Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Tool 2.3.3: Modelling present-day and future landslide potential

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1. Introduction

1.1 Overview of Tool

This tool describing the methodology used to model present-day and future landslide potential is written in two sections. The first section describes a generic methodology that can be used to calculate the probability of a rainstorm-induced landslide occurring at any point in New Zealand based on Dellow *et al* (2010). This methodology uses the datasets described in [Tool 2.3.2]. The types of maps that can be generated from the Probabilistic Rainfall-Induced Landslide Hazard Model (PRILHM) methodology are described in [Tool 2.3.4].

The basic premise of the generic PRILHM methodology is that spatially (10 x 10 metre pixel size) and temporally (24-hour rainfall totals) quantified rainfall is treated as a variable that 'falls' onto a geometrically-defined surface representing topography that is also parameterised with geology and vegetation data. This allows a landslide probability to be calculated at any site (a 10 x 10 metre pixel) within the PRILHM for a given daily rainfall. Different rainfall values return different landslide probabilities. Thus the annual exceedance probability (AEP) of a landslide occurring at a site is derived directly from the annual exceedance probability (AEP) of rainfall at a site. The rainfall AEP is calculated using daily rainfall totals from the 10 days prior to the day of interest as well as the daily rainfall on the day of interest (referred to as the rainfall index). The PRILHM uses historical rainfall correlated with contemporaneous landslide occurrence to calibrate landslide probabilities (and their uncertainties if sufficient data is available) for rainfall index AEP's of interest to the PRILHM user.

The second part of the tool describes how the PRILHM methodology was modified to account for the differences between the landslide data used in the generic methodology and the landslide data available for Wellington. The three landslide datasets available for Wellington are open-space, road network and domestic dwelling landslide datasets. The titles given to the datasets describe the 'element at risk' from the landslides in the dataset. Thus the road network landslide dataset contains landslides that have affected the road network. Duplication within the landslide datasets has been removed where it has been identified. Duplication across datasets has been deliberately disregarded because a landslide can potentially affect several 'elements at risk'.

2. The Generic PRILHM Methodology

The generic methodology has two components, rainfall and landscape. The first part of this section describes the methodology used to analyse rainfall data to obtain a rainfall-index value to calibrate historical landslide data with rainfall. The second part describes the parameterisation of the digital elevation model (DEM) using topography, geology and vegetation and how this is used to evaluate historical landslide data. The third section sets out the how the rainfall-index and the parameterised DEM are used to calculate landslide probabilities for any pixel in the DEM.

2.1 Rainfall

The rainfall input into the PRILHM is a rainfall-index (R_I), expressed in mm of rainfall. This takes:

- Antecedent rainfall or the 24-hour rainfall measurements for the ten days prior to the day of interest (as a proxy for the amount of water already in the ground at the day of interest). The antecedent rainfall is expressed in terms of mm-rainfall in the soil at the start of the day of interest (R_A);

- Actual or forecast 24-hour rainfall for the day of interest in mm (R_F);

These two values are added to produce a rainfall-index:

$$R_I = R_A + R_F \qquad [1]$$

The rainfall-index value is used as the rainfall that ‘falls’ onto the PRILHM ‘landscape’. Thus a PRILHM user can select a rainfall value for input into the model but the user needs to remember that the calculated AEP is for the rainfall-index on that day and not the 24-hour rainfall value. For example, if a user wanted to determine the probability of a landslide occurring at a site at an AEP of 0.01 (the equivalent of a 1-in-100-year event) the rainfall index (R_I) for that AEP first needs to be determined (the AEP of the 24-hour rainfall total cannot be used).

The method outlined in Glade *et al* (2000) is used to calculate the antecedent rainfall (R_A) component of the rainfall-index. The work of Glade *et al* (2000) is used because it has been derived from correlating rainfall and landslides in New Zealand and one of the three regions where they used run-off characteristics to calculate a specific regional value was Wellington. R_A is determined using the 24-hour rainfall records for the ten days prior to the day of interest. The formula used is:

$$R_{A0} = r_1 + 2^d r_2 + 3^d r_3 + \ldots\ldots + 10^d r_{10} \qquad [2]$$

Where R_{A0} is the antecedent daily precipitation for day 0; r_1, r_2, ..., r_{10} are the 24-hour rainfall totals for the day prior to day 0, two days prior to day 0, … ten days prior to day 0; and d coefficient of the flood recession decay curve for the region of interest.

