Earthquake-Induced Landslide Forecast and Hazard Assessment, Hawke's Bay Region

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

Since 1840, earthquakes within the Hawke's Bay region have shown that steep cliffs and slopes are susceptible to rockfalls and landslides in response to strong ground shaking. The 1931 Hawke's Bay earthquake caused rockfalls and cliff collapses at many steep cliffs around the region and debris slides on steeper slopes. The aim of the work presented in this report is to apply the earthquake-induced landslide (EIL) forecast tool, developed by GNS Science, to identify areas within the Hawke's Bay region – at a regional scale – that may be more susceptible to EIL. The EIL tool has been used to identify the probability of a given location within the study area failing as a landslide in response to a range of earthquake Peak Ground Accelerations (PGA) of increasing annual exceedance probability (return periods). This work is the first step needed to define the location, extent and magnitude of such hazards within the study area. The outputs of this work are intended to be used to improve community preparedness through better land-use planning decisions and emergency response planning.

The EIL tool provides an estimate of the probability of a landslide occurring at a given location, i.e. a landslide source area – defined as the area at the head of the landslide (zone of depletion) where the landslide mass (debris) is derived from. It does not provide an estimate of where the debris may travel to downslope, i.e. the debris runout area (zone of debris inundation).

In general, the landslide probabilities for sites across the region, irrespective of the PGA return period used, are relatively low, with most locations having probabilities of <10%. However, several areas show a greater density of grid cells with higher probabilities of up to 50–80%. These locations are concentrated along the western ranges of the region, particularly within the Ahimanawa and Ruahine ranges, with smaller patches located around Cape Kidnappers, the hills northeast of Frasertown, along Mahia Peninsula and areas to the south of Havelock North. Such areas may require further attention to determine the impacts on critical roads and infrastructure.

However, due to current limitations of the tool with regard to the model only currently being trained on the 2016 Kaikōura Earthquake datasets, the landslide probabilities may not completely reflect future EIL probabilities and distributions. It is recommended that the EIL tool is re-run once further landslide data, for example, detailed mapping of landslides from the 1931 Hawke's Bay Earthquake, have been incorporated into the training of the EIL algorithm. It is also recommended that infrastructure and roads covered by or near grid cells with relatively high landslide probabilities be identified and prioritised for further analyses to assess their resilience. Roads and infrastructure that are located downslope from such areas may be at risk of landslide debris runout, which has not been modelled by the tool. Further landslide runout modelling at specific locations, once identified, is recommended.

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1.0 INTRODUCTION

The 1931 Hawke's Bay earthquake, also known as the Napier earthquake, occurred in New Zealand at 10:47 am on 3 February, killing 256, injuring thousands and devastating the Hawke's Bay region. The Hawke's Bay Earthquake also caused extensive land damage; rockfall and cliff collapse were reported and photographed around the region (Figure 1.1). Landslides caused by this earthquake, and by other earthquakes both in New Zealand and overseas, tend to concentrate around locally high and steep slopes. The aim of the work presented in this report is to apply the earthquake-induced landslide (EIL) forecast tool, developed by GNS Science, to identify areas within the Hawke's Bay region (the study area shown in Figure 1.2) that may be more susceptible to EIL. The EIL tool has been used to identify the probability of a given location within the study area failing as landslide in response to a range of earthquake Peak Ground Accelerations (PGA) of increasing annual exceedance probability. This work is the first step needed to define the location, extent and magnitude of such hazards within the study area. The outputs of this work are intended to be used to improve community preparedness through better land-use planning decisions and emergency response planning.

This report has been prepared by the Institute of Geological & Nuclear Sciences Limited (GNS Science) in response to a request from Lisa Pearse, Team Leader Hazard Reduction, Hawke's Bay Civil Defence Emergency Management Group (HBCDEM), for Hawke's Bay Regional Council. This report has been prepared with consideration of details supplied by Lisa Pearse and following the meeting between GNS and HBCDEM on 6th March 2019. It presents the results of the EIL tool, applied to the Hawke's Bay study area. The outputs from this work are maps (in digital format) of landslide probability, based on PGAs that represent a given annual exceedance probability, defined using the National Seismic Hazard Model (NHSM).

1.1 Landslide Failure in Hawke's Bay

The seismic hazard in the Hawke's Bay region is high because of its proximity to a convergent part of the Australia-Pacific tectonic plate boundary (Hull 1986). One of the consequences of a high seismic hazard are EIL. Historically (since 1840), several earthquakes in the region have caused landslides and rockfalls (Figure 1.1) (Hancox et al. 2002). Some of the largest landslides in the world can be found in Hawke's Bay, such as an immense landslide that formed the barrier ponding Lake Waikaremoana. Studies show this landslide occurred 2200 years ago and was probably triggered by a large, nearby earthquake (Johnston and Pearse 1999). Landslides and ground failures are often triggered by strong earthquakes and there are many spectacular examples from the 1931 Hawke's Bay and 1932 Wairoa earthquakes. The Department of Scientific and Industrial Research account of these earthquakes, written in 1933, describes the inland hill country as suffering from considerable fissuring and slips, and because of the prolonged dry weather, clouds of dust were ejected into the air with each tremor (Johnston and Pearse 1999). The slips and ground damage varied from rockfalls off Bluff Hill to extreme distortions and/or settlements of wharves, roads, bridges and river embankments around Napier. Numerous rockfalls blocked rivers across the region, including one that blocked the Te Hoe River near its confluence with the Mohaka River (Johnston and Pearse 1999). This rockfall landslide fell from bluffs 300 m high and formed a debris dam 30 m in height that created a lake 5 km long and 200 ha in area. From the high coastal cliffs, landslides poured into the sea, and one cliff failure hear the Mohaka River mouth carried away 200 acres of farmland and formed a ridge jutting 700 m into the sea (Johnston and Pearse 1999).

Figure 1.1 Rockfall at Ahuriri caused by the 1931 Hawke's Bay Earthquake (GNS Science).

Landslides have been observed and mapped across the region, ranging widely in size, type and concentration (Figure 1.2). The New Zealand Landslide Database (Rosser et al. 2017) shows that 2084 landslides have been recorded across the Hawke's Bay region since 1904 and is available online at http://data.gns.cri.nz/landslides. The triggering events include rainfall, earthquakes or other factors, but these are not always recorded. The current distribution of landslides in the database is concentrated along the southern and central coastlines and in the ranges and hill country, the steeper areas of the region.

