landslide terrains.

3.2 Landslide catalogue

The landslide catalogue is based on the concept of an earthquake catalogue and systematically records landslides as they occur. The catalogue has been and continues to be compiled from systematic daily monitoring of news media and other sources. Landslide locations are reported as point data with an uncertainty radius ranging from 100 m to 25 km. The systematic collection of landslide information started in August 1996. The catalogue is considered complete for landslides with areas greater than 10,000 m^2 (i.e. 1 ha) for the period August 1996 – present. The catalogue data below this threshold area are incomplete (completeness of the catalogue decreases markedly with the decrease in landslide area). Table 1 presents the landslides recorded in the landslide catalogue in the Rotorua district since its inception in August 1996.

Table 1 Landslides in the Rotorua district between 1996 and 2010 as listed in the New Zealand landslide catalogue.

Date	Location	Number	Trigger (and intensity if known)
March 1987	Around Lake Rotoehu	Multiple, total unknown	Earthquake, MM7
5/09/1996	Ruato Bay, SH30, Lake Rotoiti	1	Rainfall
11-13/07/98	SH30, Lake Rotoiti, Bay of Plenty	1	Rainfall
May 1999	Rotorua area, north of lake	Multiple, total unknown	Rainfall (272 mm in 24 hr at Mangorewa)
18/07/2004	Lakes Rotoehu and Rotoma	Multiple (>100)	Earthquake MM7 + 90 mm in 24 hr (200-300 mm for 72 hr)
18/09/2005	SH30 at Lake Rotoma, Bay of Plenty	1	Rainfall
7/08/2006	Roads between Tauranga and Rotorua	Multiple, total unknown	Rainfall
29/07/2009	Parawai Rd, Ngongotaha, Rotorua	1	Unknown
6/08/2009	Pyes Pa Rd, Rotorua, Bay of Plenty	1	Other

3.3 RDC landslide records

RDC landslide data supplied to GNS to help with this study include two reports in addition to data already included through the GNS datasets. The first report deals with ongoing rock-fall and debris slide problems at Spencer Rd, Lake Tarawera (Jennings, 2005). The second report identifies landslides in the Ngati Whakaue development southeast of Lake Rotorua (Beca, 2008).

4.0 LANDSLIDE TERRAINS

Landslide terrains have been used to analyse the spatial and temporal distribution of large, pre-existing landslides in the North Island. Landslide terrains are areas of similar geology and topography combined together because similar areas often produce a characteristic suite of landslide processes. For example, the dominant rock or soil type in each landslide terrain has a characteristic strength range (e.g. hard rock, soft rock, soil) and this strongly influences the development of a characteristic topography for each landslide terrain (Dellow et al, 2005). Three landslide terrains are recognised within Rotorua District and their distribution is shown on Figure 1:

- Calderas of the Taupo Volcanic Zone (TVZ);
- Ignimbrite Sheets - Ignimbrites derived from rhyolitic volcanism in the TVZ; and
- Quaternary sediments - Quaternary-age (engineering) soils forming alluvial fans, underlying alluvial terraces and flood-plains and lake sediments.

4.1 TVZ Calderas

The caldera landslide terrain in Rotorua District is dominated by the rhyolites and tuffs of the Okataina volcanic centre (Figure 1). Other localities include rhyolite domes and tuffs in the Rotorua and Kapenga calderas. There are a range of slopes, from steeper cliffs around caldera edges and rhyolite domes to gently undulating surfaces atop rhyolite domes. No large pre-existing landslides have been identified in this terrain in the North Island (c.f. over 6000 landslides identified in the other 11 landslide terrains of the North Island). The lack of large landslides in the TVZ caldera landslide terrain is attributed to the highly active volcanic processes in this terrain regularly burying or destroying the subtle geomorphic features that would allow for the positive identification of pre-existing landslides. Small landslides are commonly rock-fall and hillside debris flows, usually occurring as first time slides (for example, landslides caused by the M_w6.6 1987 Edgecumbe earthquake (Franks *et al*, 1989). The landslide record in this terrain is poorly preserved because the common landslide types are often small (rock-fall) or poorly preserved (debris flows), on top of being masked or buried by volcanic processes (e.g. 1886 Tarawera eruption, 1800 B.P. (~200 A.D.) Taupo eruption).