Glade *et al* (2000) describe a slightly different formula used in a global context and based on US data (Bruce and Clark, 1966; constant $k = 0.84$ to replace the n^d term in Eq. 2 above). However, Glade *et al* (2000) calculated d using stream flow data from a Wellington catchment and this is used in the methodology for the Wellington data. For Wellington $d = -1.52$ with a standard deviation of ±0.52 (Glade *et al* 2000).

Projected daily rainfall values based on climate change scenarios can also be used to generate projected future values of the rainfall index. The empirical adjustment method of adjusting historic daily rainfall based on projected changes to the mean monthly precipitation described in [Tool 2.1.2 section 2.2.2, with an example application provided in section 3.3 of the same Tool] can be effectively used here.

2.2 The DEM building block

2.2.1 The DEM

The basic building block of the model is a DEM pixel. As stated previously in [Tool 2.3.2] the DEM used is derived from the NZMS260 map series 20-metre contour data. This data is processed to produce a rasterised DEM based on a 10 x 10 m pixel. Every pixel in the PRILHM DEM is initially 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. Each pixel is then also attributed with the following information:

- The slope angle is assigned to a slope angle band (5° increments; e.g. $15° \le \theta < 20°$);
- Down-slope direction (i.e. identify the adjacent pixel with the lowest elevation; if two or more pixels have the same elevation then the pixel that provides for the straightest path is selected);
- Geological unit at the pixel location;
- Vegetation class at the pixel location;
- Presence or absence of a water course/water body at the pixel location; and
- The total number of pixels in the PRILHM DEM that share the same geology, vegetation and slope band.

2.2.2 Calibrating historical landslide data

Individual landslide polygons caused by a rainstorm are obtained from the analysis of ortho-rectified remotely sensed images. For each landslide polygon in a rainstorm dataset the pixel with the steepest slope angle is identified. The centre of this pixel is assigned as the initiation point of the landslide. The geological unit and vegetation class of the DEM pixel with the steepest slope is assigned to the landslide polygon, as is the rainfall at the site associated with the rainstorm. It is now possible to produce a landslide size-distribution curve for the historical landslide data for each geology/vegetation pair for a rainfall value (Figure 2.1). This distribution curve is used as the basis for assessing the probability that a landslide will exceed a given size at any location within a geology/vegetation pair.

