Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulder rolls)

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This report in draft form was independently reviewed by T. Taig, TTAC Limited and F.J. Baynes of Baynes Geologic Pty. Ltd. Internal GNS Science reviews of drafts were provided by T. Webb and G. Dellow. L. Richards reviewed early drafts.

Risk calculations were independently checked by M. Hunt, TTAC Limited.

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Maps in appendix G were updated in July 2013 to take into account new information relating to some of the areas covered by this report.

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EXECUTIVE SUMMARY

ES.1 Scope and purpose

GNS Science has been commissioned by Christchurch City Council to assess and report on slope-instability risk in the Port Hills following the deaths of five people from rockfalls and cliff collapse in the earthquakes of 22nd February 2011. This report is one of a series of reports on selected geographic areas where much damage occurred. It specifically presents assessments of the risk to life (death) faced by an individual living below rocky bluffs where life safety is threatened by the hazard of falling debris in the form of isolated boulders rolling and bouncing at high speed for long distances downslope. This risk is expressed as the annual individual fatality risk.

The presented annual individual fatality risk is the probability (likelihood) that a particular person will be killed by rockfall in any year at their place of residence. For most localities, this probability is an imprecisely determined, very small number and the report makes extensive use of the scientific number format of expressing risk in terms of powers of ten. For example the number 10^{-4} ("10 to the power of minus 4") is the fraction 1/10,000, and the decimal number 0.0001; it may also be expressed as 0.01%. The units of risk are dimensionless probability per unit of time and the units of annual fatality risk are probability of fatality (death or loss of life) per year. It is the power of ten, and not the number in front of the ten that is the significant digit in the reported risk assessment

The reported fatality-risks are obtained through a quantitative risk estimation method that follows appropriate parts of the Australian Geotechnical Society framework for landslide risk management (AGS, 2007). It provides risk estimates suitable for use under SA/SNZ ISO31000: 2009.

The purpose of quantitative risk assessment is to make the planning processes simpler and more effective for managing risk. It makes risks assessed for different hazards directly comparable, and able to be used in quantitative planning. Risk-based planning zones help inform decisions on development. Making decisions case by case in the absence of consistent, objective risk criteria is protracted, difficult and ineffective in managing risk.

The report considers both rockfalls triggered by earthquakes (taking into account expected changes in seismic activity in the Port Hills region over time), and by other rockfall-triggering events such as rainfall and spontaneous collapse. The report:

1) presents a suburb-scale analysis of rockfall-risk for the Port Hills suburban areas that were most affected by rolling boulders in 2011; and

2) estimates the annual individual fatality risk, i.e. the risk of death of an individual, in these suburbs from rockfalls.

The suburban areas covered in this report are Avoca Valley, Bowenvale, Cashmere, Castle Rock, Heathcote Valley, Hillsborough (Vernon Terrace only), Sumner (Wakefield Avenue and Heberden Avenue areas only), Lyttelton and Rapaki Bay. Some dwellings within these areas are also affected by other earthquake-triggered landslides; movement of these landslides have made some dwellings uninhabitable, but the landslides are not believed to pose an immediate fatality risk. Users of this report are reminded that it deals only with fatality risk from rockfall.

ES.2 Conclusions

1) Following the 4th September 2010 Darfield earthquake the levels of seismic activity in the Christchurch region are considerably higher than the long-term average, and are likely to remain enhanced for several decades. As a result the fatality risks from rockfall are now considerably higher than they were before September 2010. The risk from earthquake-induced rockfall is expected to decrease as the seismic hazard decreases.

2) It is feasible to estimate, quantitatively, the annual individual fatality risk from rockfalls triggered by earthquake and other non-seismic events, in the Port Hills area, albeit with uncertainty. A suburb-scale method has been presented that has been locally field verified.

3) This report provides information to support risk-based land-use decisions regarding the tolerability or otherwise of the annual individual fatality risk at dwellings in the Port Hills that are subject to the hazard of isolated boulders falling and rolling from the slopes above.

4) To take the time-varying seismic hazard into account, the next 1- and 50-year seismic hazard models (50 years being consistent with the design life used in typical seismic hazard analysis for residential building construction), have been compared in the risk calculations discussed in this report.