4.2 Ignimbrite Sheets

The ignimbrite landslide terrain is located throughout the Rotorua district (Figure 1). The ignimbrite terrain is dominated by low-relief surfaces extending over thousands of square kilometres. These surfaces are often dissected by the narrow gorges of a deeply incised drainage network. Only nineteen large pre-existing landslides are mapped in the landslide inventory in this terrain in the North Island and none are located within the Rotorua district. The lack of large, pre-existing landslides in the ignimbrite terrain is attributed to two factors. The first is that ignimbrites are the result of the “flooding” of pre-existing terrain with pyroclastic flow deposits. This process results in the formation of a new, gently sloping but relatively planar ground surface over large areas. This topography is not prone to developing large deep-seated landslides because ignimbrites bury the existing topography and the new ground surface has a low relief (tens of metres at most). The second is that the ignimbrite deposits are close to the TVZ and more recent eruptions (e.g. Oruanui at 26 ka and Taupo at 1.8 ka) have deposited new, younger materials in sufficient thickness to bury subtle geomorphic features that would allow the identification of older pre-existing landslides.

4.3 Quaternary Sediments

The Quaternary sediment landslide terrain in the Rotorua district comprises the recent river terraces and flood plains of the streams and rivers, and lake sediments in the Rotorua District. It also includes the sediments of the older Huka Group and Hinuera Formation. The terrain is generally flat-lying except for stream and river banks and along terrace edges. There are no pre-existing large landslides mapped in this terrain in the Rotorua district. Large landslides developed in Quaternary sediments are possible but they are rare as they seldom survive for any length of time. Evidence from the landslide catalogue and earthquake generated landslide work (Hancox et al, 2002) shows the sites most susceptible to landslides in this terrain are steep or vertical river-banks adjacent to active channels. For example, areas where river erosion undermines river banks or areas where liquefaction can occur during strong earthquake-shaking and cause lateral spreading (predominantly a problem near the deltas of the streams and rivers entering lakes in the district). Because most of these landslides occur adjacent to river channels the risk they pose is potentially quite low as they occur within flood control schemes where infrastructure and assets are often minimal to protect against flood damage.