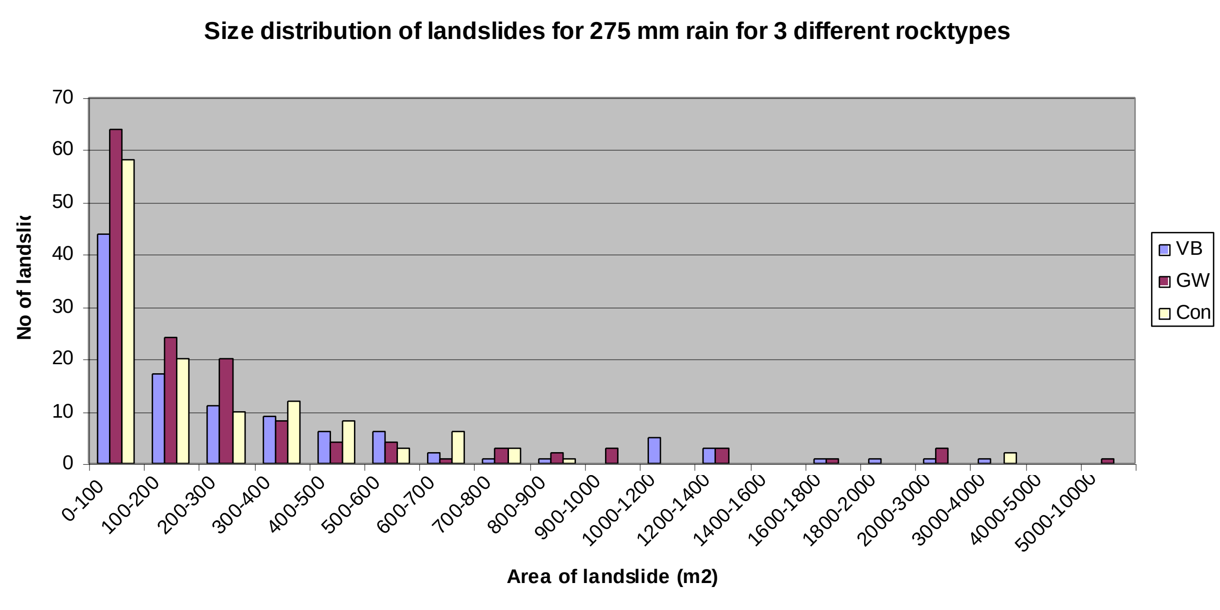

Figure 2.1: Size distribution curve for landslides populations in three different rock types under non-woody vegetation for a rainfall of 275 mm. (VB = volcanic breccia; GW = greywacke; Con = conglomerate).

The next step in analysing the historical landslide data is to establish the landslide areal frequency. Landslide areal frequency cannot just be calculated for a geology-vegetation pair as this would result in the landslides being distributed by the model without regard to slope angle. The slope angle of the initiation pixel for a landslide is used to assign the landslide to a slope band (in 5° increments) for the purposes of calculating landslide areal frequency. Figure 2.2 shows landslide areal frequency generally increases as the slope angle increases.

