A landslide susceptibility map and landslide catalogue for the West Coast region

The user guide

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Executive summary

This paper presents two tools for landslide hazard management in the West Coast region of New Zealand. As part of a Masters Degree Thesis entitled “A landslide susceptibility model for the West Coast Region, New Zealand”, a landslide susceptibility map and a landslide catalogue have been produced. This paper explains the research methodology, limitations and intended uses of these tools.

In order to avoid misinterpretation the study has been carried out in compliance with the “Guidelines for landslide susceptibility, hazard and risk zoning for land use planning”, which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes.

This study identifies areas that are susceptible to rainfall triggered landslides in the West Coast Region. The landslide susceptibility model was produced using bivariate statistics and the analytical hierarchy process. It has an accuracy that predicts 80% of all the landslides in the top 40% of the susceptibility scores on the map. As part of this process, 3221 rainfall triggered landslides and 522 earthquake triggered landslides have been mapped and digitised into a GIS. In parallel with this, a descriptive historical catalogue of 1643 landslides has been compiled from all the available sources. These two tools provide decision-makers with an enhanced means of managing landslide hazards in the West Coast region.

1. Introduction

1.1 Background

Landslides, in their various forms, are a common hazard in mountainous terrain, especially in seismically active areas and regions of high rainfall. The West Coast Region of New Zealand is dissected by many active faults, experiences frequent earthquakes and in many locations annual rainfall exceeds 10m. Consequently, landslides are widespread natural phenomena in the region and since European settlement began in the late 19th century have been responsible for 27 deaths, along with frequent damages to road and rail infrastructure, settlements and agricultural land (Benn, 2005). The continuing residential and commercial development of hilly country throughout the region combined with the increasing value of real estate has highlighted the need for better understanding of landslide occurrence and distribution.

This study identifies areas that are susceptible to rainfall triggered landslides in the West Coast Region. It also presents historic landslide data from the most complete catalogue of landslides in the region. When this information is compared to infrastructure and land use information held at the Regional and District Councils it allows the identification of sites most at risk from landslide damage.

In order to avoid misinterpretation the study has been carried out in compliance with the "Guidelines for landslide susceptibility, hazard and risk zoning for land use planning", which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes (Fell *et al.,* 2008). In 2007 GNS Science published the "Guidelines for assessing planning policy and consent requirements for landslide prone land" (Saunders and Glassey, 2007), which has become the standard reference document for Council Planners in matters relating to landslide hazard management. These guidelines should be used in combination with the hazard information contained in this study. This will help to reduce the costs associated with landslide damage and aid in disaster reduction.

1.2 Terminology

In this study a landslide is defined as a gravity driven down-slope movement of soil, debris or rock. The landslide susceptibility map does not differentiate between the various types of landslide. However, the landslide catalogue describes the different forms of landslides based on the classification system designed by Cruden and Varnes (1996), which has become accepted as the standard means of describing the form of landslides. Table 1 shows this classification

<table>
<tr><th colspan="2" rowspan="3">Type of movement</th><th colspan="3">Type of material</th></tr>
<tr><th rowspan="2">Bedrock</th><th colspan="2">Engineering soils</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="2">Falls</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="2">Topples</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="2">Slides</td><td>Rotational</td><td rowspan="2">Rock slide</td><td rowspan="2">Debris slide</td><td rowspan="2">Earth slide</td></tr>
<tr><td>Translational</td></tr>
<tr><td colspan="2">Lateral spreads</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2">Flows</td><td>Rock flow</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="5">Complex: a combination of two or more principal types of movement</td></tr>
</table>

Table 1 Types of landslides. Abbreviated version of Cruden and Varnes' classification of landslide types (Cruden and Varnes, 1996).

The use of Geographic Information Systems (GIS) requires specific terms, so a glossary of these terms and the terms used to describe the landslide hazard is included as an appendix to this paper.

1.3 Overview

The problem of landscape instability and its effects on infrastructure and people has traditionally been approached in a deterministic manner, where site specific investigations are conducted to determine the stability of a particular area of interest. In contrast to the deterministic approach, this study has used a statistical modelling technique to define areas that are more or less likely to experience landslides. The output of this statistical model is a “landslide susceptibility map”, which depicts areas likely to have landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of landslides (Yalcin, 2008).It relies on the trusted geological principle that “the past and the present are the keys to the future”. That is, future landslides are most likely to occur under the same conditions that led to past and present landslides (Dai and Lee, 2002).

The first, and most important, stage of landslide susceptibility modelling is to produce a landslide inventory map. Once this has been achieved the spatial characteristics of the landslide distribution can be explored. The aerial photography archive at the WCRC provided the majority of the input data, but other sources, such as DoC’s photo archives, field investigations and Google Earth were used where required.

Validation of the landslide susceptibility map was carried out using a new set of aerial photography obtained from the Animal Health Board. The predictive power of the map was tested using the success rate curve method of Chung and Fabbri (2003).

The landslide susceptibility map, in combination with the landslide inventory map can be used to better understand the potential for future landslide occurrences in the West Coast Region. In addition to this, an historical catalogue of damaging landslides has been compiled and stored in a format that is easily viewable in database or digital map format. These tools can be effectively used by decision-makers to aid in landslide hazard management. However, it does not replace the need for site specific geotechnical investigations.

This manual explains:

- the methodology used to produce the landslide susceptibility map and the landslide catalogue
- The limitations of these tools
- The most appropriate means of using the tools

Detailed descriptions of the mathematical formulations and techniques used for the statistical analysis and modelling can be found in the thesis entitled “A landslide susceptibility model for the West Coast Region, New Zealand” (England, 2011)

2 The landslide susceptibility map

2.1. Methodology

This study utilises the “weights of evidence” method, which was first developed by Bonham Carter (1994), for use in mineral potential assessment for the mining industry. Since Van Westen (2003) applied it to landslide susceptibility analysis, it has been successfully used for this purpose in many different and diverse study areas (Dai and Lee, 2002; Gullà *et al., 2008*, etc.). More recently, the analytical hierarchy process of Saaty (1978) has been applied to the problem of landslide susceptibility modelling, to refine and improve the results of the weights of evidence method (Boroushaki and Malczewski, 2008, Yalcin, 2008, etc.).