5) The number of dwellings exposed to a given annual individual fatality risk is very sensitive to the seismic hazard model used to estimate the annual frequencies of likely future ground accelerations.

6) When estimated using the 1-year seismic hazard model effective from the 1st January 2012, the annual individual fatality risk of a person residing in a residential property in any one of the Port Hills suburbs assessed in this report is significantly higher (by a factor of about 3 to 4) than when averaged over the next 50 years. The reduction in annual individual fatality risk over the next 10 years is not presented, because this reduction will depend on earthquakes that happen over the next 10 years.

7) The annual individual fatality risks from rockfalls triggered by non-seismic events have also been included in the risk analysis.

8) A range of risk parameters was tested to determine model sensitivity to the selected parameters. A model using reasonable input parameters and based on a seismic hazard model applicable for the next year was used in the preparation of risk maps. This model takes into account the currently elevated seismic hazard, and will become less vulnerable to other uncertainties when the seismic risk declines.

9) The results from the suburb-scale assessment were checked in the field to the extent possible by appropriately qualified members of the Port Hills Geotechnical Group of consultants. Each dwelling within the areas covered by this risk assessment has been visited and the risk maps accompanying this report take account of the results of these

visits.

10) Using the revised "field verified" risk maps there are about 554 dwellings (including those classified as "unknown") located in the annual individual fatality risk zones. On the final field verified maps (shown in Appendix G), about 192 dwellings expose people to annual individual fatality risks estimated to be greater than 10^{-3}/year, 223 expose people to risks between 10^{-3} and 10^{-4}/year, 105 expose people to risks between 10^{-4} and 10^{-5}/year and 34 expose people to risks less than 10^{-5}/year.

ES.3 Suggested Council Actions

Once Christchuch City Council has decided what levels of individual fatality risk will be regarded as tolerable and how Council will manage risk on land where fatality risk is assessed to be at various levels of intolerability, it is suggested that:

1) Council accepts the information regarding annual individual fatality risk from rolling boulders presented in this report;
2) Council uses the information in reaching decisions about future risk management for rockfall-affected dwellings in the Port Hills;
3) Council monitors performance of the fatality risk model by continuing to monitor the state of the catchments (where the rockfalls originate) above dwellings, in particular identifying any new rockfalls indicating the instability of the source areas; and
4) Council re-evaluates the fatality risks after a period of 10 years, to incorporate a seismic hazard model appropriate to the knowledge of that time, and incorporating knowledge about the post-2011 performance of rockfall sources in the Port Hills.

ES.4 Method Used

The methods adopted to achieve the results in this report are based on the Australian Geomechanics Society (AGS) 2007 landslide risk management framework summarised in Fig ES.1. The risk assessment comprised the following steps:

1) Consideration of the full possible range of rockfall-triggering events, e.g. earthquakes, rain, following the method of Moon et al. (2005) in terms of: a) a set of earthquake triggers; and b) a set of "other" triggers;
2) Selection of a small set of representative events for each type of trigger spanning the range of severity of events from the smallest to the largest;
3) Estimation, for each representative event, of:
    a) the frequency of the event and the numbers of boulders produced
    b) the proportion of boulders reaching/passing a given distance down the slope and the probability of a person at that distance finding themselves in the path of one or more boulders
    c) the probability that a person is present in the path of a boulder as the boulder reaches them
    d) the probability that a person will be killed if present in the path of a boulder;
4) Combination of 3(a) – (d) to estimate the annual individual fatality risk for individuals at

different distances downslope (from a rockfall source) contributed by each representative event;

5) Summation of the risks from all events to estimate the overall risk;
6) Two dimensional numerical rockfall modelling using the Rocscience® Rocfall™ programme. This was carried out to determine the likely distances rockfalls travel (runout) down a slope and was used to define the limits of rockfall runout;
7) Field verification (ground truthing) of the analysis results by the Port Hills Geotechnical Group; and
8) Updating of the risk analysis maps with the results from the field verification and two dimensional rockfall modelling.

The key steps (1) to (3) are briefly explained in sections ES.4.1 to ES.4.3.

