Development of a Rainfall-Induced Landslide Forecast Tool for New Zealand

Brenda Rosser, Chris Massey, Biljana Lukovic, Sally Dellow,
and Matt Hill

Abstract

Landslides kill 2–3 people per annum in New Zealand and cost the country on average NZ$200–300 million dollars per annum. The majority of landslides (90%) in New Zealand are triggered by rainfall and often involve thousands to tens of thousands of landslides being triggered by a single event that can extend over areas up to 20,000 km^2. Steep hillslopes (>26°) occupy over 60% of the New Zealand landmass, and much of this (5%) is classified as highly erodible land at risk of severe mass-movement erosion. To reduce the risk associated with landslides it is important to be able to predict where and when they might occur. To this end we are developing a landslide forecast tool for the National GeoHazards Monitoring Centre that will be used to forecast and warn the public of possible damaging rainfall-induced landslide events. We used logistic regression to investigate the influence of landslide triggering variables on landslide occurrence on a dataset of 20 recent and historic landslide-triggering rainfall events. From this we developed relationships to predict the probable spatial distribution of landslides triggered from a given forecast rainfall event.

Keywords

Rainfall induced landslide • Forecast tool • New Zealand • Threshold • Landslide modelling

Introduction

Landslides kill 2–3 people per annum in New Zealand and cost the country on average NZ$200–300 million dollars per annum (Page 2015). In New Zealand, landslides triggered by storm rainfall are the most common type of mass-movement erosion (Crozier 2005). Steep hillslopes (>26°) occupy over 60% of the New Zealand landmass, and much of this (5%) is classified as highly erodible land at risk of severe mass-movement erosion (Dymond et al. 2006). Rainfall-induced landslides most commonly occur as multiple-occurrence landslide events, that can cover areas ranging from a few to several thousand km^2, and usually involve first-time occurrences (Crozier 2005). They are predominantly small (<1000 m^2), rapid, shallow (<2 m deep) earth or debris slides and flows. Although individually small, cumulatively they can cause significant damage in a widespread rainfall event (Fig. 1). Regional scale landslide triggering storm events occur somewhere in New Zealand on average 2–3 times per year (Crozier 2005, 2017).

Landslide occurrence in New Zealand is highly correlated with rock type. The rock types most susceptible to rainfall induced landslides are young (Quaternary and Tertiary), poorly consolidated fine-grained sedimentary rocks or highly weathered, fractured or sheared older rocks. Land cover also plays an important role in determining landslide susceptibility.

In order to reduce the risk posed by landslide hazards to society, knowledge of when and where landslides occur is essential. In this paper we present the methodology we have used to develop a rainfall-induced landslide forecast tool for New Zealand.

B. Rosser (✉) · C. Massey · B. Lukovic · S. Dellow · M. Hill
GNS Science, 1 Fairway Drive, Avalon, Lower Hutt, 5010, New Zealand
e-mail: b.rosser@gns.cri.nz

C. Massey
e-mail: c.massey@gns.cri.nz

B. Lukovic
e-mail: b.lukovic@gns.cri.nz

S. Dellow
e-mail: s.dellow@gns.cri.nz

M. Hill
e-mail: m.hill@gns.cri.nz

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Fig. 1 Extensive shallow landslides triggered by the 2004 Manawatu storm (*Photo* Graham Hancox, GNS Science)

Methodology

Development of Rainfall Intensity-Duration Triggering Thresholds

Rainfall intensity-duration thresholds for triggering landslides were developed for different physiographic regions of New Zealand. A database of 1029 landslide triggering rainfall events was compiled from various sources that covered the period from 1875 to 2019. The data covered all regions of New Zealand (Fig. 2), however, some regions had more landslide data than others which reflects both the reporting of landslides (or lack of) and the variation in general landslide susceptibility between different regions (Glade 1998). For each landslide triggering event, the location of the landslide or landsliding event (multiple landslides) was recorded, along with the date and the rainfall conditions that triggered the landslide. The regions reflect broad differences in physiographic features/variables that influence landslide occurrence such as topography, lithology and meteorology, and generally conform to administrative boundaries of local or regional government or agencies responsible for responding to or managing the impact of storm events (e.g. Civil defence and emergency management groups in regional councils).