In this study, both of these methods have been used, the results compared, and the most appropriate technique chosen for the final landslide susceptibility map.

During early experimentation (in this study) with these techniques it became obvious that the terrain variables that act as control factors in the occurrence of landsides are very different across the study area. One of the criticisms of this type of modelling is that a high degree of simplification is required (Fell, *et al.,* 2008, Dai and Lee, 2002) especially in large study areas such as the West Coast region. The geologic, tectonic, geomorphic and environmental conditions in the coastal plains are very different than those present in the Southern Alps. Correspondingly, the environmental controls on landsliding are also different and the distributions of landslide occurrences reflect this. For this reason it was decided that the study area be divided into 2 distinct areas and the modelling of landslide behaviour and distribution was handled separately in these two areas. The Alpine fault is the largest tectonic feature in the West Coast region, and conveniently separates the region into 2 areas:

1. East of the Alpine Fault. The Southern Alps, comprising mainly of schist.
2. West of the Alpine Fault. The coastal plains and the granitic basement rocks of the West Coast Region, including the Paparoas and mountains in the Buller district.

Figure 1 illustrates the steps followed in this study to produce the final landslide susceptibility map of the West Coast region.

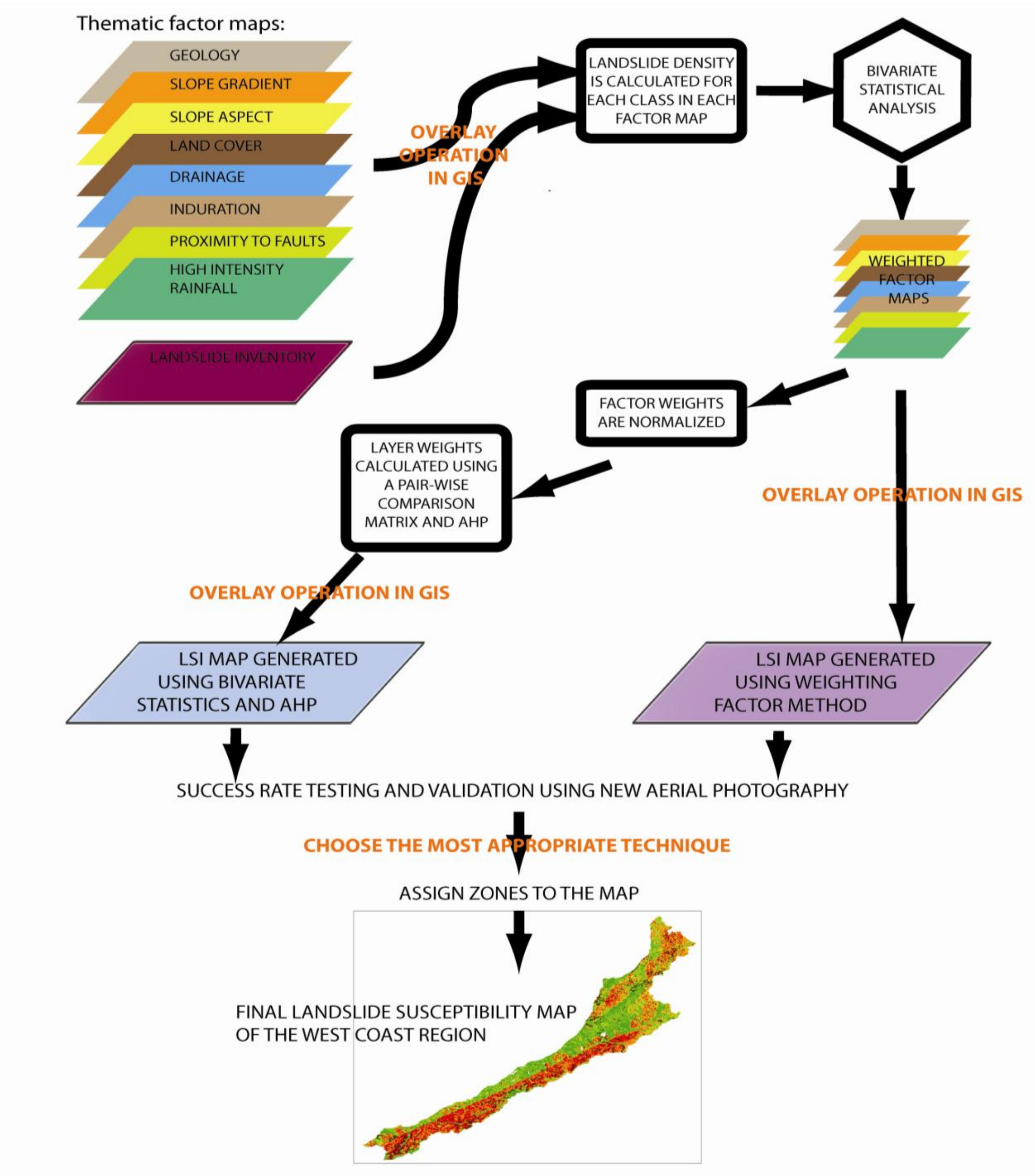

Figure 1 Flow diagram representing the steps used to produce a landslide susceptibility map for the West Coast region.

In total, 2566 rainfall triggered landslides covering a combined area of 61.4km^2 were mapped from aerial photography, satellite photography, direct field observations and extracted from other research (Smith, 2004, GNS 2010) to form the landslide inventory layer. 8 factor maps representing the factors deemed to be influential in the control of landsliding were prepared in a GIS and categorized into sensible classes to facilitate direct statistical comparisons with the landslide inventory layer. These factor maps are:

- **Geology.** The geologic units contained within the 6 QMAP's for the West Coast Region (Nelson, Greymouth, Kaikoura, Aoraki, Haast and Wakatipu) were imported into a GIS and extracted to produce a regional geology map. The resulting 45 rock types were then grouped into the 10 classes.