ES.4.1 Range of Triggering Events

Evidence gathered on rockfalls from the 2010/2011 Canterbury earthquakes in the Port Hills area provide substantial data on the numbers of boulders generated by different amounts of ground shaking. GNS Science, the Earthquake Commission and various geotechnical consultants who have worked in the Port Hills area have 10–20 years of detailed data on boulders produced from non-earthquake events (severe rainfall, and weathering, for example). Historical accounts and geomorphological evidence indicate rare events that have been at least as large as those experienced in 2011. These include accounts of previous large rockfalls and observations of prehistoric boulder clusters and talus slopes in the area. The adopted method of modelling represents all earthquake triggers of rockfall by considering a representative earthquake from each of four bands of ground-shaking severity: <0.4 g, 0.4–1 g, 1–2 g and >2 g. It represents all non-earthquake rockfall triggers by considering other events (e.g. storms) with progressively increasing return periods: 0-15 years, 15–100 years, 100–1000 years and >1000 years.

ES.4.2 Number of Boulders and Event Frequencies

For earthquake triggers, the estimated likelihood (average annual frequency over the next 1 year or next 50 years) of a given earthquake occurring were derived from a composite national seismic hazard model which includes the increased level of seismicity following the 22nd February 2011 Christchurch earthquake. The numbers of boulders produced from sources in each of the assessed areas were estimated for earthquakes using the mapped boulders that fell during the 4th September 2010 Darfield, 22nd February, 16th April and 13th June 2011 earthquakes, and for storms using historic and prehistoric data. The 23rd December 2011 earthquake occurred subsequent to the reported analysis, but served to verify the predicted outcome.

The 2010-2012 major earthquake sequence has caused the rock masses forming the rockfall source areas to become more broken, open and dilated and therefore more susceptible to both earthquake and non-earthquake triggering events. It is therefore highly likely that future rates of rockfall accumulation from non-earthquake events will be significantly elevated above the observed historical levels, at least over the next 20–30 years.

ES.4.3 Consequences of Rockfall

The size distributions of the rockfalls, and how far they travelled from their sources, were estimated using sizes and locations of 5,700 of the boulders generated by the 22nd February 2011 earthquakes in the areas of interest. The proportion of boulders that travelled a given distance downhill decreases with distance from the source area. The proportions of boulders reaching a given distance downslope were calculated for each suburban valley side, using data specific to that area.

The probability of a person present being killed in a rockfall is estimated by:

1) calculating the probability that they will be in the path of one or more boulders for a given rockfall event at a given distance downslope, assuming that boulder sources are uniformly distributed along the hill slope in the suburb in question (that is that boulders can fall from anywhere on the slopes above the suburban dwellings);
2) the proportion of time a person spends in their home (residency); and
3) the probability the person being injured if present and hit by a boulder (vulnerability).

The modelled risk has assumed 100% home residency, and 50% personal vulnerability if hit by a rockfall. These assumptions are identical in effect to assuming 50% residency in combination with 100% vulnerability, or any combination of the two whose product is 0.5.

ES.5 Uncertainties

The major uncertainties in the model inputs have been noted and their likely implications for risk have been investigated. The most important uncertainties relate to: 1) the frequency with which a given earthquake is to be expected; 2) the proportion of boulders that will travel substantial distances downslope; and 3) the assumption that on a given suburban hillside the numbers of passing boulders, and thus the risk of being hit by one, is uniform along the slope and not concentrated at certain localities. It is also possible that the future frequency of rockfalls triggered by events other than earthquakes will be higher than those previously experienced, because the recent earthquakes may have made the rockfall source areas more unstable.

In the absence of observed fatalities in the areas assessed within this report, confidence in the fatality-risk model to reliably predict personal rockfall risk has been obtained by comparing observed and calculated numbers of houses hit by rolling boulders in the 22nd February 2011 earthquakes.

The expected confidence limits on the assessed risk levels are estimated to be an order of magnitude (higher or lower), in terms of the absolute risk levels presented in this report. That is, an assessed risk of 10^{-4} per year is not likely to be more than 10^{-3} per year or less than 10^{-5} per year.