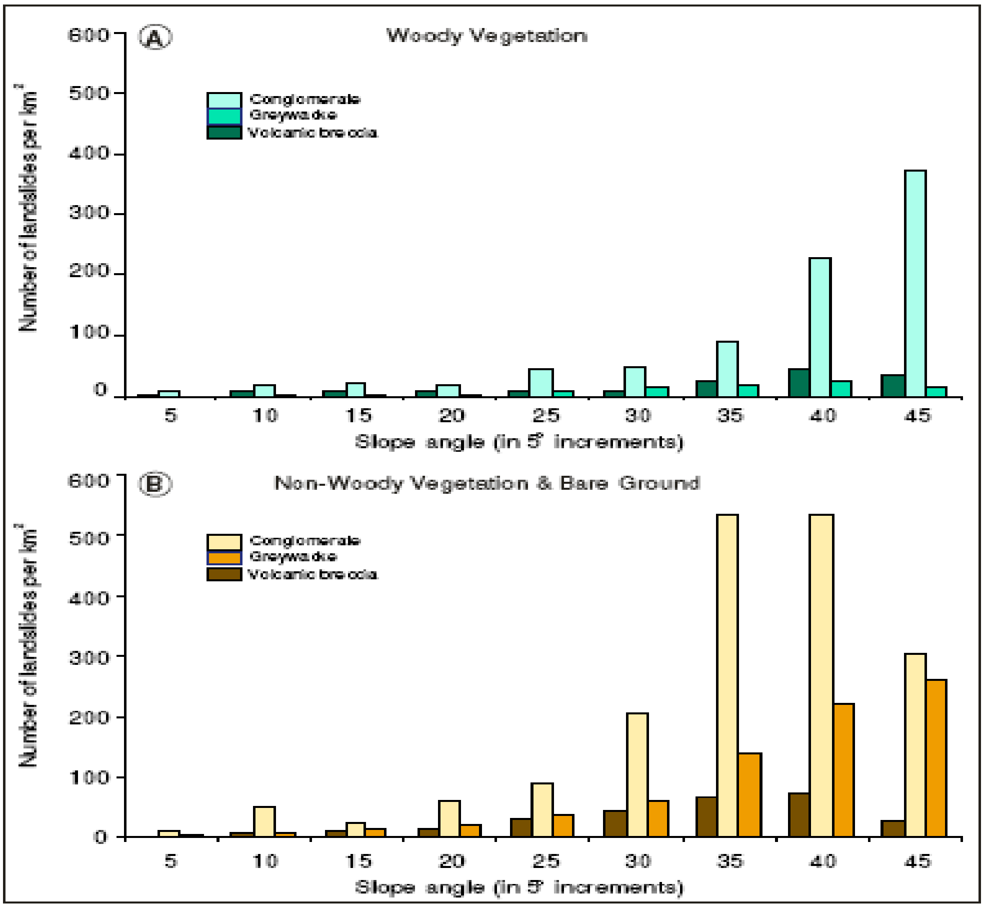

Figure 2.2: Relationship between slope angle and landslide areal frequency (number of landslides per km^2) for three different rock types under both woody and non-woody vegetation cover for a rainfall of 275 mm.

The number of landslide initiation pixels within each slope band for a given rainfall is compared with the total number of pixels within the slope band for a geology/vegetation pair. The number of landslides is normalised to produce the number of landslides initiated per km^2 at the rainfall value. A series of rainfall events are analysed for each geology/vegetation pair to estimate how landslide areal-frequency varies with rainfall intensity and to establish uncertainty bounds. The resulting correlation (Figure 2.3) provides a tool for determining landslide probabilities.

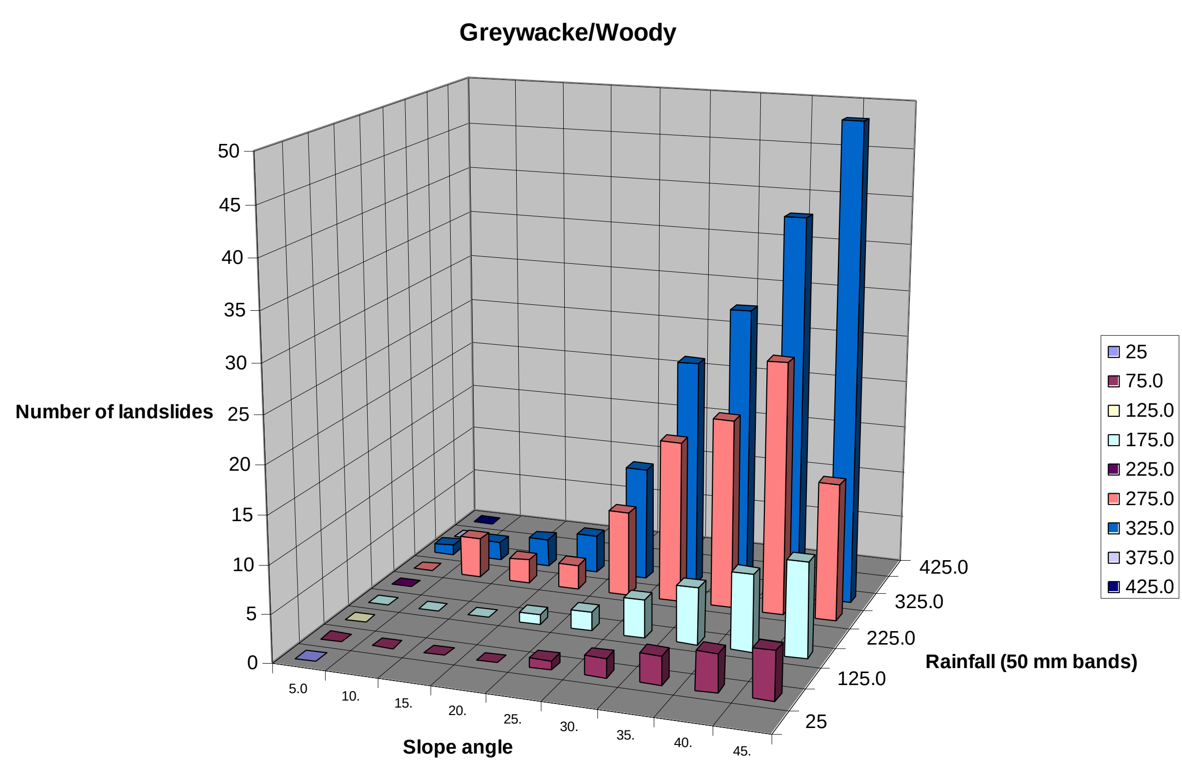

Figure 2.3: Relationship between slope angle, rainfall and number of landslides per km^2 where the underlying geology is greywacke with a woody vegetation cover. A similar graph is prepared for every unique combination of geology and vegetation.