- **Slope gradient.** A categorized slope gradient map was generated from a high resolution digital elevation model (DEM). The DEM used in this study was prepared for the Foundation for Research, Science and Technology in 2002. Land Information New Zealand provided Landcare Research with photogrammetrically derived 20m contours, spot heights, lake shorelines and coastlines, which was then used to generate a 25m cell size DEM using Landcare Research's internally developed software as described in Barringer *et al.* (2002). This DEM is available as a commercial product and was used for this study under licence for research purposes only at the University of Canterbury, Department of Geological Sciences.
- **Slope aspect.** The same DEM as described above was used to generate a slope aspect layer.
- **Land cover.** The New Zealand Climate Change Office and the Ministry for the Environment publish a Land Cover Database which is a thematic classification of 43 land cover and land use classes in New Zealand. It primarily uses SPOT 5 and Landsat 7 satellite imagery to identify the different land cover classes. The first Land Cover Database (LCDB1) was completed in 2000 and the second (LCDB2) was released in 2004, and was intended as a formal method of tracking climate change related land use/land cover changes (New Zealand Climate Change Office, 2002). This study uses LCDB2 under licence from WCRC. Land cover classes that do not relate to landsliding were removed from the map, so areas of open water, coastal sand and gravel, river bed gravel, etc have been excluded from the landslide susceptibility assessment. Similarly, areas of permanent snow and ice have been removed from the land cover thematic factor map. This was done because these areas are subject to a very different set of rules governing landscape stability, and this thesis does not make an attempt to classify snow and ice avalanches, or glacial collapse. The remaining land cover classes were grouped into 10 generalized classes.
- **Soil drainage.** Land Environments of New Zealand (LENZ) is a land classification system designed by Landcare Research, Ltd. with the underlying data layers being available for research purposes as described in Leathwick *et al.* (2003). It uses the New Zealand Land Resource Inventory and the New Zealand Soils Database, in combination with field mapping to derive values of soil properties on a national scale. This map classifies soil drainage properties into 5 groups, so no further processing was necessary for use in this study.
- **Soil Induration.** The LENZ data layers also contain information relating to soil induration. This map classifies soil induration properties into 5 groups, so no further processing was necessary for use in this study.

- **Proximity to faults.** The faults plotted on the 6 QMAP's for the region were extracted to form a regional fault map. Buffers of 100m, 1000m and 3000m were applied to all the faults thus dividing the region into 4 classes.
- **High intensity rainfall.** Since landslides are usually triggered by heavy rainfall a map of maximum expected rainfall in 24 hours for a specific return period rainstorm is more useful than a traditional annual rainfall map (Van Westen *et al.,* 2008). Fortunately, Craig Thompson of the National Institute of Water and Atmospheric Research (NIWA) developed the high intensity rainfall design system (HIRDS), which is a computer-based procedure for estimating design rainfalls in New Zealand (Thompson, 2002). The HIRDS map shows design maximum expected rainfall during a 10 year return period rainstorm. The continuous raster map was reclassified into 9 convenient classes.

These 8 factor maps were individually compared to the landslide inventory layer and a bivariate statistical analysis carried out to establish the correlation between landslides and the individual classes contained within each factor map. The factor map classes were reclassified using the weighting scores derived from this analysis and all 8 maps numerically added to produce a landslide susceptibility index (LSI) map. This is the weighting factor method of Bonham-Carter (1991). One of the criticisms of the weighting factor method is that it assumes that the various factors are conditionally independent of each other (Dahal *et al.*2008). Since the factor maps are analysed separately, the relative importance of factors within a single map (ie, whether granite is more or less susceptible to landsliding than schist for a geology map) is established, but the relationship between the separate maps is not established by this technique.

The AHP has been applied successfully to landslide susceptibility modelling by many authors (Dai *et al.,* 2001; Komac, 2004; Yalcin, 2008; Liu and Chen, 2003, etc.), and is used in this study to establish the relative importance of the separate factor maps in the control of landslide occurrence. These two techniques were trialled and the results tested and compared. The most appropriate technique was then chosen and the resulting landslide susceptibility index map was then zoned and published for use in landslide hazard management in the West Coast Region.

The usefulness of a susceptibility map is greatly increased when it is divided into 5 zones: very low, low, moderate, high and very high susceptibility to landsliding (Fell *et al.*, 2008). This zoning is accomplished by assigning LSI values to the boundaries between the zones such that a certain proportion of the mapped landslides fall within each zone.

Rules relating to land use and development planning can be attached to each of the zones and the boundaries are easily visible. Also, the spatial characteristics of the zones can be quantitatively explored giving more meaning to the classification of the zones. Figure 2 shows the visual difference between an LSI map and a zoned landslide susceptibility map.

The landslide susceptibility map should be viewed in combination with the landslide inventory. The landslide inventory contains polygons of mapped landslides and is therefore useful in identifying areas that have experienced landslides in the past. Rainfall triggered landslides are displayed separately from the larger, often prehistoric, earthquake triggered landslides.