ES.6 Acknowledgment

This work for Christchurch City Council was carried out by GNS Science, assisted by the Port Hills Geotechnical Group, and University of Canterbury staff and students. Data collection and analysis was funded in part by the New Zealand Natural Hazards Platform.

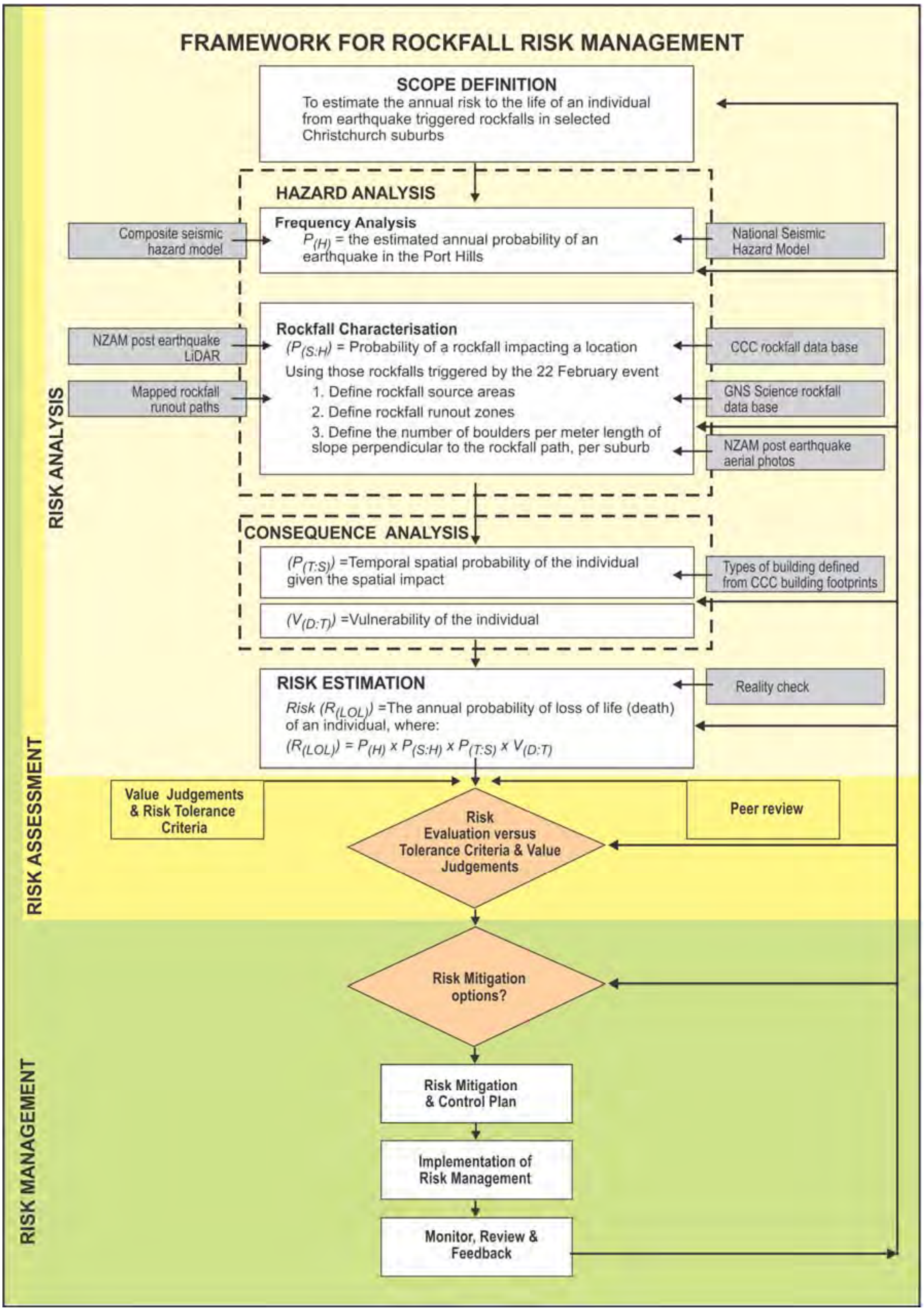

Figure ES.1 Framework used to assess the annual probability of loss of life (death) of an individual from rockfalls in the Port Hills that were triggered by the 22^{nd} February 2011earthquakes. Modified after AGS (2007) *Guidelines for landslide risk management*.