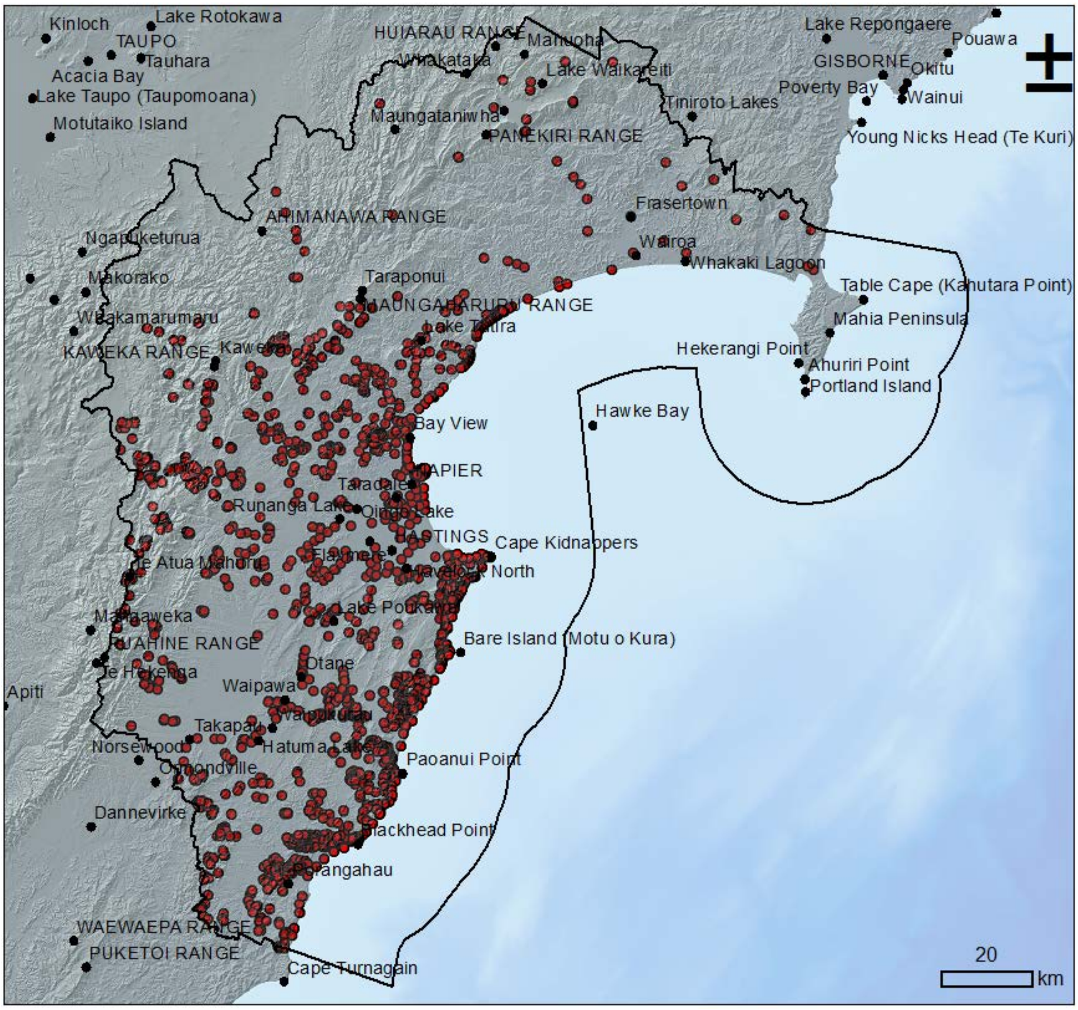

Figure 1.2 Recorded landslides (red points) in Hawke's Bay Region (data from New Zealand Landslide Database: http://data.gns.cri.nz/landslides – accessed 20th June 2020). The black line represents the extent of the Hawke's Bay region.

There are many different types of landslide mapped across the region and, based on Cruden and Varnes (1996) and Hungr et al. (2014), typical landslides in the Hawke's Bay region comprise:

- **Rockfall:** Detachment, falling, rolling and bouncing of rock fragments (Figure 1.1 and Figure 1.3) (Hungr et al. 2014).
- **Boulder/debris/silt fall:** Detachment, fall, rolling and bouncing of soil fragments such as large clasts in soil deposits or blocks of cohesive (cemented or unsaturated) soil (Figure 1.1 and Figure 1.3) (Hungr et al. 2014).
- **Gravel/sand/debris slide:** Sliding of a mass of granular material on a shallow, planar surface parallel with the ground (Figure 1.4) (Hungr et al. 2014).
- **Debris flowslide:** Very rapid to extremely rapid flow of sorted or unsorted saturated granular material on moderate slopes (Figure 1.5) (Hungr et al. 2014).

Figure 1.3 Rockfall debris along Cape Kidnappers coastal cliffs, taken 23rd January 2019 for GeoNet landslide response (GNS Science). Note that, while this particular rockfall was not known to be triggered by an earthquake, strong seismic shaking is likely to cause many rockfalls like this on high, steep, unstable cliffs.

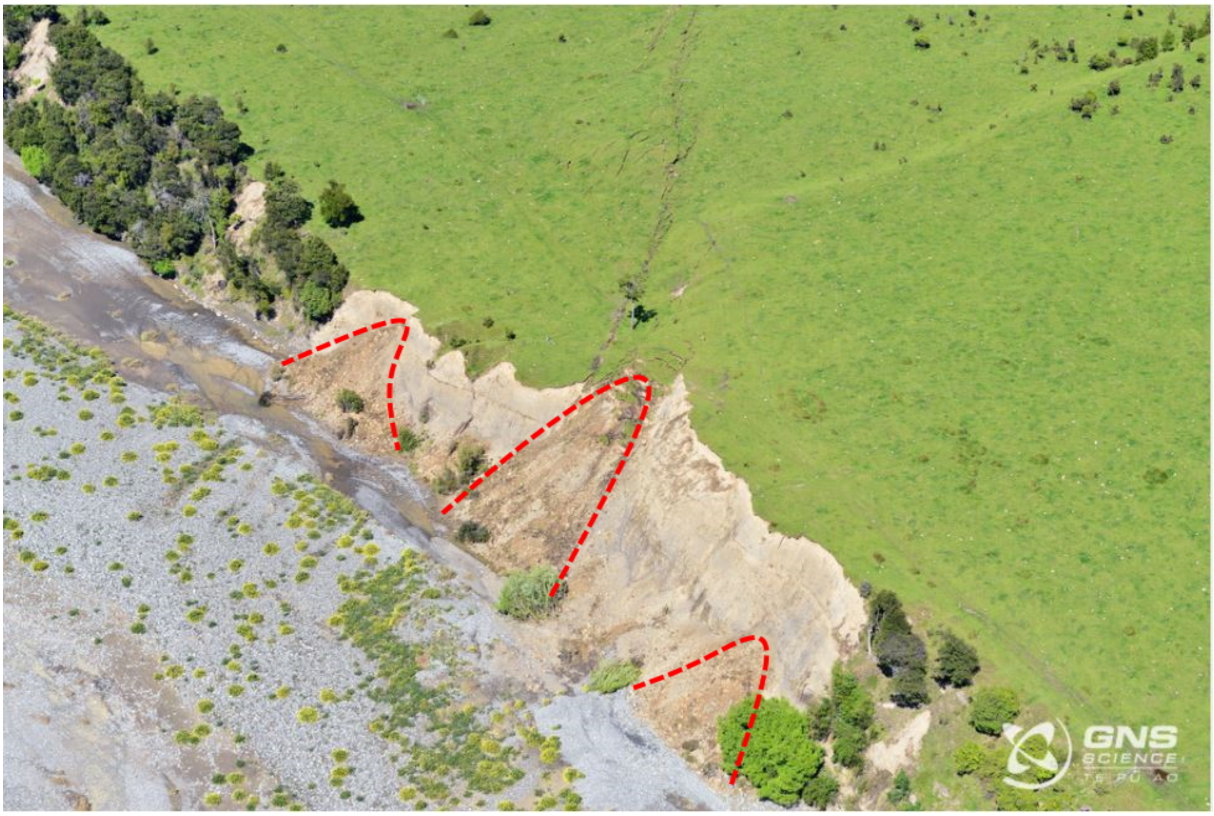

Figure 1.4 Debris (gravel) slide (outlined by red dashed lines) caused by the Kekerengu Fault rupture in Clarence River following the 2016 Kaikōura Earthquake (GNS Science).

Figure 1.5 Debris flowslide (outlined by red dotted line) resulting from the rupture of the Papatea Fault near Clarence River following the 2016 Kaikōura Earthquake (GNS Science).

1.2 Project Objectives (Scope)

The acquisition of high-quality landslide and related datasets has allowed GNS Science to develop a probabilistic EIL forecasting model. With this model now available, it is possible to estimate landslide probability across the region and use these estimates to identify areas of high EIL probability. It is important to note that the EIL tool provides an estimate of the probability of a landslide occurring at a given location, i.e. a landslide source area – defined as the area at the head of the landslide (zone of depletion) where the landslide mass (debris) is derived from. It does not provide an estimate of where the debris may travel to downslope, i.e. the debris runout area (zone of debris inundation).

When the EIL probability estimates are combined with asset data, such as roads, buildings, pipelines, etc., they can be used to identify where particular assets may be exposed to areas of high landslide probability. Identifying the locations of assets exposed to higher levels of landslide probability (hazards) will improve community preparedness through better land-use planning decisions and emergency response plans.

The objectives of this project are to:

- Run the EIL tool for the Hawke's Bay study area, adopting PGAs from the NSHM that represent annual exceedance probabilities associated with approximately 25-, 100-, 500-, 1000- and 2500-year return periods.
- Produce maps of landslide probability based on the spatial distribution of PGAs associated with each of these return periods.
- Present the results to the HBCDEM Group.

1.3 Region Description

The Hawke's Bay region, located on the eastern central North Island, covers an area of just over 14,000 km^2. It includes the hilly coastal land around the northern and central bay, the floodplains of the Wairoa River in the north, the Heretaunga Plains around Hastings in the south and a hilly interior stretching up into the Kaweka and Ruahine Ranges (Lee et al. 2011). The region is home to a population of approximately 166,000 people concentrated in the major urban areas of Napier, Hastings and Havelock North (Stats NZ 2018).