Rainfall intensity-duration thresholds were developed for each of the regions by fitting a curve of the form:

$$I = \alpha D^{-\beta}$$

where I = rainfall intensity (mm/h) and D = duration (h), developed by Caine (1980), and secondly, using a probability approach to find the scale (intercept) α and the shape (slope) β of the power law curve representing the minimum and maximum thresholds (Guzzetti et al. 2008). The rainfall ID curves for all New Zealand are presented in Fig. 3.

Fig. 2 Regions used in this study and the location of landslide-triggering rainfall events. The point marker symbolises only the location of one or more event, not the event rainfall or extent of landslide damage

The slope of the rainfall ID threshold curve indicates the relative importance of rainfall intensity versus rainfall duration for the initiation of shallow soil failures (Guzzetti et al. 2008). A steeper threshold curve, indicates that (short) rainfall duration is more significant for landslide generation than for a less steep curves (Guzzetti et al. 2008). This indicates that in general, short duration (<24 h) rainfall is an important control for landslide initiation in New Zealand, however there is considerable variation between regions. Guzzetti et al. (2008) attributed differences in the ID thresholds to the typical meteorological conditions and characteristic rainfall patterns which trigger shallow landslides in different climatic regions, as well as to local physiographic characteristics such as geology, soil types, vegetation and slope morphology that govern landslide susceptibility.

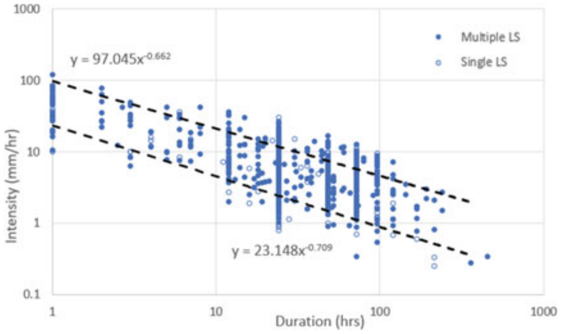

Fig. 3 Rainfall intensity-duration threshold curve for all New Zealand. The upper curve is the power fit to the 90th percentile and represents the upper ID threshold above which landslides will always occur. The lower curve is the power fit to the 2nd percentile and represents the rainfall ID threshold above which landslides will likely occur (as per Guzzetti et al. 2008)

Compilation of Storm Landslide Inventories

Existing storm landslide inventories were compiled for 20 storm events during the period 1938–2019 (Table 1). There were 16 existing storm datasets, and an additional 4 datasets compiled for the project (or as part of ongoing Geonet Landslide responses). The existing landslide datasets included a variety of data types and formats. A new GIS inventory using the data format outlined by Massey et al. (2018) was developed for the project and the data converted to a single consistent format. Both points (representing the top of the landslide source area) and polygons (representing the landslide source area) were used in the analysis. The spatial distribution of the datasets is shown in Fig. 4.

Table 1 Storm events with mapped landslide distributions used in this study

Storm, year	Storm rainfall
Kaikoura, 1975	561 mm/48 h
Coromandel, 1981	500 mm/72 h
Tasman, 2018	235 mm/18 h
Hawke’s Bay, 2011	646 mm/96 h
Hunua, 2017	200 mm/12 h
Ligar Bay, 2011	674 mm/48 h
Manawatu, 2004	215 mm/52 h
Nelson, 2011	423 mm/48 h
Northland, 2007	400 mm/36 h
Orongorongo, 2002	194 mm/24 h
Orongorongo, 2004	316 mm/72 h
Orongorongo, 2006	157 mm/24 h
Orongorongo, 2008	185 mm/24 h
Paekakariki, 2000	92 mm/72 h
Paekakariki, 2003	119 mm/24 h
Paekakariki, 2005	103 mm/24 h
Paekakariki, 2006	49 mm/24 h
Paekakariki, 2007	40 mm/24 h
Uawa, 2018	252 mm/24 h
West Coast, 2019	1087 mm/48 h