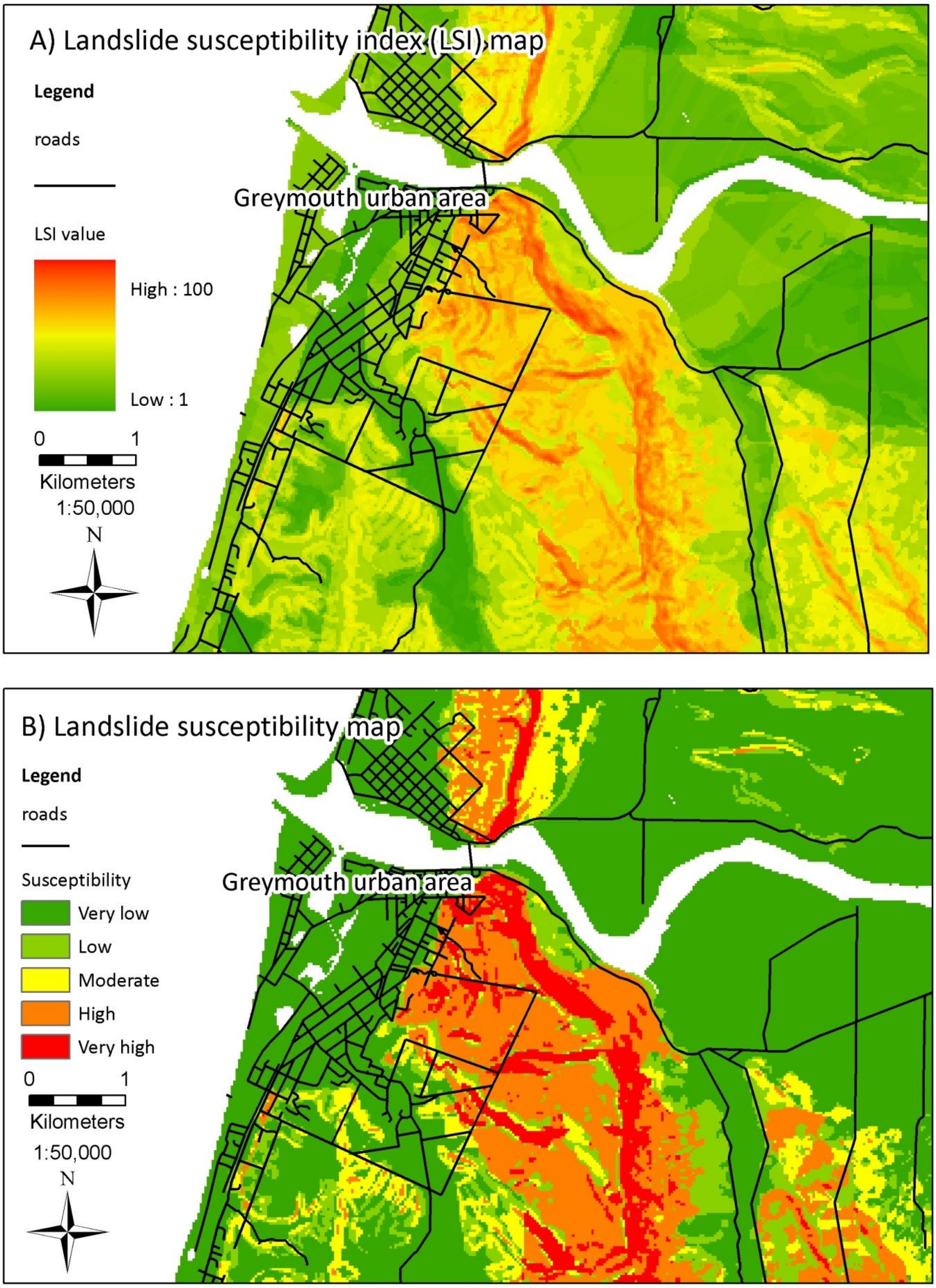

Figure 2. A comparison of an LSI map, with a continuous variable (A) and a zoned landslide susceptibility map (B)

2.2 Success rate testing

The above procedure produced 4 LSI maps:

- LSI map of the Eastern area generated using the weighting factor method (WFM_E).
- LSI map of the Western area generated using the weighting factor method (WFM_W).
- LSI map of the Eastern area generated using the analytical hierarchy process method (AHP_E).
- LSI map of the Western area generated using the analytical hierarchy process method (AHP_W).

These maps were tested for their predictive power using the success rate curve method of Chung and Fabbri (2003). The success rate is calculated by ordering the pixels of the LSI maps and grouping into 100 classes from high to low values, in a quantile distribution based on the frequency information from the histogram of their distribution. After that, the landslide inventory is overlayed with the categorised LSI map and the joint frequency is then plotted on a scatter graph (Chung and Fabbri, 2003; Frattini *et al.* 2010). A hypothetical success rate curve coinciding with a diagonal from 0 to 100 would be equivalent to a totally random prediction. The further up and away the success rate curve is from that diagonal, the better the predictive value of the map. Likewise, the greater the gradient in the first part of the curve the greater its predictive capability (Chung and Fabbri, 2003; Remondo *et al.*2003). Figure 3.shows the validation success rate curves for the 4 susceptibility maps. Clearly, the maps generated using the AHP method show a greater predictive accuracy than the ones which use the weighting factor method alone.

From this it can be seen that in the case of AHP_W, 40% of the landslides occurred in 20% of the map with the highest susceptibility values and 80% of the landslides occurred in 40% of the map with the highest susceptibility values.

The susceptibility maps for the eastern area (Southern Alps) show a marginally better fit than the western maps in the first part of the curve, but towards the ends of the curves it is clear that the eastern maps do not perform as well. For example, in the case of both western maps, all the validation landslides (100%) occurred in 70% of the map, but for the case of the eastern maps there were still landslides occurring in the lowest 10% of the susceptibility classes.

The area under the curve for the AHP maps is significantly larger than for the WFM maps, which proves the superior predictive capability of the AHP method in generating landslide susceptibility maps. On the basis of these results, the most appropriate maps to use for landslide hazard management in the West Coast region are the ones generated using bivariate statistics and the analytical hierarchy process.