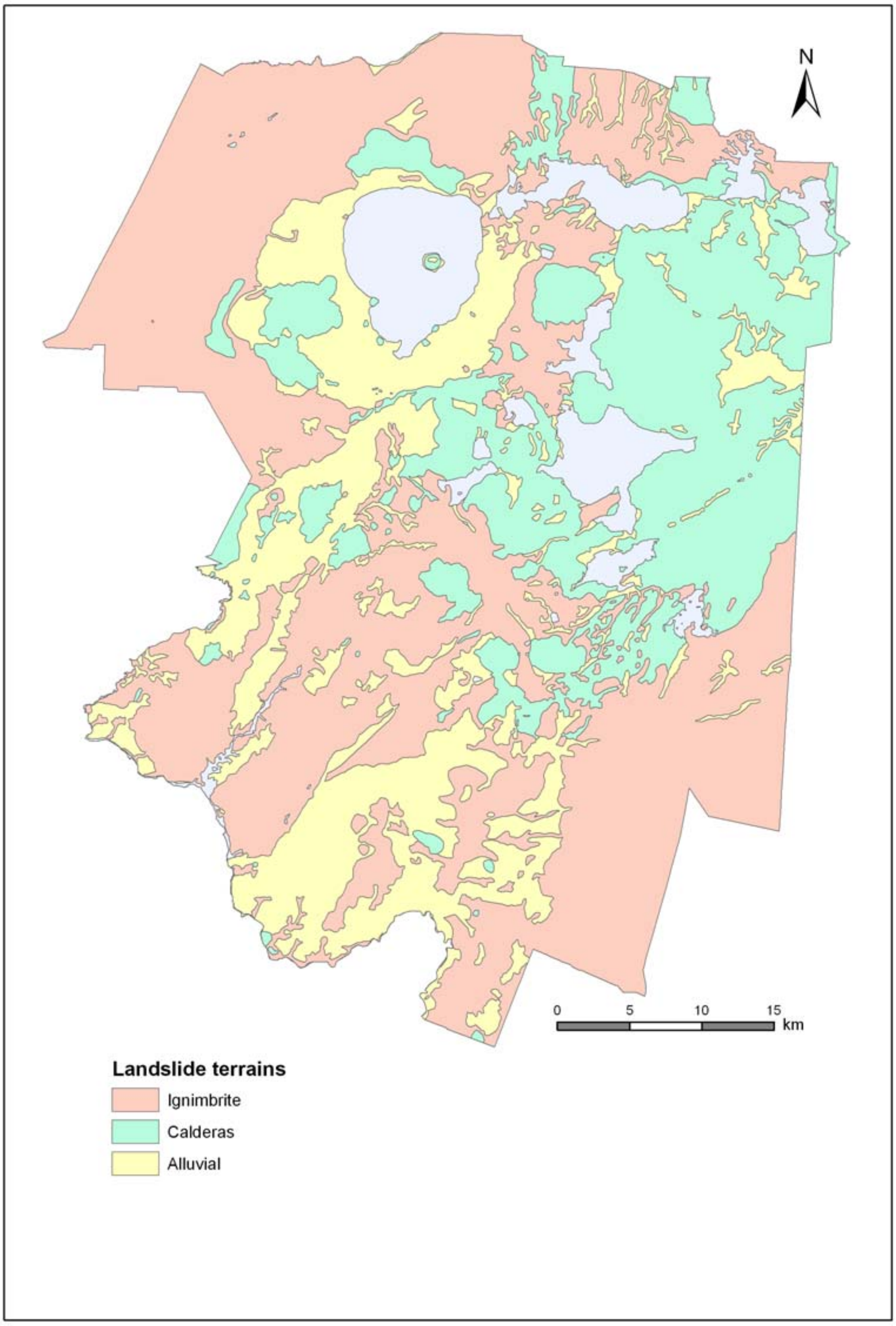

Figure 1 Landslide terrains in Rotorua District. The landslide terrains are based on geological mapping and show areas where the geological units are likely to have similar properties and therefore a similar suite of landslide processes occurring. These terrains are used for analysing the large, pre-existing landslide hazard.

5.0 LANDSLIDE TRIGGERS AND CAUSES

5.1 Rainfall-induced landslides

Most of the landslides listed in the GNS Landslide Catalogue were triggered by rainfall. The paucity of data, both for landslides and rainfall make it difficult to match rainfall intensity with landslide areal frequency in the Rotorua district. However, a broad picture emerges of needing more than 200 mm in 24 hours before a rainstorm will trigger multiple landslides. Below this threshold individual landslides may trigger due to site specific factors such as recent slope modification.

HIRDS data indicate that 200 mm in 24 hours is about a one in twenty year rainfall event. Excluding the earthquake generated landslide events there are two rainfall events that generated multiple landslides over a 14 year period between 1996 and 2010. Given that the rainfall events were limited in their extent in the district, the rainfall threshold of 200 mm in 24 hours (1 in 20 year event), to have two multiple landslide generating rainstorms or 20-year storms in a 14 year period actually matches the rainfall data quite well (the rainfall and landslide datasets were collected independently).

The most significant rainfall-induced landslide event since 1996 was the storm of May 1999 when rural roads north of Lake Rotorua were extensively damaged by landslides. The landslides and associated flooding triggered a civil defence emergency, with some estimates of the rainfall suggesting a 1 in 200 year return period in places.

The storm of 15-18 July 2004 caused very few landslides prior to the Rotoehu earthquake of 18 July 2004 when extensive landslides occurred in response to the strong ground shaking. This event is further discussed below under earthquake-induced landslides.

5.2 Earthquake-induced landslides

The strong ground shaking associated with large, shallow earthquakes can cause landslides in susceptible terrain (Keefer, 1984, Hancox *et al*, 2002). Hancox et al. (2002) studied the environmental effects of 22 New Zealand earthquakes that occurred in the period 1855 – 1995, with magnitudes in the range M_w 5.1-8.2. These earthquakes affected a wide range of terrains and ground conditions with intensities ranging up to MM10 in the four largest events. The wide range of events studied enabled a comprehensive range of types of ground damage to be assessed and quantified, at all relevant intensities, including landslides, incipient landslides, i.e. cracks and rents in slopes and ridges, lateral spreading of natural and made-ground, subsidence of fill and embankments, and various liquefaction effects.