The Hawke's Bay area can be broadly divided into several geomorphic regions that have distinct features reflecting the underlying geology (Kamp 1992; Lee et al. 2011) (Figure 1.6). These include:

- **Southern Hawke's Bay hill country** consists of rolling hills composed of erosion-resistant Pliocene shelly limestone or Late Cretaceous–Miocene turbidite sandstone, siliceous mudstone and calcareous mudstones, deformed by a series of faulted-controlled anticlines (Lee et al. 2011). Towards Cape Kidnappers, the hills are capped with Quaternary marine terrace deposits of gravel, sand and silt up to 150–200 m above sea level. Surficial slumping and erosion are common along these coastal cliffs (Lee et al. 2011).
- **Ruataniwha Plains**, between Dannevirke and Tikokino, form terraces reaching elevations of approximately 500 m above sea level and are underlain by Quaternary alluvial gravels derived from the Ruahine Range. These have been folded and faulted by primarily blind reverse faults (Lillie 1953; Beanland et al. 1998).
- **Heretaunga Plains**, located between the Hawke's Bay hill country, Napier, Hastings, and parts of Havelock North, are sited on this extensive alluvial plain (Lee et al. 2011). Lagoon and beach sediments overlie surficial alluvial gravels deposited before progradation of the coastline (Lee et al. 2011). Part of the coastal area between the Napier harbour entrance and the Esk River mouth, formerly known as the Ahuriri Lagoon, was uplifted by at least one metre during the 1931 Hawke's Bay Earthquake.
- **Northern Hawke's Bay hill country** is mudstone-dominated but contains many prominent northeast-trending strike ridges of Neogene sandstone, limestone and conglomerate some >1000 m above sea level, predominantly southeast-dipping (Lee et al. 2011). Mudstone and interbedded tephra layers are prone to slope instability and landsliding here (Lee et al. 2011).
- **North Island axial ranges** trend southwest–northeast and include the Ruahine and Ahimanawa ranges as well as the Kaimanawa Mountains (Lee et al. 2011). These ranges consist of indurated but variable fractured metasedimentary 'greywacke' rock overlain by Paleogene and Neogene sedimentary rocks and, in the northwest, by Quaternary volcanic deposits. In places, major reverse and oblique-slip faults follow valleys within the ranges (Lee et al. 2011).
- **Ngamatea-Mangaohane plateau** is a large erosion surface exposed at the southern margin of the Kaimanawa Mountains and is overlain by late Neogene sedimentary rocks (Lee et al. 2011). Thin ignimbrite and reworked pumiceous alluvium of the Taupo Pumice Formation form terraces along many of the rivers that cut through the plateau (Lee et al. 2011).

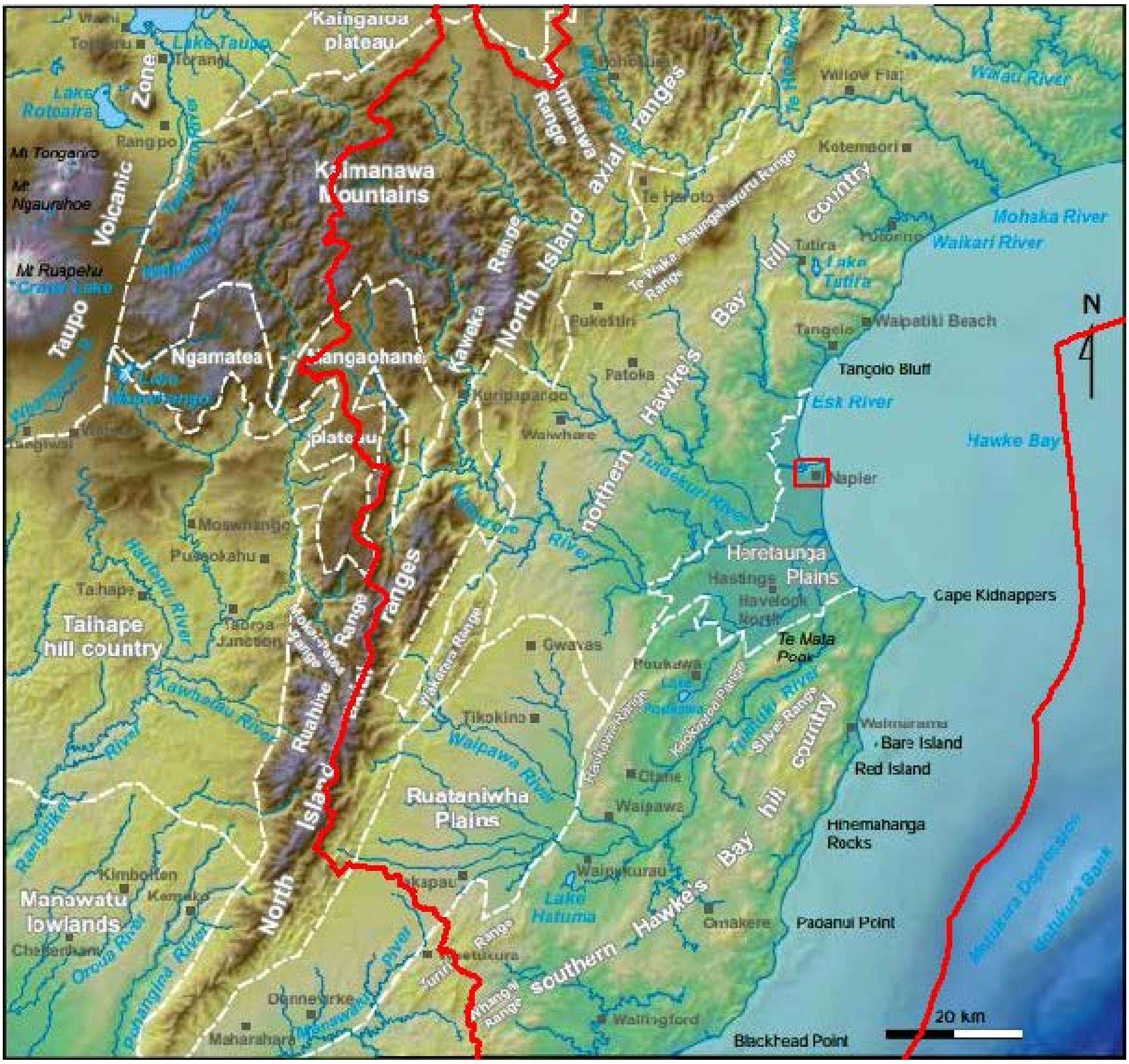

Figure 1.6 Map showing summary physiography, geomorphic regions and place names of the Hawke's Bay area as discussed in the text (from Lee et al. 2011). Outline of the Hawke's Bay region shown in red.

The type of rock/soil can affect the type, location, magnitude and frequency of landslides in the region. The greywacke of the axial ranges is relatively strong but closely fractured, and landslides typically comprise small debris slides (Lee et al. 2011). Landslides in weakly cemented Paleogene to Neogene sandstones, limestones and siltstone rocks can form due to the presence of rock mass defects, such as bedding planes, and lithological strength and permeability contrasts. Such landslides typically comprise translational or rotational slides in rock and soil. Stronger limestone units can form small cliffs and are prone to rockfall. Quaternary deposits are often associated with shallow landslides, triggered by changes associated with saturation levels and soil properties (Lee et al. 2011).

The high seismic hazard in Hawke's Bay is due to its position above and adjacent to a plate boundary (Lee et al. 2011). East of the North Island, the continental shelf extends up to 50–70 km offshore, narrowing to the south where it extends 15–20 km offshore. The Hikurangi Trough, which marks the deformation front between the Pacific and Australian plates, lies 130–150 km east of the coast (Wallace et al. 2009; Lee et al. 2011).

2.0 DATASETS

Landslide susceptibility across a region depends on a range of variables. These can be divided into variables that vary spatially but do not change significantly over time, referred to here as ‘static’, and those that vary in space and time, referred to as ‘dynamic’, known to be influenced by relatively static variables of topography, particularly steep ground and rock strength, as well as other factors such as vegetation. Particularly relevant to determining EIL susceptibility are the dynamic parameters such as earthquake proximity and magnitude.

The EIL tool used in this study is based on the Version 1.0 algorithm described by Massey et al. (2018) and later updated in Massey et al. (2020b). The tool adopts the following variables to forecast landslide probability: 1) Slope angle, 2) Elevation, 3) Local slope relief, 4) Distance to an active fault, 5) Geology and 6) PGA. Their derivations are described below.

2.1 Static Datasets

2.1.1 Digital Elevation Model

A digital elevation model (DEM) is the digital representation of the land surface elevation in a grid form and is used to derive other terrain parameters such as slope angles, slope heights and slope roughness, and is used as an input to compute local slope relief.