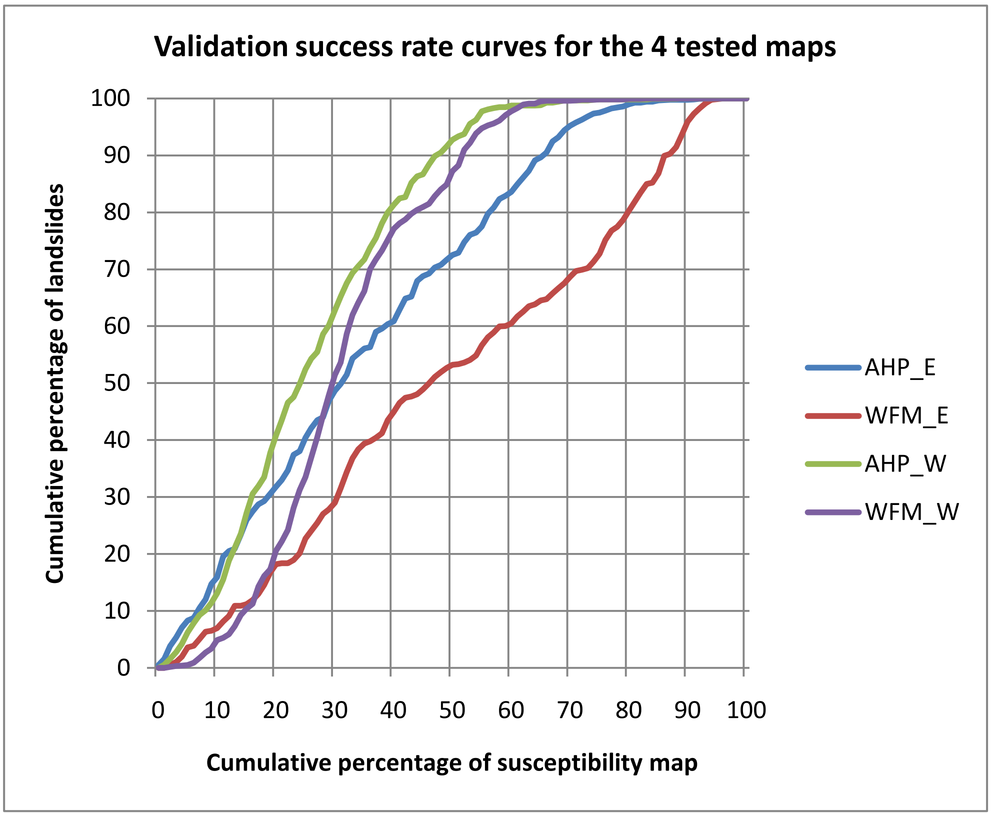

Figure 3. Validation success rates for the 4 LSI maps of the West Coast Region

2.3 Assigning zones to the maps

By extracting all the landslide polygons (from the original dataset and the validation dataset) from the LSI map and ordering those pixels from high to low it is possible to find the corresponding LSI value that relates to a certain percentage of landslides. Table 2 shows the percentage of landslides and the LSI values that were used to assign the zones to the final susceptibility map. So, 54 % of landslides occur in the very high susceptibility zone, 30% in the high susceptibility zone, etc.

Table 2. Percentage of landslides in each susceptibility zone and their corresponding LSI values.

Susceptibility zone	Percentage of all landslides	LSI values	
		East	West
Very low	2	0-7	0-24
Low	4	8-15	25-33
Moderate	10	16-29	34-44
High	30	30-58	45-70
Very high	54	59-100	71-100

Figure 2 (page 10) illustrates the difference between an LSI map, showing a continuous variable of landslide susceptibility index scores and a susceptibility map, which has 5 distinct zones.

Once the zones are established the spatial characteristics of these can be explored which will help in the final use of the susceptibility map.

Table 3 illustrates the spatial distribution of the 5 susceptibility zones. It is worth noting here that 34% of the area to the East of the Alpine fault is classed as “very high” susceptibility to landsliding, whereas the corresponding zone on the Western side of the fault is only 24% of the land area. This is in accordance with the expected results.

Table 3. Area of the region covered by the different susceptibility zones.

Susceptibility zone	% of Eastern area of West Coast Region	% of Western area of West Coast Region	% of West Coast Region
Very low	5.72	27.20	19.45
Low	9.58	11.10	10.55
Moderate	18.09	11.61	13.95
High	32.62	25.83	28.28
Very high	34.00	24.26	27.78

Further analysis of the spatial characteristics of the map is useful to define the meanings of the zones. Table 4 shows the land area, landslide density and % of the land surface affected by landslides in each zone.

Table 4. Spatial characteristics of the landslide susceptibility zones.

Susceptibility zone	Area/km^2	Landslide density: number of landslides/10km^2	% of land surface affected by landslides
Very low	4302	0.0	0.003
Low	2334	0.3	0.012
Moderate	3085	0.6	0.056
High	6256	1.5	0.218
Very high	6145	3.8	0.513

2.4 Limitations of the landslide susceptibility model

By definition, a landslide susceptibility map does not define the temporal characteristics of the occurrence of landslides (Fell *et al.*, 2004) Since timeframe is an essential part of the risk equation, a susceptibility map should not be used for detailed risk assessments.

This is a regional scale study and should be used as such. The scale used for the initial landslide mapping was 1:25,000 so the susceptibility maps should be viewed at that scale. The minimum mapping unit in this study is the 25m x 25m pixel, so this mapping roughness should also be taken into account when using the susceptibility map.

This study models the landscape's susceptibility to rainfall triggered landslides. It does not delineate the areas that are more or less likely to experience land instability issues during an earthquake.

Any landslide susceptibility study has a certain level of uncertainty (Guzetti, *et al.*, 2006). Sources of uncertainty include:

- Errors and incompleteness in the landslide inventory
- Errors in the thematic factor maps
- Limitations in the technique chosen for the susceptibility analysis
- The inherent natural variability of the landslide phenomena

With regard to the sources of uncertainty, the introduced error derived from an incomplete landslide inventory is certainly an area of concern for this (and any landslide susceptibility) study. Due to the partial coverage of aerial photography for the region, the landslide inventory is incomplete. This will be true of all landslide susceptibility models, and must be taken into account when using the final map. The thematic factor maps are the best available, but due to scale and mapping roughness there may be errors introduced to the model from these sources.

This model has an accuracy that predicts 80% of the landslides in the top 40% of the susceptibility scores. However, the model can not claim to accurately delineate the probability of occurrence in each of the susceptibility zones.

As with any natural process, landslides do not occur with a regularity that enables complete prediction of their behaviour. This model should be used with this in mind.

3. The historic landslide catalogue

3.1 Methodology

An historical catalogue of 1643 landslides in the region was compiled from all the available sources as described in table 5. For all entries, x,y coordinate pairs were assigned and where possible, 24 hour preceding rainfall amounts were added for rainfall generated landslides and volume estimations made from the descriptions. In contrast to the landslide susceptibility map, which models the occurrence of landslides triggered by rainfall alone, the landslide catalogue details all landslides regardless of the trigger mechanism.

The catalogue can then be displayed in a GIS to be used in further classifying the landslide characteristics for a selected area. Interrogation of the catalogue can also be used to put a temporal dimension to the prediction of future landsliding in certain cases.

Table 5. Pre-existing landslide catalogues used in this study.

Study	Geographic area	Dates	Sub-sources	Comments
Smith, 2004.	Otira-Arthur's Pass to Jacksons on SH73. Taramakau valley-Jacksons to Greymouth on SH73 and SH6. Arnold and Grey valleys-Jacksons to Greymouth on Midland Railway line and SH7.	27/02/1918 to 19/02/2003	Transit NZ Ltd. Ministry of Works. Grey District Council. Transfield Ltd. Tranzrail Ltd. WCRC natural Hazards Review	Study area limited to the transportation corridors from Arthur's Pass to Greymouth.
Cooper, 2000.	Buller District.	1999	Buller District Council	No information on dates of failure, so simply shows a "snapshot" of observable landslides during the study period. Also, limited to personal observations by the author.
GNS landslide catalogue.	Nationwide, so covers the entirety of this study area.	12/08/1997 to 12/01/2009	National and local newspapers. Hazardwatch. National Radio. Original research	Limited to slides >1km^2. Not focused on infrastructure.