However, there is often a significant variation in the type, density and area affected by landslides caused by earthquakes of similar magnitude or producing similar levels of shaking intensity in the same area (Hancox *et al*, 2002). Thus, the landslide response of the landscape can appear highly variable if only seismological criteria (*e.g.* magnitude, depth, fault type) are taken into account. Antecedent groundwater conditions at the time of an earthquake strongly influence the consequent landslide damage (*i.e.* similar seismological parameters can produce very different landslide responses in the same landscape or the counter-intuitive situation where a smaller earthquake causes more landslides in the same terrain than a larger earthquake) (Dellow and Hancox, 2005).

Two earthquakes have produced recorded earthquake-induced landslides in the Rotorua district in the last 170 years. These are the 1987 Edgecumbe earthquake and the 2004 Rotoehu earthquake. In both cases the maximum shaking intensity was MM7 on the Modified Mercalli Intensity scale. This is the intensity at which the relative widespread occurrence of earthquake-induced landslides begins. Of note is that the two earthquakes occurred in markedly different seasonal settings. The Edgecumbe earthquake (the larger of the two earthquakes) struck after a relatively long dry spell (the earthquake occurred at the end of summer). In contrast the Rotoehu earthquake struck immediately following three days of heavy rainfall (200-300 mm spread reasonably evenly over 72 hours). The landslides size and areal frequency was greater after the Rotoehu earthquake (the smaller earthquake) demonstrating that antecedent groundwater conditions are an important influence on the distribution of landslides from an earthquake. A dataset of 50 reasonably well located landslides for the Rotoehu earthquake event provides a test set for the susceptibility modelling (Figure 3).

5.3 Pre-existing

Large (volumes greater than one million cubic metres) pre-existing landslides (or the remains of a landslide) can often be identified in the landscape from geomorphic features. For the Rotorua District, large pre-existing landslides have been searched for by systematically examining vertical aerial photographs. As a result of this work no pre-existing large landslides have been identified in the Rotorua District. Due to the lack of data the probability, or hazard, of large landslides occurring cannot currently be determined quantitatively. Based on the lack of evidence for large landslides in the landslide terrains of the Rotorua district and the fact that there is a lack of large landslides in these terrains outside the district, there is currently no large, pre-existing landslide hazard in the Rotorua district.

5.4 Other

First-time landslides not triggered by high-intensity rainfall or earthquake-shaking occur occasionally. Some of these fail in association with rainfall but there are often other contributing factors such as recent slope modification. They have predominantly occurred in the high and very high susceptibility zones at a frequency of 1 every 2-3 years based on landslide catalogue data.

6.0 LANDSLIDE HAZARD IN THE ROTORUA DISTRICT

The landslide hazard in the Rotorua district is portrayed in this report as a landslide susceptibility map based on geology and slope angle. The susceptibility map has been compiled using geological and topographic (slope angle) data. All geological polygons with the same unit code on the new Rotorua QMap have been used. The mapped surface expression of the geological unit is then placed over a DEM.

The DEM information is derived from the Land Information New Zealand (LINZ) NZMS260 DEM 20-metre contour information with a pixel size of 30 m by 30 m. Each LINZ DEM pixel is divided into nine 10 m by 10 m pixels using an interpolation process. Every pixel in the DEM is attributed with a slope angle (assigned to the centre of the pixel) using the difference in elevation between the adjacent pixels with the highest and lowest elevations.

Placing the geological map over the DEM allows every pixel in the DEM to be attributed with a geological unit. For each and every unique geological unit in the QMap Rotorua area the slope angle data are collated and graphed as the number of pixels in each slope band. Previous work has shown that different geological units often have very different pixel-based slope-angle populations. Based on the distribution of this slope angle data individual susceptibility classes are developed for each geological unit (Table 2).

The susceptibility mapped is essentially a crude ranking of the probability of a landslide initiating at a particular DEM pixel. Because insufficient data is currently available of landslide size distributions after multiple- landslide triggering events, calculating the probability of a landslide occurring at any given site for a range of rainfall intensities is not possible.

Table 2 The definitions for the landslide susceptibility classes shown on Figure 3 are described in the table below.