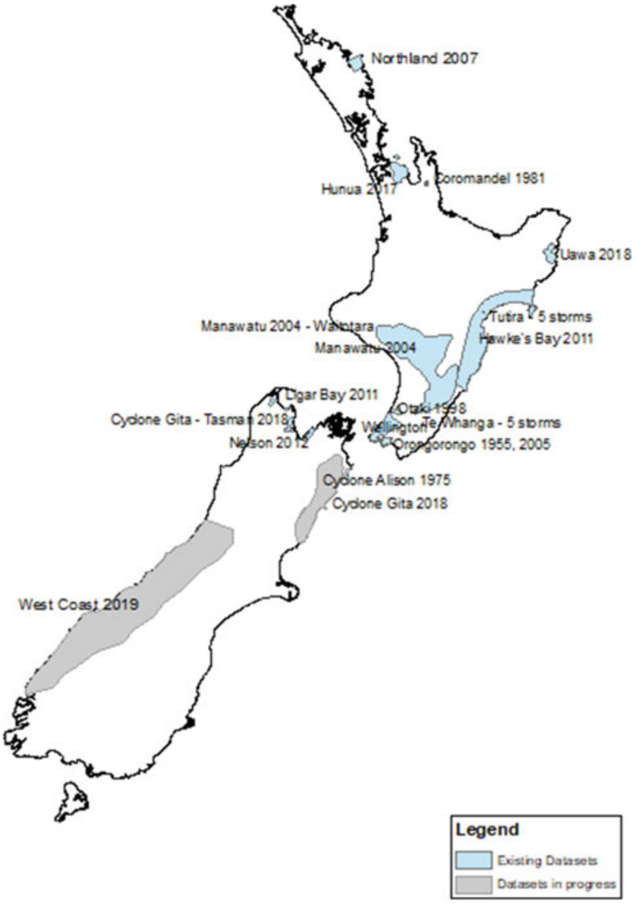

Fig. 4 Spatial distribution of rainfall-induced landslide datasets used in the analysis

Compilation of Landslide Susceptibility and Rainfall Data

National GIS datasets representing landslide susceptibility factors (dominant rock type, slope, local slope height, aspect, slope curvature, vegetation) were compiled into a GIS database. The variables that contributed to landslide occurrence were determined in a pilot study carried out in Wellington City, using a database of 16,000 landslides mapped for 11 storm events over the period 1939–2016. National GIS datasets were compiled at a grid size of 30 m by 30 m for the whole country.

Rainfall data for each storm event was provided by NIWA, New Zealand's National Institute of Water and Atmospheric research from the National Climate Database (www.cliflo.niwa.co.nz). Rainfall data included 24 h maximum and storm rainfall totals derived from the national rain gauge network. Soil moisture data, representing the modelled soil moisture deficit for the day before each storm event was provided by NIWA from the Virtual Climate Station Network (https://niwa.co.nz/climate/our-services/virtual-climate-stations). The Virtual Climate Station Network estimates climatic parameters, including soil moisture, on a regular (~5 km) grid covering the whole of New Zealand. The estimates are produced every day, based on the spatial interpolation of actual data observations made at climate stations located around the country.

Data from each of the landslide susceptibility and rainfall GIS layers was extracted for each landslide in the storm landslide inventory (n = ~300,000). Each landslide point therefore had its own landslide susceptibility factors (dominant rock type, slope, local slope height, aspect, vegetation) and triggering conditions (rainfall, soil moisture) associated with it.

Logistic Regression Modelling

We used the mapped landslide distributions from the 20 storms to explore the relationships between landslide occurrence and the variables that may control its occurrence. The variables included the landslide triggering variables (rainfall, soil moisture) and landslide susceptibility variables (dominant rock type, slope, local slope relief, aspect, vegetation and anthropogenic modification). The variables that contribute to landslide occurrence must have a physical influence on landslide occurrence and contribute statistically to the fit of the model (discussed below).