2.2.3 Calculating Probabilities

Using the methodology and datasets described above a probabilistic landslide hazard model for rainfall-induced landslides (PRILHM) can be produced. A PRILHM can produce unique landslide hazard maps for different rainfall values, including data based on future rainfall scenarios. To produce the map, two probabilities need to be determined for each pixel in the DTM. These are:

1. The probability that a landslide initiates or is sourced in a given pixel P(S);
2. The probability that a landslide will enter or move through the pixel P(M).

The probability of any pixel being affected by a landslide P(L) is:

$$P(L) = P(S) + P(M) \qquad [3]$$

Calculating P(S)

P(S) can be calculated for a particular R_I value when the following data is available:

- Landslide areal-frequency for each slope band expressed as landslides per km^2 (N_L) knowing that there are 10,000 pixels per km^2;
- Number of pixels (N_P) in each 5º slope band in the area of interest; and

$P(S) = N_L \times (N_P/10000)$.

So P(S) = probability of any pixel in the total population of pixels within a 5º slope band acting as an initiation point for a landslide. Therefore for a given rainfall a probabilistic map of the likelihood of a given pixel acting as a landslide initiation point can be calculated.

Calculating P(M)

For the purpose of fully modeling the landslide hazard, the probability of a landslide moving beyond its initiation or source pixel needs to be considered. The first step is to identify all the potential landslide travel paths. A landslide travel path originates in every pixel in the DEM. The travel path is determined by the convention that a landslide will travel down-slope (i.e. to whichever of the eight adjacent pixels that has the lowest elevation). If two or more pixels have the same slope the probability is shared equally between the pixels. The travel path continues until it encounters a pixel where a water course or water body is present or if all the surrounding pixels have a higher elevation (i.e. a sinkhole). If either of these conditions is met landslide movement ends.

Thus travel path T_A can be defined as consisting of a series of pixels p_{1A}, p_{2A}, p_{3A}, ……p_{zA},

$$T_A = p_{1A}, p_{2A}, p_{3A}, \ldots, p_{zA-1}, p_{zA}, \qquad [4]$$

Where a P(S) has been calculated for pixel p_{1A}, pixel p_{2A} has the lowest elevation of the eight pixels surrounding pixel p_{1A}, and pixel p_{3A} has the lowest elevation of the eight pixels surrounding pixel p_{2A}, etc … until pixel p_{zA} has the lowest elevation of the eight pixels surrounding pixel p_{zA-1}, and pixel p_{zA} meets the movement ending criteria (presence of water or a sinkhole). Travel paths are able to be pre-defined and only change if the underlying DEM changes. Almost every pixel can have multiple travel paths contributing to the calculation of P(M).

For each pixel where P(S) is calculated, the probability of the landslide moving into an adjacent pixel is calculated based on the size distribution of the landslides for the geology/vegetation pair of the initiation pixel. For a down-slope travel path consisting of pixels (p_1, p_2, p_3, … p_{z-1}, p_z,) the probability of a landslide moving into the adjacent pixels is calculated as follows:

- For pixel p_1 the probability is P(S) (i.e. in the originating pixel of a travel path the probability of a landslide occurring is simply the probability that that pixel acts as an initiation source).
- For pixel p_2 the probability P(M) of a landslide originating in pixel p_1 moving into pixel p_2 is P(S) multiplied by percentage of landslides exceeding one pixel in size (obtained from the landslide size distribution for the geology-vegetation pair).
- For pixel p_3 the probability P(M) of a landslide originating in pixel p_1 moving into pixel p_3 is P(S) multiplied by percentage of landslides exceeding two pixels in size.
- For pixel p_z the probability P(M) of a landslide originating in pixel p_1 moving into pixel p_z is P(S) multiplied by the percentage of landslides exceeding (z-1) pixels in size.