The DEM used in this study is the New Zealand 2012 8 m DEM from Land Information New Zealand (LINZ), available through the LINZ Data Service website. All the DEM derivatives were generated at 8 m resolution and aggregated to 32 m to be used in the assessment at the regional scale.

2.1.1.1 Slope Angle

A slope-angle model was been derived from the 8-m-resolution DEM; it represents the gradient of each cell within the grid. The resulting slope-angle model at 8 m resolution was aggregated to a 32 by 32 m grid, adopting the mean of all the 8 by 8 m cells. This variable is a proxy for the static shear stresses in the slope materials.

2.1.1.2 Hillslope Elevation

Local hillslope elevation was calculated from the 8-m-resolution DEM, adopting the mean value of all the 8 by 8 m cells, aggregated to 32 m grid cells. This variable represents the observation that topography can limit the size of a landslide. For example, slopes that are higher in elevation tend to have larger slope-surface areas and therefore generate larger landslides than those at lower elevations.

2.1.1.3 Local Slope Relief (LSR)

A local slope relief (LSR) model has been derived from the 8-m-resolution DEM using the Focal Statistics tool in ArcGIS. It approximates the height of local slopes and is calculated as the maximum difference in elevation between the processing cell and any other cell within an 80 m (10 cells) search radius from the processing cell. The resulting LSR model at 8 m resolution was aggregated to 32 m using the maximum value of difference within the search radius. Larger values of LSR represent locally steep slopes that commonly amplify ground shaking (Massey et al. 2016). Therefore, the LSR is assumed to be a proxy for topographic amplification of shaking.

2.1.2 Fault Distance

Distance to potentially seismogenic structures was calculated as the distance of each cell from the mapped active faults, extracted from GNS Science's Active Faults Database (accessed on 5th March 2018).

2.1.3 Geology

Geological units have been extracted from the NZL_GNS_250K_geological_units layer of the NZL GNS 1:250K Geology dataset (2nd edition) (Heron 2018). Units have been grouped into four 'dominant' classes: Quaternary deposits, Neogene sedimentary deposits, Cretaceous–Paleogene sedimentary deposits and Mesozoic basement greywacke.

2.2 Dynamic Dataset

2.2.1 Peak Ground Acceleration

Peak ground accelerations (PGAs) are measured with strong motion recording instruments located at specific sites affected by earthquakes; they can also be modelled across regions based on records of historic earthquake magnitude and frequency, as well as levels of damage to natural features and manmade structures when calibrated with the instrumental data. Mean estimates of the PGAs across the study area for the return periods used in this study were derived from the 2010 version of the NSHM for the Heretaunga Plains. PGAs across the study area were calculated adopting annual exceedance probabilities (AEP) of 0.04 to 0.0004, which are equivalent to return periods of approximately 25 to 2500 years. Table 2.1 shows the AEPs and associated return periods used to calculate the PGAs for this study. It should be noted that the PGAs at any given grid cell, for a given AEP, will vary across the study area, as they are influenced by geospatial factors such as proximity to faults, past earthquakes and site class (material type). For this study, the PGAs were calculated from the NSHM adopting a site class of weathered rock.

Table 2.1 PGA annual exceedance probabilities and their corresponding return periods.

Hawke's Bay Sites PGA Return Periods Used in this Study					
Annual Exceedance Probability (AEP)	0.04	0.01	0.002	0.001	0.0004
Return Period (Years)	25	100	500	1000	2500

3.0 METHODOLOGY

3.1 Background

The EIL forecast tool produces estimates of landslide probability resulting from earthquake-induced ground shaking, derived either from instrument data in near-real time or from models (Massey et al. 2018). The Version 1.0 tool uses the 2016 Kaikōura-Earthquake-related landslide, ground shaking and other relevant datasets discussed previously. The algorithm used in the tool was trained on the mapped distribution of landslides triggered by that event. Subsequent versions of the tool have been trained on datasets relating to other New Zealand earthquakes but still includes the 2016 Kaikōura Earthquake.

It is appropriate to apply the EIL tool to Hawke's Bay as the geology of the Kaikōura area has many similarities to the geology of Hawke's Bay, including a Mesozoic greywacke basement to covering Paleogene and Neogene sedimentary rocks with Quaternary alluvial gravels. Although steeper and higher in places, the topography of the Kaikōura area has led to similar types of landslide failures. The tool has been built within ESRI ArcGIS software using Python scripts. The processing within the EIL forecast tool is undertaken using ESRI ArcGIS tools (version 3.1) and Python scripting language (version 2.7.8).

The EIL tool requires five datasets (local slope relief, local hillslope elevation, slope angle, distance from active faults and geology, described above) as inputs to a static model of the landscape, to which the modelled estimated/predicted PGAs for various return periods are applied to then produce EIL forecast maps. The EIL forecast tool was originally developed to produce landslide forecast maps for the GeoNet landslide duty officers in near-real time after a significant earthquake. The original function of the tool was to provide rapid advisory information about the severity and likely location and impacts of landslides following a major earthquake, where ground shaking data recorded by the GeoNet strong motion instrument network is used as the input for the tool. The EIL forecast tool was the first of several to be developed as part of a larger landslide forecast project being carried out by the GNS Science landslide and social science teams, and others. The aims of the overall project are to allow the GeoNet landslide duty officers (the current end users) to: 1) rapidly identify whether an earthquake or a rain event can generate landslides and the severity of landsliding; 2) rapidly generate advisory information, such as a spatial representation (map and table) of where landslides could occur in a significant earthquake or rainfall event and where the debris might travel, which can be used to help target response activities. However, for this report, we have used PGA estimates for the given annual exceedance probabilities (AEPs), derived from the NSHM model, as inputs to the EIL tool rather than strong motion data associated with a specific earthquake event.

The EIL tool is used in this report to produce maps showing landslide probabilities for PGAs associated with specific AEPs (Table 2.1), noting that the PGAs associated with each specific AEP vary across the Hawke's Bay region.

3.2 Pre-Processing

Pre-processing is undertaken to extract the required static data layers from the source datasets. Static data layers were generated nationally as gridded raster datasets at 32 m resolution, described in Section 2.

The topographic datasets were derived from the LINZ 8 m DEM. The ArcGIS software was used to generalise 8 m grids to 32 m resolution, with the MEAN aggregation function used for the Local Hillslope Elevation and Slope Angle and the MAX aggregation function used for the Local Slope Relief.

The fault distance gridded data layer was created nationally at 32 m resolution using the ArcGIS Euclidean Distance tool with the Active Fault layer (AF250_05032018).

The geological unit's raster dataset was created nationally at 32 m resolution from the geological unit polygons and grouped into four-unit classes:

1. Quat_Deposits
2. Neo_Sedimentary
3. Cret_Paleo_Sedimentary
4. Base_Greywacke.

Each geology class was given an integer code before the geological polygons were converted to a gridded dataset. These classes are broad categories representing a range of soil and rock strengths, derived from the known behaviour determined through their statistically similar performance in response to earthquake shaking or assigned using expert elicitation undertaken by experienced engineering geologists. There are uncertainties in extrapolating the EIL forecasts beyond the boundaries of the Kaikōura Earthquake inventory (the uncertainties in the model are discussed in Massey et al. [2018]), and these are currently being further elevated as part of the EIL tool development.

3.3 Processing

Landslide probabilities have been derived based on the performance of slopes at different levels of shaking during historical earthquakes. The results presented in this report are based on the high-quality EIL dataset compiled after the 2016 Kaikōura Earthquake and the modelled variation of ground shaking during this earthquake (Version 1.0 of the EIL tool). The processing for Hawke's Bay Region is consistent with the national-scale EIL tool. The processing is done by running a sequence of Python scripts, collectively known as the EIL Forecast Tool, that complete different elements of the required processing. The variables are passed from script to script, and the individual scripts cannot be run separately.

The control script imports the required Python modules and sets scripting variables. It checks if required static data, input files and map templates are present and terminates processing if any of the required data are missing. It creates a processing folder, processing and scratch geodatabases and an output folder, if they do not already exist. After the processing is finalised, a result folder is created by the script and the final outputs, required for producing maps, are copied there. The output table and maps are also placed in the result folder.