Study	Geographic area	Dates	Sub-sources	Comments
WCRC landslide archive.	West Coast Region	13/01/1945 to 29/07/2009	Benn, 1990. Benn, 1992. Patterson and Berrell, 1995. Greymouth Evening Sar. Westport News. Lowe, 2001. Fulton, 2004. Power and Anderson, 1992. The Press. Patterson and Bourne-Webb, 1994 Johnston, 1971 Buller District Council. Westland District Council. Grey District Council. Personal observations by WCRC Natural Hazards Analyst, M. Trayes.	Sporadic entries-some years missing. Essentially based on Benn's (1990) inventory, which was derived from a flood hazard study. Newspaper archives formed the bulk of Benn's (1990) study, which did not include the Westport News archives. Only recent entries from Westport News are included.
OPUS Consultants	West Coast Region, State Highway network	08/01/2004 to 17/11/2009	Roading Contractors	Data limited to date, location and volume of material transported away from the site. No description of trigger or actual movement characteristics.
OnTrack	West Coast Region, Railway Network: Midland line, Stillwater-Westport line, Rapahoe line, Hokitika Industrial line.	01/01/2005 to 11/01/2010	Locomotive Engineers, maintenance staff.	Results of a search of the OnTrack Incident Reporting System (IRIS) with landslide, slip and subsidence as keywords.

Further additions to this catalogue were accomplished by searching the archives of the Westport News at the Westport News offices in Westport, searching the archives of the Grey Star and the Hokitika Guardian at the Grey Star offices in Greymouth. Personally observed landslides were included wherever possible.

Each catalogue entry is identified by a unique identification number (ID number) and the following fields have been populated to give as complete a record of the landslide events as possible:

- Date. Essential for calculating magnitude/frequency relationships and temporal distribution patterns.
- Location. A descriptive term is included and the corresponding Easting and Northing was recorded to allow display in GIS. Where coordinate pairs were not recorded a search of the descriptive names of landslide locations on standard topographic maps, internet searches and local knowledge was used to assign coordinate pairs where possible. For entries concerning road and railway records the calculation of coordinates from Exact Road Positions (ERP) locations or Railway Miles locations was possible using the Calibrate Routes tool in ArcGIS toolbox.

- Description. A brief description of the landslide was included where the observer had recorded this. Unfortunately, this field is blank in many cases as the observer simply records the date, damage and location.
- Type. Slope movement classification was included where the description was adequate. In the interests of uniformity of terminology between studies, the classification system of Cruden and Varnes' (1998) was used and the abbreviations used in the catalogue are as follows:
  Rock fall (RF), Debris fall (DF), Earth fall (EF), Rock topple (RT), Debris topple (DT), Earth topple (ET), Rock slide (RS), Debris slide (DS), Earth slide (ES), Rock flow (RFL), Debris flow (DFL), Earth flow (EFL)
- Trigger information is recorded where possible and has been divided into rainfall generated (R), earthquake generated (EQ), erosion by river or coastal action (E), anthropogenically generated (A) and unknown (U).
- 24 hour rainfall amount was recorded for rainfall generated landslides. Rainfall records were obtained from the "Hilltop" meteorological database held and maintained by the WCRC. This database holds rainfall records from a network of gauges maintained and operated by the MetService, NIWA, WCRC and BDC. Records from 2 gauge stations owned and maintained by Solid Energy at Stockton were also used. Figures for the preceding 24hr period are presented. Database entries are generally by date only, with no time information, so a period of 12 noon on the preceding day to 12noon on the day of the landslide was used as the 24 hour rainfall figure. The gauge station closest to the landslide event was used regardless of prevailing wind and incident weather direction.
- EQ magnitude was recorded for earthquake generated landslides.
- Volume of slip material was estimated in cubic meters and recorded where possible.
- Additional comments were also recorded.
- Deaths. Where a landslide has resulted in death this has been recorded.
- Data source and sub-source has also been recorded. For example, if a record of a landslide was found in the Greymouth Evening Star and included in Smith's (2004) inventory it will be recorded as Greymouth Evening Star in "Source" and Emily Smith as the "Sub-source".

The resultant landslide catalogue is by far the most complete record of damaging landslides ever compiled for the West Coast region. This should be updated by the Natural Hazards Analyst at the WCRC and forwarded annually to all interested parties.

It can be used to illustrate the history and character of landslides for a selected area, or to give regional trends of landslide types, rainfall trigger levels, etc.

3.2 Limitations of the landslide catalogue

The landslide catalogue relies on reporting of incidents, so will be incomplete to varying degrees depending on the research efforts of the people who compile and maintain it.

Also, the reporting of landslide occurrences will often be carried out by people who are untrained in the observation of landslides, or who are reporting them for purposes other than landslide hazard management. For example, many of the landslides included in the landslide catalogue were taken from newspaper articles. These entries often do not contain volumes, landslide type, or other pertinent information. Similarly, a roading contractor who reports on a landslide may give a reasonable estimate of the volume and type of material, but almost certainly will not give an accurate description of the type of failure.

4. Use of these tools for landslide hazard management in the West Coast Region.

Broadly, the RMA requires for Regional and District Councils to identify and avoid or mitigate natural hazards via a self managed suite of policies, plans and building and land-use consent approval processes. The CDEMA supports these planning provisions and aims to build community resilience, through the implementation of the reduction, readiness, response and recovery (4R's) emergency management approach (Glavovic, 2010). When viewed as a whole, these legislative provisions and the hazard information contained in this study provide a solid practical, policy and legal foundation which will enable local government planners to avoid or mitigate landslide hazard risks and help build sustainable, hazard resilient communities in the West Coast Region. In addition to this, these tools can also be used by CDEM groups, lifelines providers, property developers and individuals to help make better informed decisions relating to landslide hazard management.

The landslide susceptibility map was generated in ARC GIS 9.3, so can easily be viewed on this platform. It is also possible to import the map into other display programs such as Map TV and Landscape, which are more widely used at the Councils. This is also true of the landslide catalogue which can additionally be explored as a database or spreadsheet.