1.0 INTRODUCTION

GNS Science has been commissioned by Christchurch City Council to assess and report on slope-instability risk in the Port Hills following the deaths of five people from rockfall in the earthquakes of 22nd February 2011. This report, which is one of a series of reports on selected areas where much damage occurred, specifically presents assessments of the risk to life (life-threatening injury or death) faced by an individual living below rocky bluffs where life safety is threatened by the hazard of falling debris in the form of isolated boulders rolling and bouncing at high speed down slope. The areas covered in this report are Avoca Valley, Bowenvale, Cashmere, Castle Rock, Heathcote Valley, Hillsborough (Vernon Terrace only), Sumner (Wakefield Avenue and Heberden Avenue areas only), Lyttelton and Rapaki Bay.

The main M_w6.2 earthquake on the 22nd February occurred at 12:51 pm New Zealand Daylight Time, when many people were not at home. Of the people killed by falling rock, two were killed while walking on park tracks in the Port Hills, and three were killed on residential land (one died in their home, one died in their garden, and the other died at a construction site). It is uncertain how many of these people died from rockfalls triggered by the main earthquake, but one is known to have died in a later earthquake on the same day.

For this study of rockfall risk more than 5000 individual fallen boulders were mapped among approximately 800 dwellings causing severe damage to many homes (Figure 1) — 65 homes were struck by rockfalls and 29 were penetrated by boulders typically of a metre or greater in maximum dimension. None of the people killed were in the homes included in this study.

Since the 22nd February 2011 earthquakes, several other earthquakes have triggered widespread rockfalls in the Port Hills, including earthquakes on 16th April, 13th June, and 23rd December 2011. Many other earthquakes have been recorded; however, in most cases these triggered only a few rockfalls that affected only a small number of sites. The rockfalls triggered by the 22nd February 2011 earthquakes, however, were the most widespread and numerous.

Many features of the ground-shaking in the Christchurch earthquakes have not been seen in New Zealand in previous earthquakes, and are rare internationally. The most notable is the exceptionally high ground accelerations—in particular the high acceleration of the ground vertically may be responsible for the large number of rockfalls in the Port Hills. Both internationally and in New Zealand, vertical ground accelerations are not usually factored into models for determining earthquake hazards. For these reasons, there is limited information from elsewhere that can be applied to the Port Hills.

This report provides a suburb-scale (overview) assessment of the average fatality risk to individuals from average rockfalls. It does not assess the risk of damage to critical infrastructure, nor does it assess the particular risks to particular people at particular places such as roads and right-of-ways.

A) B)

Figure 1 Rockfall damage to residential homes, A) Rapaki Bay and B) Morgan's Valley, Heathcote. This rockfall damage occurred in the main 22nd February 2011 earthquake.

1.1 Aims and objectives

The objectives of this work are to:

1) Undertake a suburb-scale rockfall life-safety risk assessment for those Port Hills suburbs where many dangerous-building notices have been issued to dwellings affected by rockfalls (use of the home is prohibited under the Building Act until the building is no longer dangerous); and
2) Estimate the annual fatality risk to an individual (herein fatality risk is assumed to include life-threatening injury) in these areas from rockfalls triggered by earthquakes and compare these to risks of rockfalls from other events (such as rainfall).

This work was undertaken in conjunction with field inspections and rockfall remediation work carried out by the Port Hills Geotechnical Group. The Port Hills Geotechnical Group is a consortium of geotechnical engineers contracted to Christchurch City Council to assess slope instability in the Port Hills.

Analysis of risk is based largely on data collected from the rockfalls triggered by the 22nd February 2011 earthquakes. The analysis is therefore not able to identify any of the effects the various forms of rockfall mitigation that were in place on that date. Remediation work undertaken since 22nd February 2011 was not able to be considered in the analyses presented here, because no effect of the initial remediation for life safety is identifiable in the available database.