3.4 Output

The results from the EIL tool are gridded data layers that show the estimated probability of each 32 m x 32 m grid cell being the source area for a landslide/rockfall given the PGA applied at the given cell. The EIL tool results do not show the area potentially affected by runout of debris from landslides. Determining the extent of landslide runout and associated probabilities requires additional analysis that the EIL tool is not yet capable of performing or the application of other tools. The results from the EIL tool are probabilistic and should therefore be seen as a guide to help identify those slopes that may be potentially more susceptible to EIL. It does not advise whether a given slope will or not fail in response to an earthquake.

4.0 EIL RESULT MAPS

The probability results from the EIL tool have been grouped into classes. These 'class' maps show the probability of landslides occurring across each of the 32 m resolution grid-cell sites (here on in referred to as a 'site') for each of the given return periods (25, 100, 500, 100 and 2500 years).

The class maps range from 0% (no probability of landslides occurring) to a theoretically possible 100% (certain probability of a landslide occurring). It should be noted that the modelling of the landslides here represents the source of the landslide failure and not the runout associated with such an event. To assess the runout potential of these materials, further modelling is required, which is outside the scope of this report.

4.1 25-Year PGA

Figure 4.1 shows the spatial distribution of landslide probability across the region, adopting the 25-year return period PGAs, which range from 0.021 to 0.085 %g. A low landslide probability (<1–10%) for sites is generally predicted across the Hawke's Bay region, with most of the region showing sites with a landslide probability of <1%. There are isolated sites that show an elevated probability of landslides. These include parts of the Ahimanawa Range and the coastal cliffs at Cape Kidnappers (30–40% probability of landslides in places) and the hills located northeast of Frasertown (20–30% probability of landslides in places). The distribution of the predicted landslides is concentrated on the Ahimanawa Ranges in the northwest of the Hawke's Bay region and the Kaweka and Ruahine ranges located to the west and southwest, respectively. Several smaller patches of landslides are forecast around Cape Kidnappers to the northeast of Wairoa and Frasertown and on Mahia Peninsula.

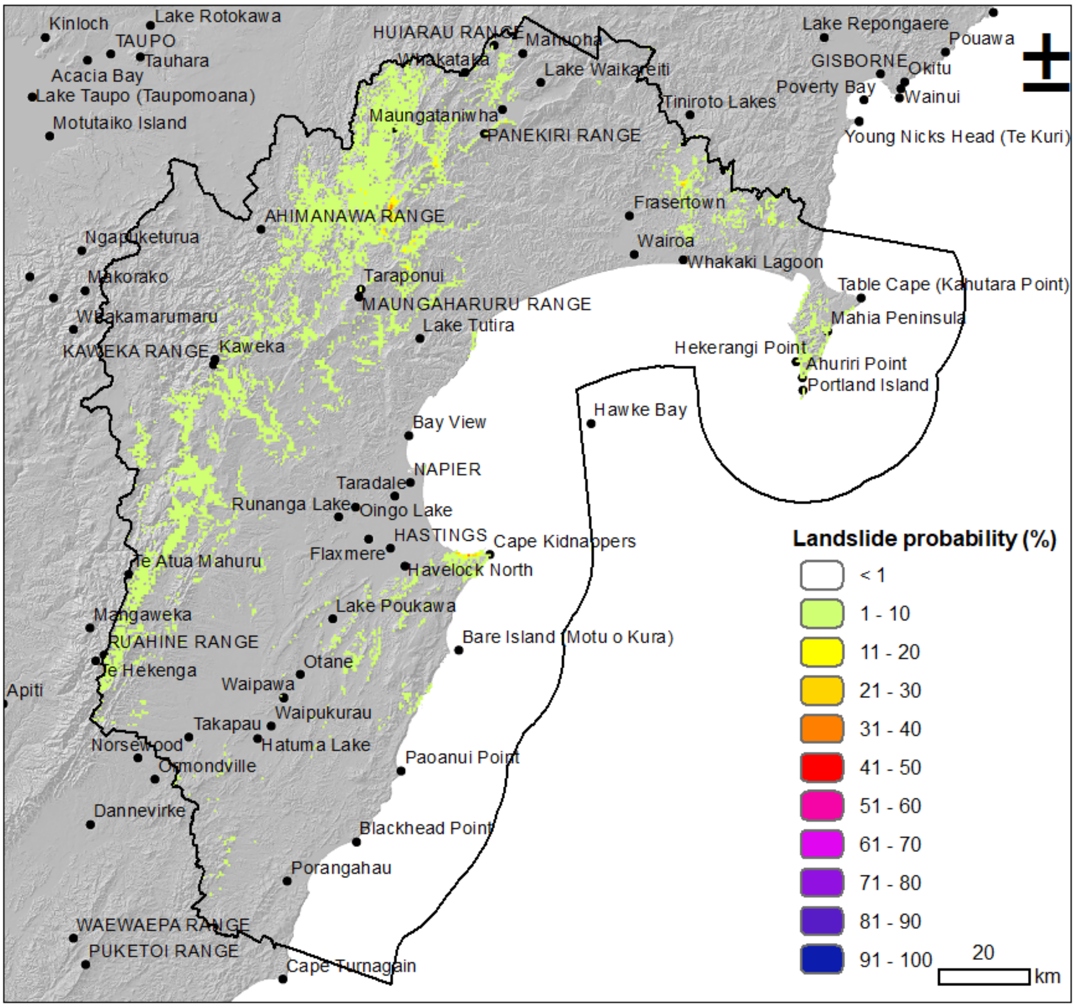

Figure 4.1 EIL probability class colour map of the Hawke's Bay region based on the 25-year return period PGAs.

4.2 100-Year PGA

Figure 4.2 shows the spatial distribution of landslide probability across the region, adopting the 100-year return period PGAs, which range from 0.045 to 0.196 %g. It also shows a generally low landslide probability (1–10%) across the Hawke's Bay region with slightly higher probability of landslides (10–40%) in places in the Ahimanawa Ranges, the cliffs at Cape Kidnappers and the hills northeast of Frasertown. Distribution patterns are similar to those described above for the 25-year model output, though a slight increase in densities around these areas is noted.

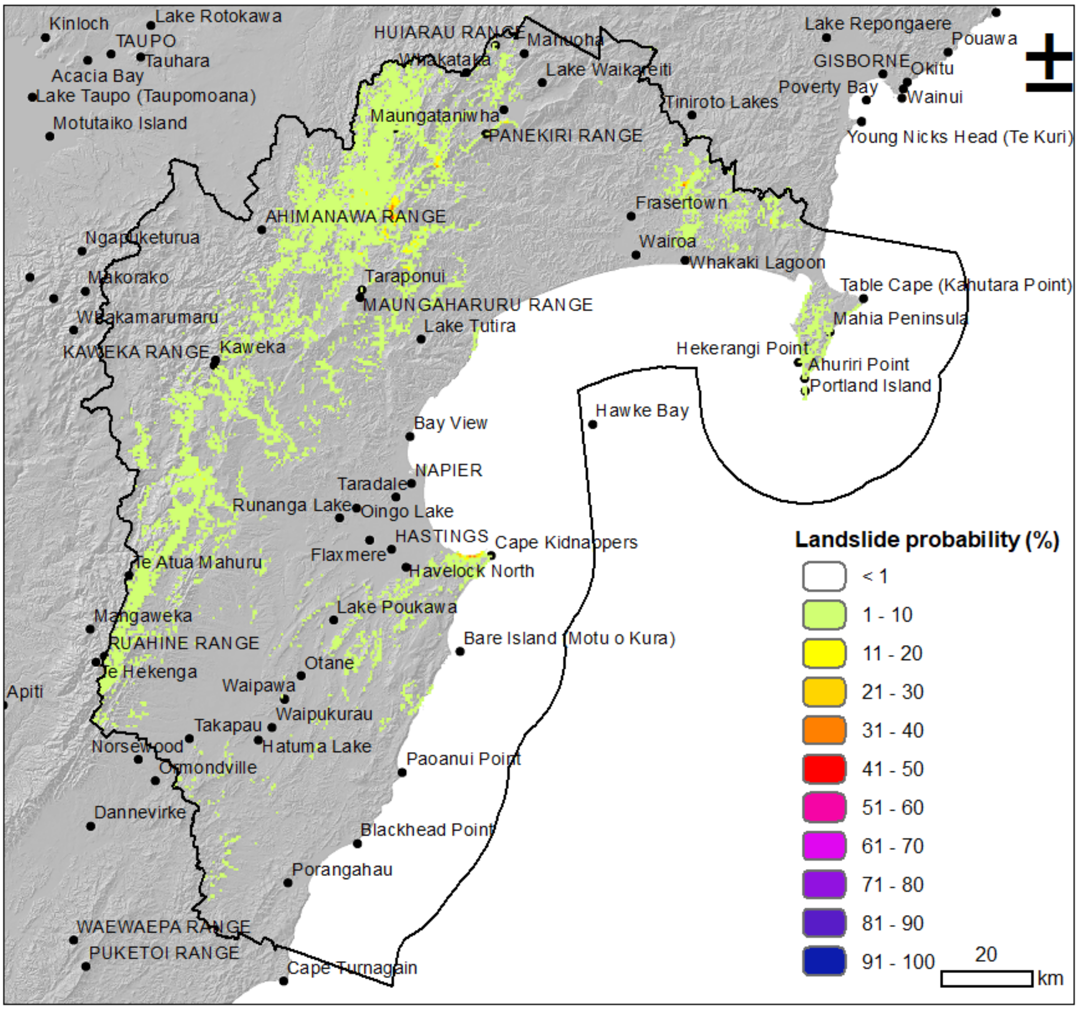

Figure 4.2 EIL probability class colour map of the Hawke's Bay region based on the 100-year return period PGAs.