The zones of the landslide susceptibility map range from very low to very high susceptibility to landslides. The quantification of these zones is achieved by assigning the zone boundaries such that a certain percentage of all landslides in the region are expected to occur in each zone. This is described in table 2. The spatial characteristics of these zones are described in table 4.

The landslide susceptibility zones, when used in combination with asset information held at the councils, will be useful in making land use change decisions. For example, different levels of hazard can be acceptable to various elements at risk depending on the consequences of a landslide occurring at a particular site (Saunders and Glassey, 2007). To classify buildings, in terms of elements at risk, a classification of Building Importance Category (BIC) is one option that can be used. The most appropriate system is the Australia/New Zealand Standard for Structural Design Actions, Part 0 General Principles (AS/NZS 1170.0:2002). This is illustrated in table 6. This classification does not cover roads, bridges, or other essential infrastructure, but these items could be placed into a BIC category based on the relative importance of the item in question.

Table 6. Building Importance Categories: a modified version of New Zealand Loading Standard classifications (AS/NZS 1170.0:2002). Taken from Saunders and Glassey, 2007.

Building Importance Category (BIC)	Description	Examples
1	Low consequence for loss of human life, or small or moderate economic, social, or environmental consequences.	Structures with a total floor area of less than 30m2 Farm buildings, isolated structures, towers in rural situations Fences, masts, walls, in-ground swimming pools
2a	Medium consequence for loss of human life, or considerable economic, social, or environmental consequences	Timber framed single-storey dwellings
2b	(As above)	Timber framed houses of plan area more than 300m2 Houses outside the scope of NZS3604 "Timber Framed Buildings" Multi-occupancy residential, commercial (including shops), industrial, office and retailing buildings designed to accommodate less than 5,000 people and also those less than 10,000m2 gross area. Public assembly buildings, theatres and cinemas of less than 1000m2 Car parking buildings

Building Importance Category (BIC)	Description	Examples
3	High consequence for loss of human life, or very great economic, social, or environmental consequences (affecting crowds)	Emergency medical and other emergency facilities not designated as post disaster facilities Buildings where more than 300 people can congregate in one area Buildings and facilities with primary school, secondary school or day care facilities with capacity greater than 250 Buildings and facilities with capacity greater than 500 for colleges or adult education facilities Health care facilities with a capacity of 50 or more residents but not having surgery or emergency treatment facilities Airport terminals, principal railway stations, with a capacity of more than 250 people Any occupancy with an occupancy load greater than 5,000 Power generating facilities, water treatment and waste water treatment facilities and other public utilities not included in Building Importance Category (BIC) 4 Buildings and facilities not included in BIC 4 containing hazardous materials capable of causing hazardous conditions that do not extend beyond the property boundaries
4	High consequence for loss of human life, or very great economic, social, or environmental consequences (post disaster functions)	Buildings and facilities designated as essential facilities Buildings and facilities with special post-disaster function Medical emergency or surgical facilities Emergency service facilities such as fire, police stations and emergency vehicle garages Utilities required as backup for buildings and facilities of importance level 4 Designated emergency shelters Designated emergency centres and ancillary facilities Buildings and facilities containing hazardous materials capable of causing hazardous conditions that extend beyond the property boundaries
5	Circumstances where reliability must be set on a case by case basis	Large dams, extreme hazard facilities

AS/NZS 1170.0:2002 outlines design criteria for the different BIC's based on a risk estimation procedure. Risk is defined as the combination of the likelihood (probability) of an event and the consequences (damages and/or loss of lives) of a particular hazard. Since the landslide susceptibility map explicitly does not take time frame into account it does not display probabilities, so can not be used for a detailed risk assessment. However, it can be used a guideline for potential new developments, or to highlight potential problem areas.

Table 7 (below) defines the susceptibility zones in terms of landslide potential. It also gives suggested actions. However, any regulations and rules to apply to each of the zones must be decided on by the Regional or District Councils, as this requires local knowledge of risk acceptance (tolerance) levels and will be a function of agreed local government policy.

Table 7. Meanings and suggested actions relating to the five landslide susceptibility zones.

Susceptibility zone	Meaning	Suggested action
Very low	Effectively free of landslide hazard	Building and other activities need not take landslide hazard into account
Low	Landslides occur infrequently and will be small and easily managed	Building and other activities need only consider landslides as a minor threat
Moderate	Landslides occur infrequently, but on rare occasions may be large enough to cause property damage	Landslide hazard should be considered when planning a development, but need not be a restrictive concern, except where the proposed activity has high consequence for loss of life. For example, BIC 3, 4 or 5
High	Damaging landslides occur occasionally and smaller landslides may be frequent	Building should be restricted to BIC 1 and 2a. A safe building site should be identified and mitigative measures designed by a suitably qualified person. Existing property owners in this zone should be notified of and educated about the hazard
Very high	Damaging landslides are common	Building should be restricted to BIC 1. Existing property owners in this zone should be notified of the landslide hazard and encouraged to take mitigative or avoidance actions

This landslide hazard information should be included in regional and district plans. Rules can be applied to each of the susceptibility zones to control various aspects of development in landslide-prone areas, including design, construction, location, usage and density. These rules need to relate to the avoidance or reduction of exposure to landslide hazard (Saunders and Glassey, 2007). It can also be used to guide the regional development plan to avoid the development of landslide prone land and encourage the use of land shown as very low or low susceptibility to landslides.

When viewing the landslide susceptibility map, it is also useful to view the landslide inventory layers. These display the outlines of the disturbed areas of all the rainfall triggered landslides that were used to construct the model, and the mapped outlines of the large landslides triggered by earthquake and other means.

The landslide catalogue, when displayed in a GIS, can be queried to display all the landslides that have occurred in a specific area. This is useful in the early stages of an investigation to characterise the types, frequency and damages caused by landslides in that area. Further analysis of these landslide data is then possible to give probabilities of occurrence, rainfall amount trigger levels, etc. for some areas.

The landslide susceptibility map and the landslide catalogue should be used as a “first pass” assessment of landslide potential for an area of interest. This may be enough to persuade a potential developer to look for an alternative site, or to consider modification of development plans. They can also be used as supporting evidence for expert based geotechnical investigations.