Thus for any pixel in the model, P(L) or the probability it will be affected by a landslide for a particular rainfall value is determined by:

$$P(L) = P(S) + P(M);\ \text{where} \qquad [5]$$

$$P(S) = N_L \times (N_P / 10000);\ \text{and} \qquad [6]$$

$$P(M) = P(M)T_A + P(M)T_B + \ldots\ldots + P(M)T_Z \qquad [7]$$

3. Wellington Case Study

In this section the datasets used to produce a PRILHM for Wellington City are described. The uncertainties and limitations of these datasets are identified where possible.

3.1 Wellington landslide data

Three separate landslide datasets have been used to assess and calculate the landslide hazard in Wellington. The landslide datasets were sourced from the national PRILHM, the Wellington City Council (WCC) and the Earthquake Commission (EQC). Each dataset has been collected by a different agency and the datasets are therefore not able to be combined. Collectively the datasets provide a relatively complete picture of rainfall-induced landslides in Wellington City allowing an assessment of landslide hazard to be made. Each of the three landslide datasets is described below.

3.1.1 Open-space landslide data

The open-space landslide dataset is sourced from landslides in greywacke terrain from around New Zealand. The data is produced by processing satellite images to establish the location and size of landslides that have occurred in response to a rainstorm on greywacke terrain (Joyce et al, 2008). Ortho-rectified images from pre- and post-rainstorms are analysed to capture a polygon for each landslide spatially constrain its location. Only new landslides in the post-event image are used to compile the landslide dataset for a particular rainstorm.

For the open-space dataset the only currently available data is from a rainstorm in 2007 that caused landslides on greywacke terrain with a rainfall index of between 250 and 300 mm. Landslide distributions for other rainfall index values are interpolated from this dataset. This is the most poorly constrained of the landslide datasets and has the greatest uncertainty around the consequent landslide hazard.

3.1.2 Road network landslide data (the WCC Slips Database)

The road network landslide data was obtained from the Wellington City Council (WCC) and included a ten year record (21.08.1999 – 15.03.2010) of landslides occurring on council land, principally the road network. The total number of landslides recorded in the dataset was 4033 (Figure 3.1) after processing the provided data to remove non-landslide events (e.g. flooding events related to problems with the storm-water system) and duplicate landslide entries.