4.3 500-Year PGA

Figure 4.3 shows the spatial distribution of landslide probability across the region, adopting the 500-year return period PGAs, which range from 0.085 to 0.526 %g. There is a noticeable increase in density of areas affected by potential landslide activity at this level of modelled PGA, though the distribution of these modelled landslides remains focused in the areas as described above. Probabilities across the region generally remain low at between 1 and 10%, with isolated patches showing probabilities up to 20% or higher. Several patches, including the Ahimanawa Range (20–60%), Cape Kidnappers (20–50%) and the hills northeast of Frasertown (20–50%), show noticeably higher landslide probabilities, though these patches tend to be rather isolated.

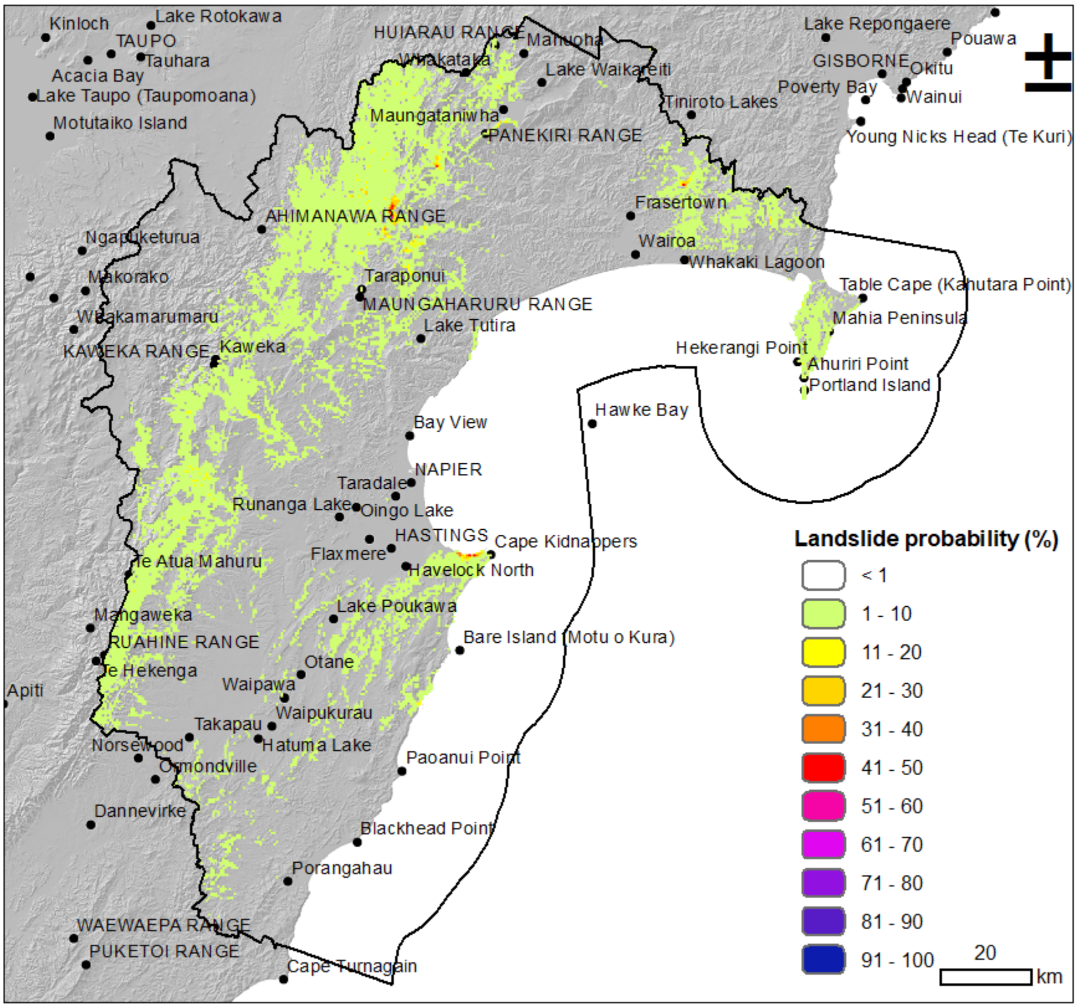

Figure 4.3 EIL probability class colour map of the Hawke's Bay region based on the 500-year return period PGAs.

4.4 1000-Year PGA

Figure 4.4 shows the spatial distribution of landslide probability across the region, adopting the 1000-year return period PGAs, which range from 0.104 to 0.673 %g. Again, the spatial distribution of the areas modelled to be affected by potential landslide/rockfall events remains very similar to those described previously, though a noticeable increase is seen in the southern areas of the Hawke's Bay region south of Havelock North. Landslide probabilities remain relatively low across much of the region at between 1 and 20%, though the higher landslide probability patches (20–60%), as described for the 500-year PGA map, are noted to have increased in size and affect a larger area around the Ahimanawa Range, Cape Kidnappers and northeast of Frasertown.

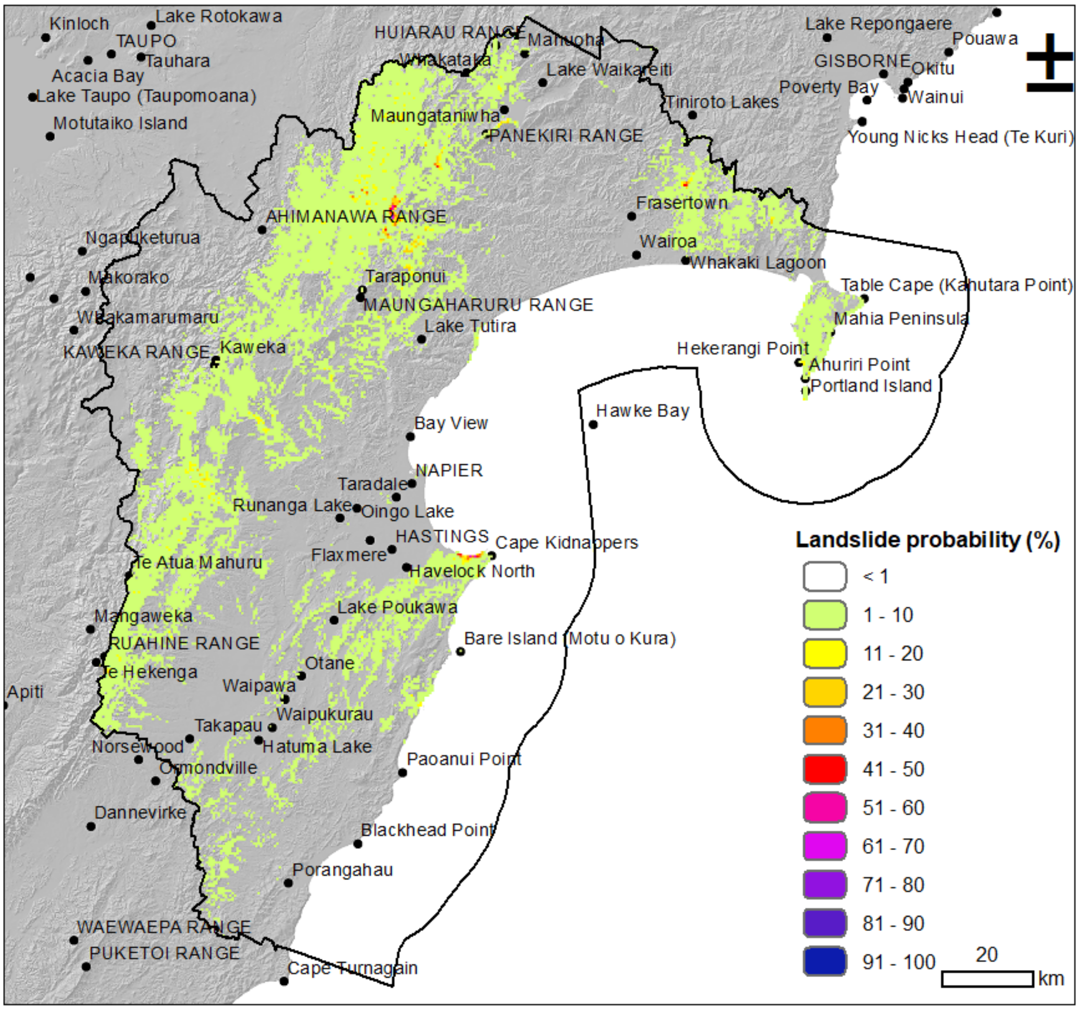

Figure 4.4 EIL probability class colour map of the Hawke's Bay region based on the 1000-year return period PGAs.