We used logistic regression to investigate the influence that the triggering and susceptibility variables have on the spatial distribution of 11,000 rainfall-induced landslides attributed to 11 storm events in Wellington (Massey et al. 2019). The results indicated that the variables, which had the most influence of predicting landslide susceptibility, in rank order were: 24-hour rain; slope angle; slope aspect; local slope relief; land cover (vegetation); soil moisture; and material type. The model developed for Wellington was adapted for the entire country by including landslides from other storms (Fig. 4) along with the variables listed previously as the training data sets. The revised model-coefficients allow us to forecast landslide probability in each 32 × 32 m cell (covering the whole country) for a given 24 h rainfall and soil moisture (e.g., Fig. 5).

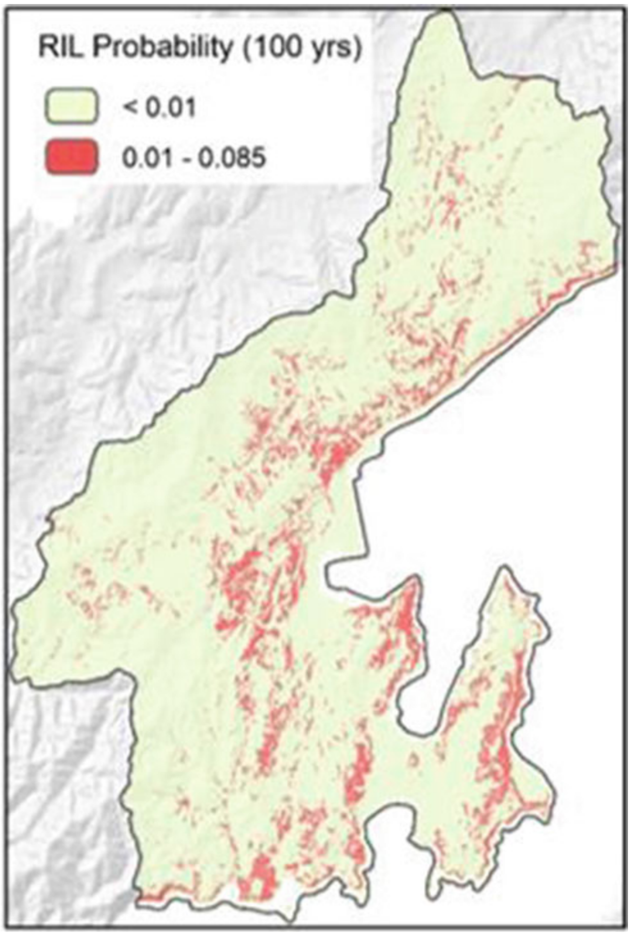

Fig. 5 Probability of a landslide occurring at a given location in Wellington if subjected to 24-hour rain amounts of 100-year return period

Rainfall-Induced Landslide Forecast Tool Development

Logistic regression model/s were converted to a forecast tool by incorporation of forecast and actual rainfall amounts and intensities supplied by MetService, New Zealand's national weather authority. The application of the Rainfall-induced Landslide (RIL) forecast tool requires two sets of data; (a) static data comprising the landslide susceptibility variables and the regional rainfall triggering thresholds and (b) dynamic event data (rainfall and soil moisture). Initially the RIL tool will run with forecast rainfall data at 72, 48, and 24 h prior to landfall, if forecast rainfall exceeds triggering thresholds, then actual rainfall data from rain radar will be used, complimented by data from the rain gauge network, and accumulated on an hourly basis. The RIL forecast tool will also be applied if the actual rainfall amounts during a storm event exceed rainfall triggering thresholds.

Conclusions

A rainfall-induced landslide forecast tool has been developed for New Zealand. Logistic regression modelling was used to determine the influence that landslide triggering and susceptibility variables had on a dataset of landslides initiated by 20 storm events across the country. The relationships developed by logistic regression modelling were applied at the national scale using national landslide susceptibility GIS datasets. The forecast tool will be run when regional rainfall ID thresholds for landslide initiation are exceeded. When combined with forecast rainfall amounts, the RIL forecast model can predict the probability of landslide occurrence, thus the spatial distribution of landslides for given forecast rainfall amounts. The RIL forecast tool will be used by the National GeoHazards Monitoring Centre to forecast and warn the public of possible damaging rainfall-induced landslide events.

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