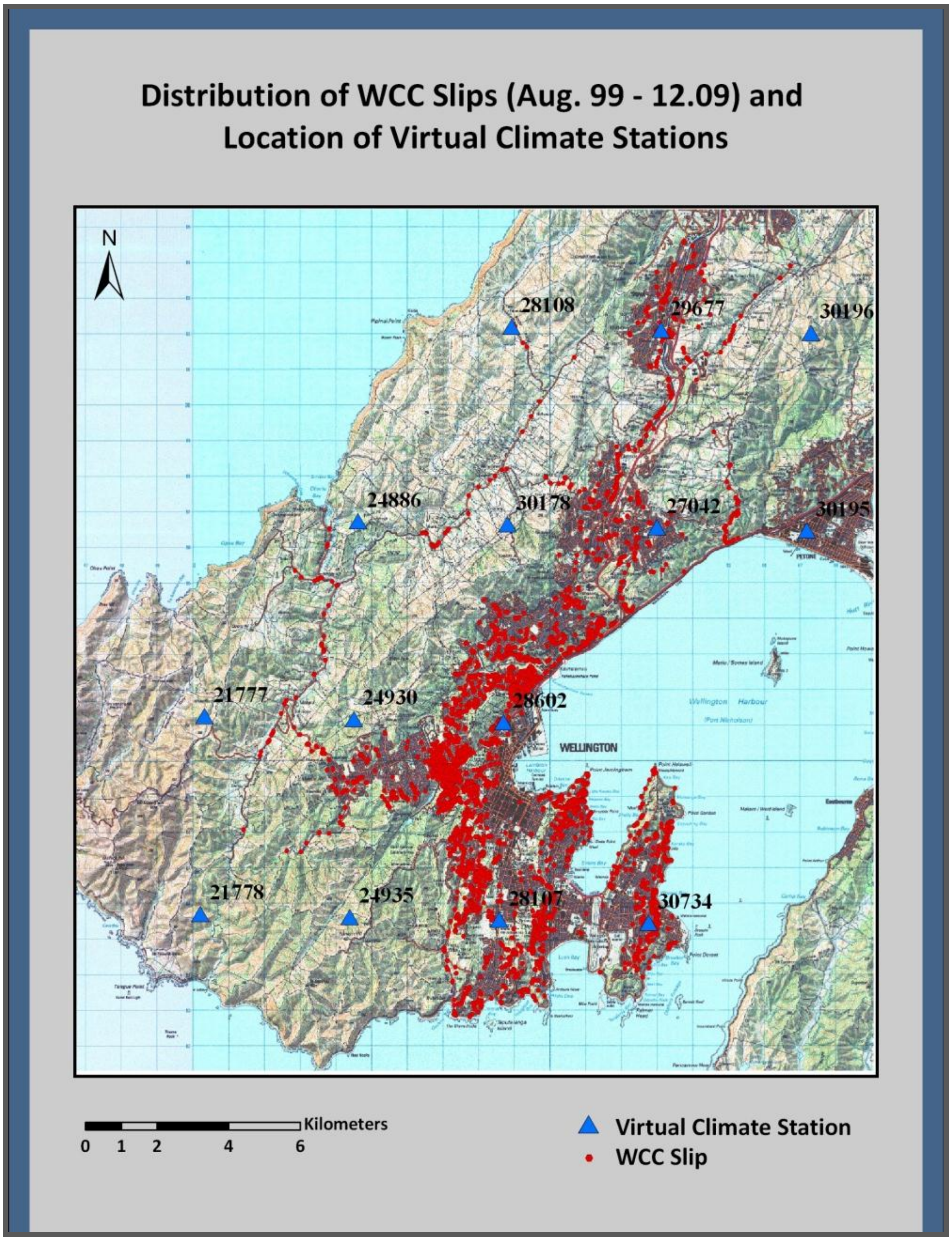

Figure 3.1: Map of WCC slips and virtual climate station (VCS) locations.

The information contained in the database was received from the public via telephone (and occasionally by letter). The public were reporting landslides that had affected their property or landslides they had encountered on council owned land. Notes from the phone calls were included in the database.

The date of the phone call was used as the date of the landslide unless the date was otherwise specified. The location of the landslide in the database was a street address. Variations in property size mean the street address has a varying degree of accuracy.

The location was refined because often a house number was given, or a description of the whereabouts of the slip, enabling a reasonably accurate identification of the landslide site. The street view in Google Maps was also capable of refining the location as landslides frequently occurred on the roadside and with a description of the location more accurate identification of the site was often possible.

The addresses had to be converted into a coordinate system in order to load the information into a GIS. This was achieved using mapping software (TUMONZ) to allocate an easting and northing to each landslide. An estimated degree of accuracy (EDA) was also assigned to each individual landslide. The minimum EDA for a landslide is 10 m, whereby the value indicates the radius from the point representing a slip.

The size of the landslide was often not available, but where it was the way the size was reported was often in terms of material removed from the site on clean-up. As the volumes were usually small it was decided to assign a maximum size of 100 m^2 to the landslides in this dataset as this also corresponds to the size of the DEM pixel used in the PRILHM. When modeling the WCC landslide dataset what is being modeled is the initiation of a landslide which is often smaller than 100 m^2.

3.1.3 The domestic dwelling landslide data (EQC claims dataset)

The third landslide dataset used was compiled from Earthquake Commission (EQC) insurance claims for landslide damage to domestic housing. This dataset also provided information on the fragility and vulnerability for different types of building construction and the consequence risk to occupants of any dwelling. The time period covered by the dataset was January 1999 to December 2009 and 1303 landslides are in the dataset.

The date of the EQC data is only recorded by month so two methods for assigning a day to the landslide were analyzed. The first method simply assigns the day in the month with the highest rainfall-index as the date of the slip. The second method assigns the day in the previous month with the highest rainfall-index as the date of the slip. Although the methods are not ideal they allow landslide-data and rainfall to be correlated, albeit with a larger uncertainty around the date of the landslide than other landslide datasets.