4.5 2500-Year PGA

Figure 4.5 shows the spatial distribution of landslide probability across the region, adopting the 2500-year return period PGAs, which range from 0.137 to 0.917 %g. The distribution of the landslide probability map shows a marked increase in areas affected, particularly along the western ranges of the Hawke's Bay region. A noticeable increase in areas affected is also noted in the southern portions of the Hawke's Bay region. Probabilities across much of the region remain low (1–20%), though noticeable isolated patches around the Ahimanawa Ranges, Cape Kidnappers and northeast of Frasertown show areas with probabilities reaching upwards of 60–80%. Furthermore, patches north of the Ruahine Range show areas with probabilities between 20 and 40%.

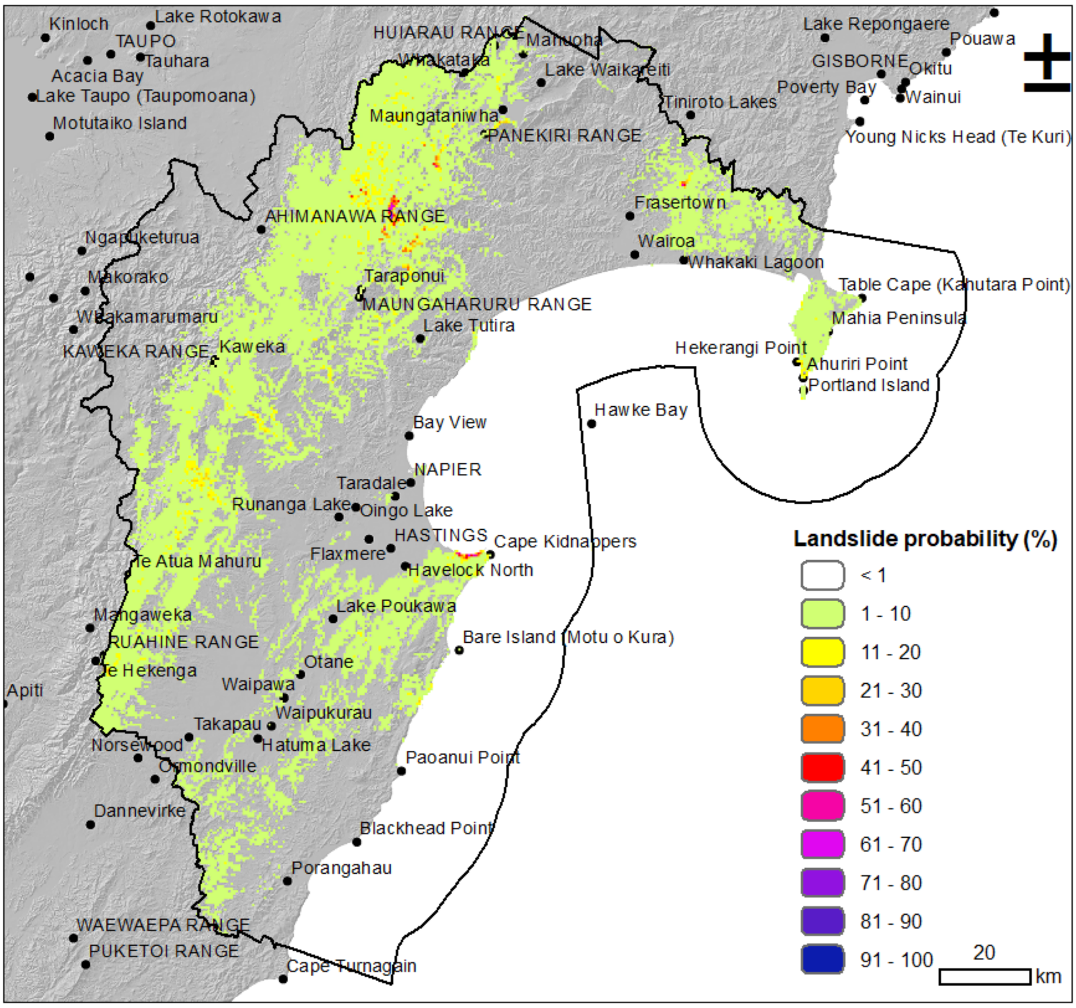

Figure 4.5 EIL probability class colour map of the Hawke's Bay region based on the 2500-year return period PGAs.

5.0 DISCUSSION

The EIL modelling over the Hawke's Bay region shows that potentially unstable areas occur across much of the area, particularly along the western axial ranges, Cape Kidnappers, northeast of Wairoa and Frasertown and along Mahia Peninsula.

Based on the 25- and 100-year return period PGAs, the Hawke's Bay region is expected to experience minor disruption from landslides/rockfall. Our modelling suggests that this is likely to be concentrated along the western ranges of the region, particularly within the Ahimanawa Ranges, with more isolated concentrations located around Cape Kidnappers, the hills northeast of Frasertown and along the Mahia Peninsula coastline. It is likely that rockfall/landslides may affect access routes through the ranges, particularly those that run through the western Hawke's Bay region, many of which are important transport routes. It is recommended that any routes or infrastructure that run through the ranges are assessed to determine whether additional site-specific modelling work to understand landslide runout would aid the design and implementation of landslide mitigation works to improve their resilience. It has been well documented that the coastal cliffs around Cape Kidnappers are susceptible to rockfall (de Vilder et al. 2019; Massey et al. 2020a). The landslide modelling similarly suggests that costal cliffs around Cape Kidnappers have a high probability of failure during and after an earthquake. The EIL maps based on PGAs with 500-, 1000- and 2500-year return periods show an increase in distribution and numbers of sources with higher probabilities, compared to those from the models adopting the 25- and 100-year return period PGAs.

In general, the landslide probabilities for sites across the region, irrespective of return period used, are relatively low, with most locations having probabilities of <10% (Table 5.1). However, several areas show a greater density of grid cells with higher probabilities of up to 50–80%. These locations include isolated patches within the Ahimanawa Ranges, hill country north of the Ruahine Ranges, Cape Kidnappers coastline and the hills northeast of Frasertown, that is, places where there are high steep slopes located close to active faults. As a result, roads that provide vital routes, buildings and major infrastructure located in these higher probability areas are at greater risk of being affected by landslide/rockfalls. Roads/infrastructure that are within a few pixel lengths of the modelled source area of higher landslide probability are also potentially at risk from debris inundation hazards (landslide debris runout), which could lead to disruption. It is suggested that major roads and infrastructure downslope of these areas of higher landslide probability are identified and assessed by Hawke's Bay Regional Council. We are currently unable to determine if or how the landslide runout at these locations will affect these routes. Landslide runout modelling at critical sites can be used to determine whether such sites are prone to debris inundation.

Table 5.1 Percentage of the Hawke's Bay region within a given landslide probability class for the different return periods.