The report uses information gathered from the following suburban areas, where the majority of the dangerous-building notices related to rockfall risk were posted: Avoca Valley, Bowenvale, Cashmere, Castle Rock, Heathcote Valley, Hillsborough (Vernon Terrace), Sumner (Wakefield and Heberden Avenues), Lyttelton and Rapaki Bay. No areas beyond these are covered in this report.

1.2 Rockfalls (boulder rolls)

A rockfall is the individual fall of a loose rock (boulder) from a steep slope (following Cruden and Varnes, 1996). The boulder starts by sliding, toppling or falling before descending the slope very rapidly to extremely rapidly (> 5 m/sec) by any combination of falling, bouncing and rolling. Rockfalls (sometimes referred to as "boulder rolls") are here considered separately from the other rock-slope failures (debris avalanches and blockslides) triggered by the recent Canterbury earthquakes. In part, this is because rockfalls tend to travel further from their source areas along less predictable paths and also because the displaced rock material consists of one or a few boulders that follow separate paths, rather than a mass of countless boulders travelling one path. Mostly, they are treated separately because the data collected about them are different (Figure 2); the position, and size of every rock-fall boulder was recorded, but it was impossible to record the position and size of every boulder in the debris avalanches.

Figure 2 Illustration of the difference between debris avalanches caused by cliff collapse (left at Raekura Place, Redcliffs) and rockfall (boulder roll) (right at Rapaki Bay). The large boulder in the foreground of the Rapaki view fell from the peak (Rapaki) in the background, passed through the home in the mid-ground, and came to rest on the foreground road, 60 m from the house. These landslides occurred in the main 22nd February 2011 earthquake. Photographs taken by G Hancox (left); D Barrell (right), GNS Science.

1.3 Geology and slopes of the areas affected by rockfalls

Rockfalls triggered by earthquakes on 22nd February 2011 affected a region of about 65 km^2, extending from Mount Pleasant in the north to Lyttelton in the south, and from Godley Head in the east to Governors Bay in the west (Hancox et al., 2011) (Figure 3). This covers much of the area referred to as the Port Hills. Most, but not all of the rockfalls were triggered by the main shock.

The Port Hills are the northern sector of the eroded extinct Lyttelton basalt volcano, comprising five overlapping volcanic cones (Hampton, 2010). The rocks forming the 400–500 m high ridge, slopes, and sea cliffs of the Port Hills (Summit Road, Sumner and

Redcliffs areas) belong to the Lyttelton Volcanics Group rocks of late Tertiary (Miocene) age, and are about 10–12 million years old (Forsyth et al., 2008). These volcanic rocks consist of layers of hard, jointed, basaltic and trachytic lava flows cut by numerous intruded dykes, and interbedded with breccia (scoria), agglomerate (coarse angular gravel), compact sandy tuff (ash) beds, and ancient buried soils. The volcanic rocks are mantled by soils derived from wind-blown sand and silt (loess) typically about 1 m thick and locally more than 5 m thick. The lava flows and dykes in the Lyttelton area are strong, and the interbedded scoria, tuff and ancient soils are softer but compact. Lava flows in the Lyttelton area are closely and irregularly cracked by cooling joints, forming blocky rock masses that episodically release blocks of rock that roll downhill and accumulate as talus (scree) at the base of slopes. Many natural slopes around Lyttelton Harbour are formed on strong interbedded lava flows and stand at steep angles, forming cliffs on many coastal slopes (such as those around Diamond Harbour and Quail Island).

The steep coastal cliffs of Lyttelton harbour and the outer coast extend inland into the suburbs from Sumner to Redcliffs. In these suburbs the cliffs are no longer being actively cut by the sea, and the cliffs furthest inland may not have been affected by wave action for the past ~9,000 years (Brown and Weeber, 1992). These steep (~75–85°) cliffs are typically 15 to 30 m high and locally up to ~70 m high. Old sea cliffs and the talus at their bases were locally modified by quarrying up until the early 1900s to construct, among other things, the causeway across McCormacks Bay.