Other potential uses of the landslide catalogue and susceptibility map include:

- Selection of suitable positions of power poles for new electricity transmission lines
- Planning the routes and design considerations for other lifelines
- Civil defence planning for heavy rainfall events
- Backcountry activity risk assessments
- Preliminary guidance for new road alignment
- Guidance on other land use changes

References

Barringer, J.R.F., Pairman, D. and McNeill, S.J., 2002. Development of a high resolution digital elevation model for New Zealand. Landcare Research Contract Report: LC0102/170.

Benn, J.L., 2005. Landslide events on the West Coast, South Island, 1867-2002. New Zealand Geographer, 61: 3-13.

Bonham-Carter, G.F., 1994. Geographic information systems for geoscientists. Computer methods in the geosciences, 13. Pergamon, Ottawa.

Boroushaki, S. and Malczewski, J., 2008. Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS. Computers & Geosciences, 34(4): 399-410.

Chung, C.-J.F. and Fabbri, A.G., 2003. Validation of Spatial Prediction Models for Landslide Hazard Mapping. Natural Hazards, 30(3): 451-472.

Cruden, D.M. and Varnes, D.J., 1996. Landslide types and proesses, National Research Council, Washington DC.

Dahal, R. et al., 2008. GIS-based weights-of-evidence modelling of rainfall-induced landslides in small catchments for landslide susceptibility mapping. Environmental Geology, 54(2): 311-324.

Dai, F.C., Lee, C.F. and Ngai, Y.Y., 2002. Landslide risk assessment and management: an overview. Engineering Geology, 64: 65-87.

Dai, F.C., Lee, C.F. and Zhang, X.H., 2001. GIS based geo-environmental evaluation for urban land-use planning: a case study. Engineering Geology, 61: 257-271.

DTEC, 2002. West Coast Regional Council: Natural Hazards Review, Dtec Consulting.

England, K., 2011. A landslide susceptibility model for the West Coast Region, New Zealand. University of Canterbury Christchurch.

Fell, R. et al., 2008. Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology, 102(3-4): 85-98.

Frattini, P., Crosta, G. and Carrara, A., 2010. Techniques for evaluating the performance of landslide susceptibility models. Engineering Geology, 111(1-4): 62-72.

Glavovic, B., 2010. The role of land-use planning in disaster risk reduction:an introduction to perspectives frtom Australasia. Australasian Journal of Disaster and Trauma Studies, 1(1).

Gullà, G., Antronico, L., Iaquinta, P. and Terranova, O., 2008. Susceptibility and triggering scenarios at a regional scale for shallow landslides. Geomorphology, 99(1-4): 39-58.

Guzzetti, F., Reichenbach, P., Ardizzone, F., Cardinali, M. and Galli, M., 2006. Estimating the quality of landslide susceptibility models. Geomorphology, 81(1-2): 166-184.

Komac, M., 2004. A landslide susceptibility model using the Analytical Hierarchy Process method and multivariate statistics in perialpine Slovenia. Geomorphology, 74: 17-28.

Leathwick, J.R. et al., 2003. LENZ technical guide, Ministry for the Environment, Wellington.

Liu, Y.C. and Chen, C.S., 2003. A new approach for application of rock mass classification on rock slope stability assessment. Engineering Geology, 89: 129-143.

New Zealand Climate Change Office, 2002. New Zealand Land Cover Database 2. User Guide. Ministry for the Environment., Wellington.

Remondo, J. et al., 2003. Validation of Landslide Susceptibility Maps; Examples and Applications from a Case Study in Northern Spain. Natural Hazards, 30(3): 437-449.

Saaty, T.L., 1978. Modeling unstructured decision problems -- the theory of analytical hierarchies. Mathematics and Computers in Simulation, 20(3): 147-158.

Saunders, W. and Glassey, P., 2007. Guidelines for assessing planning, policy and consent requirements for landslide prone land. Institute of Geological and Nuclear Sciences., Wellington.

Smith, E., 2004. Mass movement hazard to infrastructure, Arthur's Pass to Greymouth. University of Canterbury, Christchurch.

Thompson, C.R., 2002. The High Intensity Rainfall Design System: HIRDS. In: NIWA (Editor), Wellington.

van Westen, C.J., Castellanos, E. and Kuriakose, S.L., 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102(3-4): 112-131.

van Westen, C.J., Rengers, N. and Soeters, R., 2003. Use of Geomorphological Information in Indirect Landslide Susceptibility Assessment. Natural Hazards, 30(3): 399-419.

Yalcin, A., 2008. GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey): Comparisons of results and confirmations. CATENA, 72(1): 1-12.

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Glossary

Hazard: The probability or likelihood of a potentially damaging event occurring in a unit of time. Often expressed as the probability of occurrence of a given magnitude of event.

Landslide catalogue: An historical list of landslides with dates and information relating to type of movement, size, damage caused, trigger, remedial measures in place, and any other pertinent information. Usually compiled from newspaper records, maintenance records, etc.

Landslide inventory: A spatial dataset of mapped landsides (often compiled from one trigger event), usually derived from aerial photograph interpretation (API), satellite image interpretation, and direct field mapping. Can also contain the same information types as a landslide catalogue.

Landslide susceptibility: A quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in a given area. Although it is anticipated that landsliding will be more frequent in the more susceptible areas, timeframe is explicitly not taken into account in a susceptibility analysis.

Raster: A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same value represent the same type of geographic feature.

Risk: A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by calculating the probability of an event of a given magnitude multiplied by the consequences.

Vector: A coordinate-based data model that represents geographic features as points, lines, and polygons. Each point feature is represented as a single coordinate pair, while line and polygon features are represented as ordered lists of vertices. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

Vulnerability: The degree of loss to a given entity within the area affected by a landslide. For property it will be expressed as the damage relative to the value of the property; for people it is expressed as the probability of loss of life.

Zoning: The division of land into homogeneous areas and their ranking according to degrees of actual or potential landslide susceptibility.

CD ROM containing:

- The landslide susceptibility map (ESRI grid file)
- Rainfall triggered landslide inventory (ESRI shape file)
- Inventory of large landslides triggered by earthquake and other sources (ESRI shape file)
- Landslide catalogue (ESRI shape file)
- Landslide catalogue (Microsoft Excel spreadsheet)