		Probability								
Return Period (Years)	**PGA(g) Range**	**<1%**	**1–10%**	**10–20%**	**20–30%**	**30–40%**	**40–50%**	**50–60%**	**60–70%**	**70–80%**
25	**0.021–0.085**	89%	11%	<1%	<1%	<1%	0	0	0	0
100	**0.045–0.196**	86%	14%	<1%	<1%	<1%	0	0	0	0
500	**0.085–0.526**	78%	21%	<1%	<1%	<1%	<1%	<1%	0	0
1000	**0.104–0.673**	73%	26%	<1%	<1%	<1%	<1%	<1%	<1%	0
2500	**0.137–0.917**	66%	33%	1%	<1%	<1%	<1%	<1%	<1%	<1%

Aftershocks are likely to result in further landslides and rockfalls, with the number and volume being dependent on the PGA of the original earthquake and the subsequent aftershock(s). An example of such a response is shown in Figure 5.1, which shows the landslide volumes that fell from a selection of slopes in the Port Hills of Christchurch during and after the 2010/11 Canterbury earthquake sequence. The number and frequency of non-earthquake-triggered landslides and rockfalls (e.g. triggered by rain) also tend to increase after a slope has been strongly shaken by an earthquake. This is thought to be because the earthquake has 'damaged' the ground by generating cracks as well as debris from EIL, which can subsequently fail and/or be more easily mobilised post-earthquake by rain and other environmental landslide triggering factors. Such ground 'damage' tends to occur on and behind the crests of higher and steeper cliffs/slopes, which tend to amplify ground shaking, thus producing larger permanent ground displacements and landslides (e.g. Massey et al. 2017).

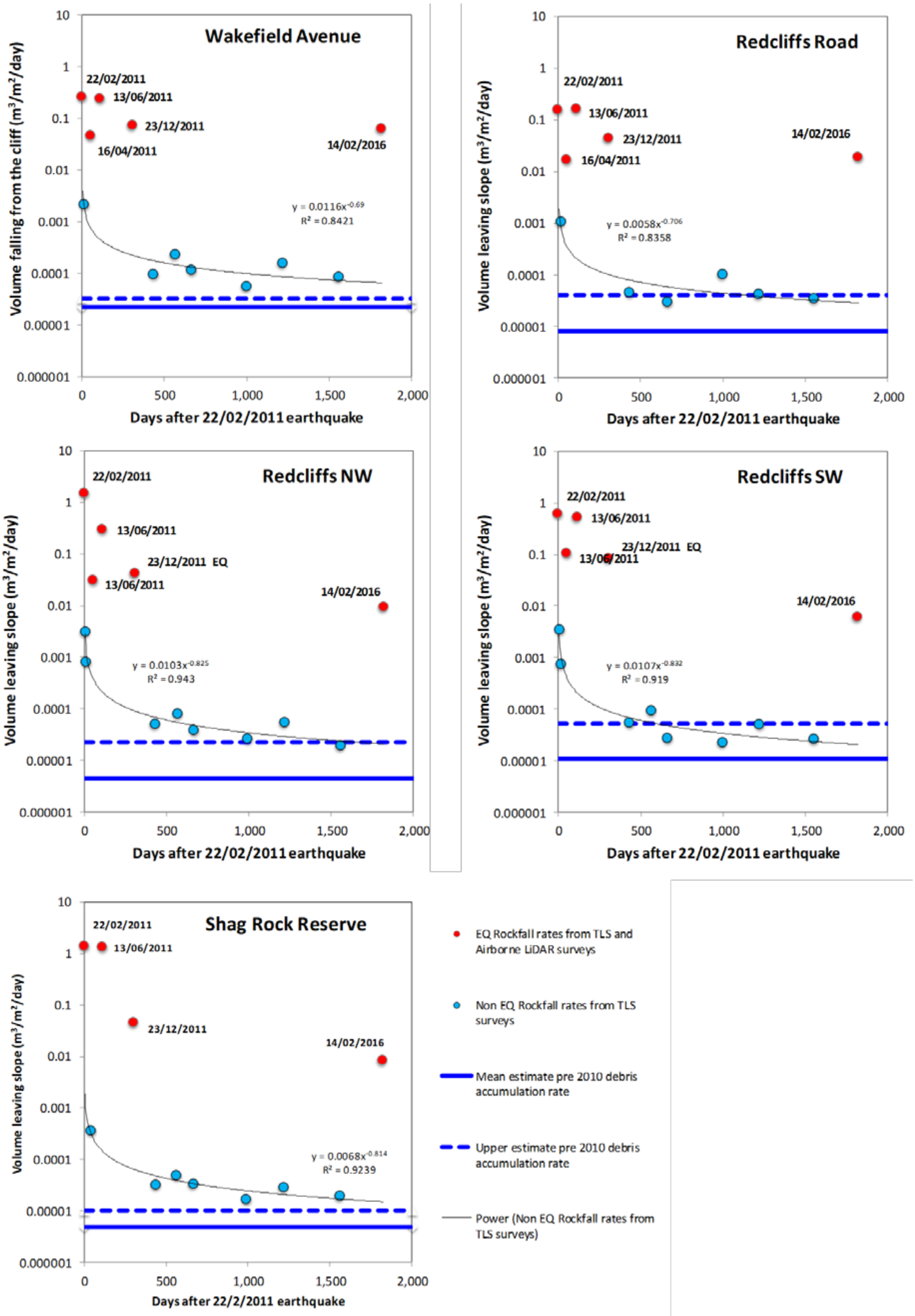

Figure 5.1 Earthquake and non-earthquake rockfall rates from terrestrial laser scan and airborne LiDAR surveys of selected rock slopes in the Port Hills of Christchurch, which were shaken by the 2010/11 Canterbury earthquake sequence. The pre-2010 debris accumulation rates (mean and upper estimates) are estimated from dating surfaces on top of which pre-2010 debris (debris present before the start of the 2010/11 Canterbury earthquake sequence) from the slopes lie (Olsen et al. 2020).

6.0 LIMITATIONS

The landslide probability maps produced for the Hawke's Bay region by the EIL tool have some limitations. Although the tool produces landslide probability forecasts for each 32 by 32 m grid cell, it is based on regional-scale datasets at nominal scales of between 1:25,000–1:250,000. The results from this tool should not be used at a site-specific scale.

Version 1.0 of the tool uses Kaikōura-Earthquake-related datasets that were calibrated against the observed distribution of landslides triggered by the 2016 Kaikōura Earthquake. For example, the geological deposits present in the North Canterbury and Marlborough region were grouped into four broad classes based on their statistically determined landslide response, which was broadly reflective of their rock and soil strengths (Quaternary deposits, Neogene deposits, Cretaceous to Palaeocene deposits and basement greywacke).

Every geological unit in Hawke's Bay has been assigned to one of these four broad classes in order to produce EIL maps across the Hawke's Bay region. Although there are similarities in the geology between the regions, these four classes are, at best, a simplification of the geology in the region. Each of the four broad classes will have variations within them that impact on slope stability and these are not captured by the current EIL model.

7.0 RECOMMENDATIONS

It is recommended that:

1. The EIL tool is re-run once further landslide data, for example, detailed mapping of landslides from the 1931 Hawke's Bay Earthquake, have been incorporated into the training of the EIL algorithm. This will improve the statistical performance of the EIL tool in the Hawke's Bay region. This work is currently underway via an Endeavour research grant funded via MBIE, called the 'Earthquake-Induced Landscape Dynamics Programme'. It is recommended that the landslide probabilities are re-calculated using the Version 2.0 EIL tool, once available.
2. Any infrastructure (e.g. critical roads and buildings) covered by or near grid cells with relatively high landslide probabilities be identified and prioritised for further analyses to assess their resilience. Roads and infrastructure that are located downslope from such areas may also be at risk from landslide debris runout, which has not been modelled by the tool. Further landslide runout modelling work at specific locations is recommended.

8.0 CONCLUSION

An earthquake-induced landslide (EIL) forecasting tool, developed using the landslide dataset mapped after the 2016 Kaikōura Earthquake, has been applied to the Hawke's Bay region.

The application of the EIL tool across the Hawke's Bay region has produced a suite of maps forecasting the regional-scale landslide probability (likelihood) for each 32 by 32 m grid cell, based on peak ground accelerations associated with return periods of approximately 25-, 100-, 500-, 1000- and 2500-years.

The EIL modelling shows that EILs are more likely in the western ranges of the region, particularly within the Ahimanawa Ranges and the Ruahine Ranges, around Cape Kidnappers, in the hills northeast of Frasertown, along the Mahia Peninsula coastline and in areas to the south of Havelock North.

The spatial distribution of landslide probability derived from the EIL tool can be used by Hawke's Bay Regional Council to compare with asset datasets (for example, buildings and roads) to identify and prioritise areas where important assets may be exposed. Further work to understand and manage landslide hazards would improve the resilience of the Hawke's Bay region.

9.0 ACKNOWLEDGEMENTS

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