Susceptibility Class	Definition
Very High	All slopes over 45°
High	Highest 33% of slope angles between 5° and 45°
Moderate	Middle 33% of slope angles between 5° and 45°
Low	Lowest 33% of slope angles between 5° and 45°
Very low	All slopes under 5°

The initial geology/DEM analysis is carried out over the entire Bay of Plenty geological map so the consequent susceptibility classes are based on regional rather than local data. This reduces the chances of local variations skewing the data which would be a possibility if only the geology of the Rotorua district was analysed.

The resulting susceptibility map is shown as Figure 3. Plotted on the susceptibility map are locations of over 50 landslides that are reasonably well located (accuracy is mostly around +/- 100 m but could be as large as +/- 500 m). Most of the landslides plotted on Figure 3 are from the 2004 Rotoehu earthquake.

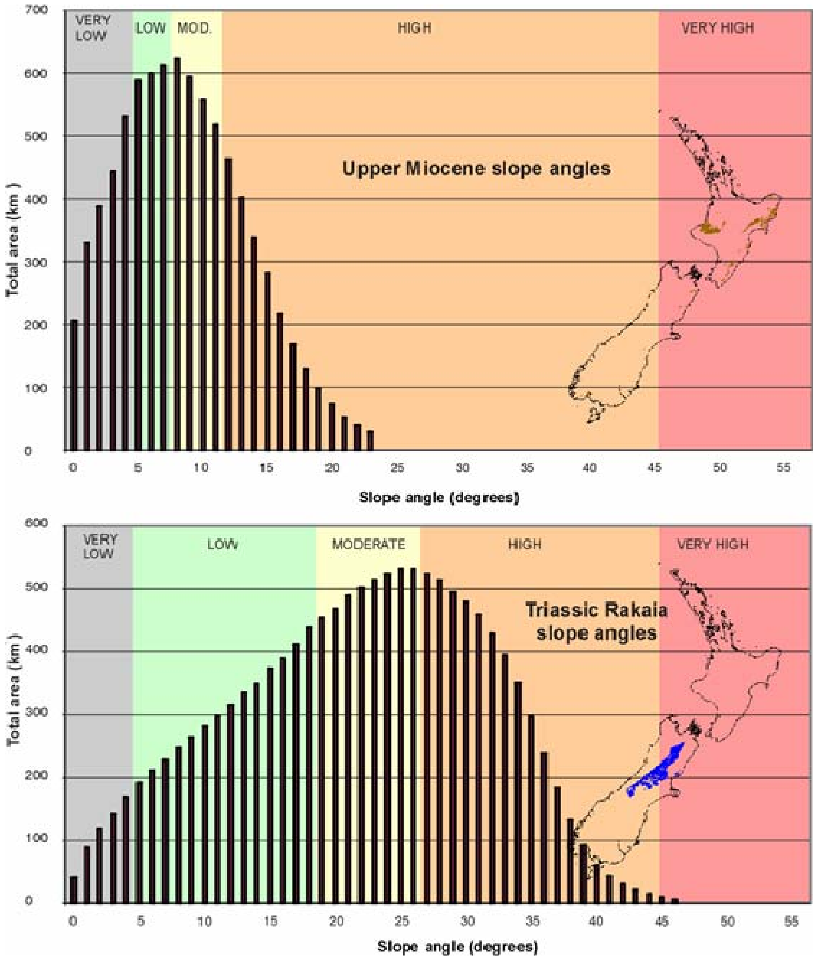

Figure 2 The susceptibility classes assigned to a geological unit are based on the distribution of slope angles within that particular geological unit. In the example shown above, the markedly different slope angle distributions result in different boundary locations for the susceptibility classes of different geological units.

As can be seen from the susceptibility map the locations of 55 of the 57 reasonably well constrained landslide locations from the GNS landslide catalogue coincide well with the high to very high susceptibility classes. The two exceptions are a landslide on the shores of Lake Rotoiti where the local slope could be a constructed slope (road-cut) up to 40 m high that would not be well picked up by the LINZ derived DEM. The other exception is a landslide report of poor provenance (single, short-lived report on the AA Roadwatch website not corroborated by other sources).

The Spencer Road rock-fall hazard area on the margins of Lake Tarawera is located in a high landslide-susceptibility zone. The landslides and landslides and erosion zones shown in the geotechnical report describing the Ngati Whakaue development southeast of Lake Rotorua are associated with a zone of mixed susceptibilities ranging from high to very low. The output from the landslide susceptibility map presented here and the Ngati Whakaue development geotechnical report landslide and erosion map both demonstrate areas of higher landslide hazard in this area.