Again the location of the landslide is associated with an address and the address had to be converted into a coordinate system in order to load the information into a GIS. Again this was achieved by determining an easting and a northing for each landslide via mapping software (TUMONZ) and the knowledge that for an EQC insurance claim to be successful the landslide would usually be within eight metres of a house or its access. An estimated degree of accuracy (EDA) was assigned to each landslide. The minimum EDA for a landslide is 10 m where the value indicates the radius from the point representing a slip.

The size of the landslide was often not available. Using knowledge of the characteristics of landslide distributions (e.g. Joyce *et al.*, 2009) it was decided to assign a maximum size of 100 m^2 to the landslides in this dataset as this also corresponds to the size of the DEM pixel used in the PRILHM. When modeling the EQC landslide dataset what is being modeled is the initiation of a landslide which is often smaller than 100 m^2.

3.2 Rainfall data

Rainfall data was obtained from the National Institute of Water and Atmospheric Research (NIWA). The rainfall data used for this project is taken from NIWA's Virtual Climate Stations (VCS) for the period Jan. 1999 – Dec. 2009. These data are estimates of daily rainfall records on a 0.05° latitude/longitude grid (Figure 3.1) covering all of New Zealand using a second order derivative tri-variate thin plate smoothing spline spatial interpolation model (for a detailed description of the method, refer to Tait *et al.*, 2006). This interpolated rainfall record for each VCS is based on 24 hour measurements of rainfall starting and finishing at 9 a.m. Because the rainfall data used for this analysis extended only until the end of 2009, the slips occurring during the first three months of 2010 were excluded from the assessment, reducing the total count of slips in the road network landslide dataset to 4004.

The PRILHM was also run using daily rainfall readings for the same time period from four actual rainfall gauge sites in the WCC area. This was done to allow comparison of the results derived from regularly spaced virtual data with results from a few irregularly spaced recording stations.

Projected daily rainfall for two future periods, 2040 and 2090, and for three emission scenarios, B1, A1B and A2, were also produced for the same VCS grid points shown in Figure 3.1. The empirical adjustment methodology [Tool 2.1.2 section 2.2.2] was used to generate these future daily rainfall data series.

3.3 Geological data

The geology of the WCC area is relatively uniform with most of the area being either old greywacke (> 70 million years old) or young sediments (< 2 million years old). Given that the sediments are dominantly in the flatter areas the geology of the area has been treated as uniformly greywacke in the PRILHM.

3.4 Vegetation data

Vegetation data from the NZMS260 map series (Sheets R26 and R27) is used as the default vegetation dataset for this study. As the vegetation data is only used in the open-space landslide hazard model this is not expected to bias the results. Vegetation data is not used in conjunction with the road network or domestic dwelling landslide datasets because it is not readily available at the required scale. For the road network or domestic dwelling landslide datasets an assumption is made that the vegetation cover is the equivalent of pasture (lawns) or bare-ground (cut slopes in rock).

3.5 Water body/ water course data

The water body/water course data is sourced from from the LINZ NZMS260 1:50,000 map series, sheets R26 and R27.

3.6 Digital Elevation Model data (DEM)

The DEM information used in the Wellington study is derived from the Land Information New Zealand (LINZ) NZMS260 20-metre contour data. The 20-metre contour data has been converted to a DEM raster with a pixel size of 30 m by 30 m. For the PRILHM each LINZ DEM pixel is divided into nine 10 m by 10 m pixels using an interpolation process to match the resolution of satellite imagery sourced landslide data.

Every pixel in the PRILHM 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.

Each pixel is then also attributed with the following information:

- The slope is assigned to a slope angle band (5° increments; e.g. $15° \leq \theta < 20°$);
- Down-slope direction (i.e. identify the adjacent pixel with the lowest elevation; if two or more pixels have the same elevation then the pixel that provides for the straightest path is selected);
- Geological unit at the pixel location;
- Vegetation class at the pixel location;

- Presence or absence of a water course/water body at the pixel location; and
- The total number of pixels in the PRIHLM DEM that share the same geology, vegetation and slope band.

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