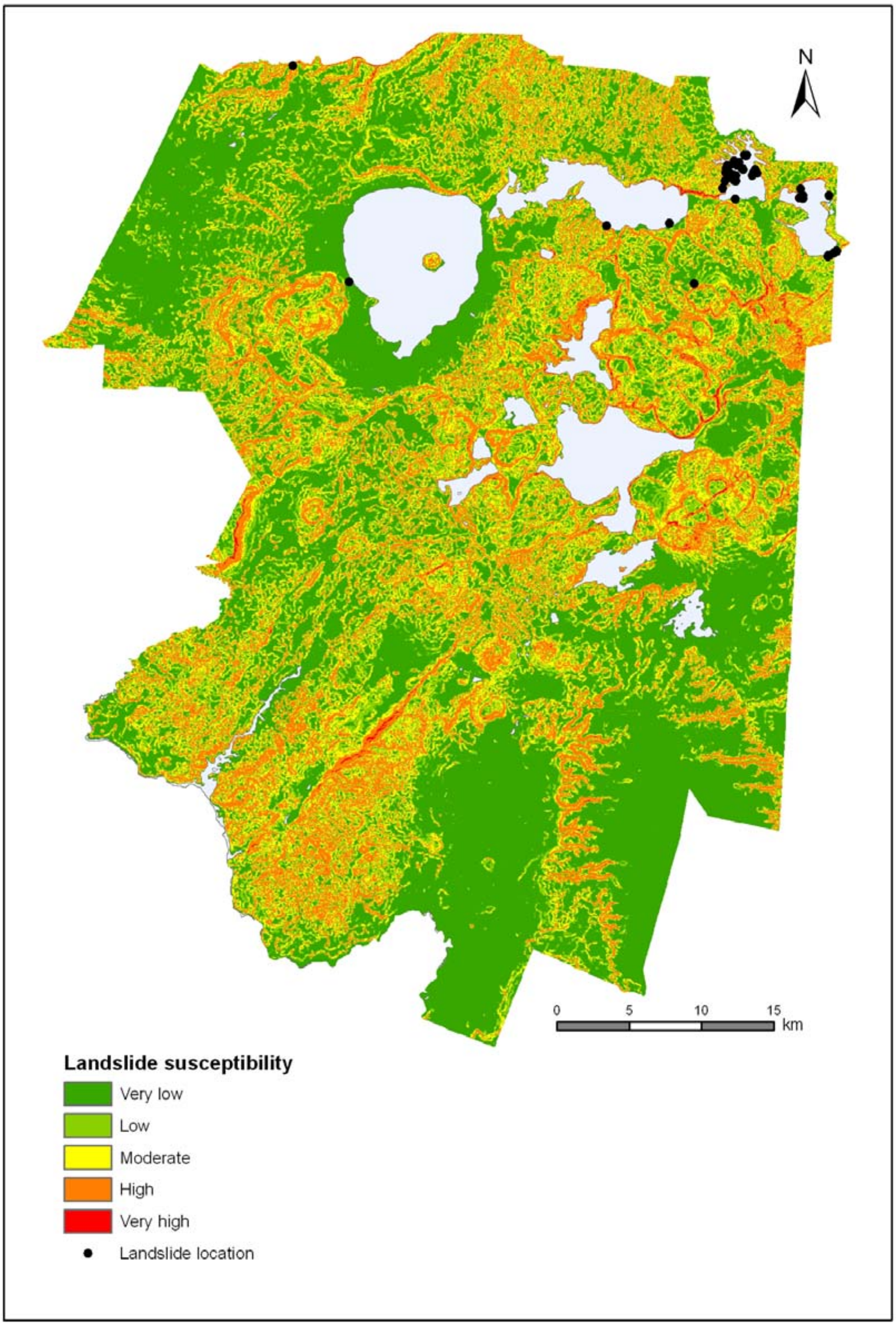

Figure 3 Landslide susceptibility map for the Rotorua district. Black dots are reasonably well located landslides and correspond well to the high and very high susceptibility classes.

7.0 CONCLUSIONS

A landslide susceptibility map has been prepared for the Rotorua District Council. The susceptibility map is based on the analysis of geological and topographic data in a GIS. Five susceptibility classes are developed for every geological unit. The map shows the distribution of relative landslide susceptibilities in the Rotorua district.

The landslide susceptibility map prepared using the methodology outlined in this report is in good agreement with the known landslide information in the Rotorua district. The agreement between the susceptibility model and historical landslide data provides confidence that the relative landslide susceptibility displayed on the map effectively discriminates relative landslide hazard.

Two rainfall events generated multiple landslides over a 14 year period between 1996 and 2010. Analysis of rainfall data indicates that 200 mm of rainfall in 24 hours is the threshold for causing multiple landslides. Given that the rainfall events were limited in their extent in the district and a threshold of 200 mm of rain in 24 hours (approximately a 1-in-20 year return period event based on HIRDS data), to have two multiple landslide generating rainstorms or 20-year storms in a 14 year period matches the rainfall data well (the rainfall and landslide datasets were collected independently).

The landslide damage caused by the 2004 Rotoehu earthquake is equivalent to MM8 in the epicentral area around Lakes Rotoehu and Rotoma. The 1987 Edgecumbe earthquake caused landslide damage equivalent to MM6 in the same area. In Rotorua City MM8 intensity has a return period of about 2500 years but for areas east of the city MM8 has a return period of 500 years. In Rotorua City MM7 intensity has a return period of about 500 years. For areas east of the city MM9 has a return period of 2500 years. Thus the landslide distribution in the epicentral area of the Rotoehu earthquake is a reasonable analog for the type of landslide damage that might be expected during MM8 shaking in Rotorua which is expected to occur an average once every 2500 years.

Large pre-existing landslides have been searched for by systematically examining vertical aerial photographs. No pre-existing large landslides have been identified in the Rotorua district. Based on the lack of evidence for large landslides in these terrains nationally, there is no large, pre-existing landslide hazard in the Rotorua district.

First-time landslides not triggered by high-intensity rainfall or earthquake-shaking occur occasionally. Some of these occur in association with rainfall but there are often other contributing factors such as recent slope modification.

8.0 RECOMMENDATIONS

The following recommendations are made with respect to landslide hazards in Rotorua District:

It is recommended that the RDC develop a policy in relation to the district plan requiring mitigation of landslide hazards. Examples of mitigation options available to parties required to operate under this policy include, for example, slope remediation (e.g. rock-bolts, drainage), debris containment structures (e.g. rock-fall catch fences, debris-flow retention dams) or avoidance.

It is recommended that all development within very high or high landslide susceptibility areas require an assessment of the slope stability hazard. This needs to address slope stability hazards at the site being developed by considering the hazard at the site itself and any potential off-site landslide hazards that may impact the site. If a landslide hazard is determined then it needs to be mitigated as per RDC policy.

In the areas of moderate landslide susceptibility it is recommended that all constructed slopes require a slope stability assessment. If a landslide hazard is determined then it needs to be mitigated as per RDC policy.

9.0 ACKNOWLEDGEMENTS

Biljana Lukovic is thanked for her work in preparing the maps used in this report. Rob Langridge and Dick Beetham are thanked for their timely and thorough reviews of the report.

10.0 REFERENCES

Beca Carter, Hollings & Ferner Ltd, 2008: Ngati Whakaue Master Plan Geotechnical Desktop Appraisal. *Beca Carter, Hollings & Ferner Ltd, 2008.*

Dellow, G.D.; McSaveney, M.J.; Stirling, M.W.; Berryman, K.R. 2005. A probabilistic landslide hazard model for New Zealand (abs). p. 24 In: Pettinga, J.R.; Wandres, A.M. (eds) Geological Society of New Zealand 50th annual conference, 28 November to 1 December 2005; Kaikoura: programme & abstracts, Geological Society of New Zealand. Geological Society of New Zealand miscellaneous publication 119A.

Dellow, G.D.; Hancox, G.T. 2006 The influence of rainfall on earthquake-induced landslides in New Zealand. p. 355-368 In: *Earthquakes and urban development: New Zealand Geotechnical Society 2006 Symposium, Nelson, February 2006.* Wellington: Institution of Professional Engineers. Proceedings of technical groups / Institution of Professional Engineers New Zealand 31(1)

Franks, C.A.M., Beetham, R.D., and Salt, G., 1989: Ground response and seismic response resulting from the 1987 Edgecumbe earthquake, New Zealand. *New Zealand Journal of Geology and Geophysics, 32: 135-144.*

Hancox, G.T.; Perrin, N.D.; Dellow, G.D. 2002. Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity; New Zealand Bulletin of the New Zealand Society for Earthquake Engineering, 35(2): 59-95

Jennings, I., 2005: Spencer Road - Lake Tarawera Rock Fall Hazard Assessment: Geotechnical assessment report. *Opus International Consultants Limited: Geotechnical Report 2328.*

Johnson, D., Perrin, N., McVerry, G., Dowrick, D., and Scott, B., 2002: A review of earthquake, landslide, geothermal and volcano information for the Rotorua Lifelines Project. *Institute of Geological and Nuclear Sciences Science Report 2002/04.*

Keefer, D.K., 1984: Landslides caused by earthquakes. *Geological Society of America Bulletin 95: 406-421, April 1984.*

Leonard, G.S., Begg, J.G., Wilson, C.J.N., (compilers) (in prep): Geology of the Rotorua area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 5. 1 Sheet. Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited.

APPENDIX 1 GLOSSARY OF LANDSLIDE RELATED TERMS

Abbreviations

B.P.	Number of years before present.
DEM	Digital elevation model – computer generated model of the elevation of the earth's surface.
GIS	Geographic information system – software package for processing and analysing geo-spatial information.
Ha	Hectare.
HIRDS	High intensity rainfall design system.
ka	Thousand years.
LINZ	Land Information New Zealand – a government department.
MM	Modified Mercalli Intensity scale – a scale for measuring the strength of earthquake shaking using building damage.
mm	Millimetres.
M_w	Moment magnitude – preferred means for measuring the size of an earthquake.
NZMS260	New Zealand Map Series 260 – topographic maps at a scale of 1:50,000.
TVZ	Taupo Volcanic Zone.

Technical terms

Landslide: A *landslide* is the down-slope movement of rock or soil. This can be a purely gravitational process (rare) but is most commonly triggered by rainfall or ground shaking at susceptible sites. The definition is deliberately very broad and encompasses many different types of processes that can be called "landslide" that include (but are not limited to) debris flows, earth flows, river erosion, block slides and rock avalanches.

Landslide Qualifiers:

Process: The *landslide process or type* of movement (*e.g.* fall, slide or flow).

Terrain: A *landslide terrain* is a landscape unit with a distinctive suite of landslide types or processes.

First-time: A *first-time* landslide is a landslide that occurs at a site that is undisturbed or *in situ* (*i.e.* where there is no recognisable landslide debris).

Pre-existing: A *pre-existing landslide* is landslide debris that can be identified in the landscape from distinctive geomorphic features. Pre-existing landslides can be either inactive (not moving) or creeping (slow moving).

Shallow: *Shallow* landslides are typically about one metre deep and involve the soil and regolith horizon.

Deep-seated: *Deep-seated* landslides have a failure surface beneath the influence of vegetation.

Fast: A *fast landslide* moves faster than walking speed.

Slow: A *slow landslide* moves slower than walking speed.

Magnitude: *Landslide magnitude* is the size of a landslide. In this report the size of the affected **area** (source + debris) is used and is measured in square metres.

Frequency: *Landslide frequency* is how often a landslide of a given magnitude occurs (often expressed as a return period or time between landslide events of the same magnitude).

Susceptibility: Landslide *susceptibility* is a qualitative ranking of the landslide hazard.

Hazard: The *landslide hazard* in quantitative terms is the probability of a landslide occurring at a particular site in a given time frame (frequency).

Vulnerability: *Landslide vulnerability* is expressed as either asset/infrastructure exposure to the hazard (in terms of the dollar cost per unit time), or as people's exposure to the hazard (in terms of the number of fatalities per unit time).

Risk: *Landslide risk* can be expressed for a stipulated landslide magnitude in terms of the dollar cost per year or as a number of fatalities per year, giving a useful basis for comparing landslide risk across the diverse range of landslides. Risk can be expressed in terms of the dollar cost per unit time or as a number of fatalities per unit time.

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657