Slopes on the northern and southern sides of the Summit Road ridge north of Lyttelton, which extends from Mount Pleasant (499 m Above Mean Sea Level, AMSL) at the eastern end near Evans Pass, to Marley's Hill (502 m AMSL) at the western end near Dyers Pass Road, are classified as steep to very steep. The upper slopes near the ridge crest are very steep to near vertical (~50–75°) in places and extend 500 to 1,500 m down steep (~30–35°) and moderately steep (~20–30°) slopes to the urban areas of Lyttelton, Cass and Rapaki Bay and the northern shore of Lyttelton Harbour.

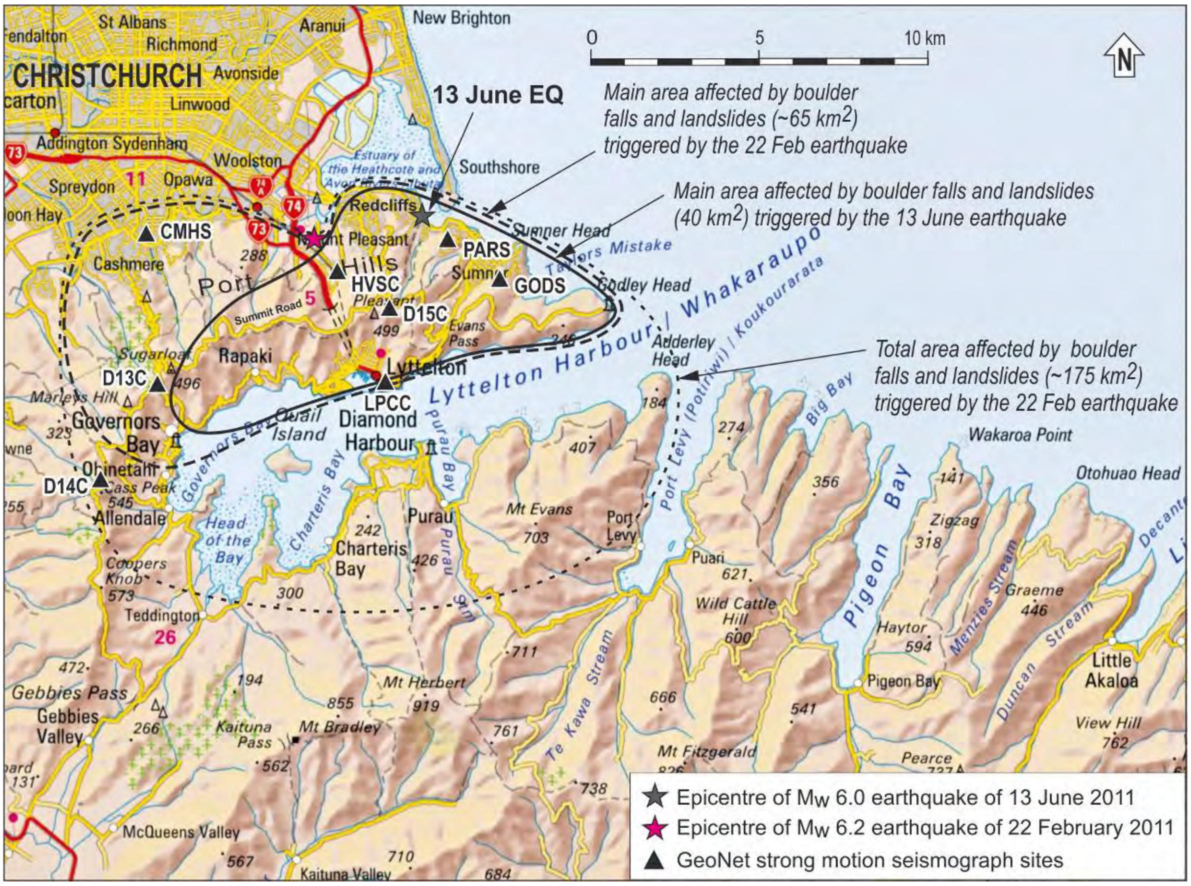

Figure 3 Location map showing the area affected by rockfalls triggered by the 2010/2011 Canterbury earthquakes (modified after Hancox et al., 2011).

1.4 The 2010/2011 Canterbury earthquakes

The 2010/2011 Canterbury earthquakes that have affected the Port Hills and the resulting types of slope instability are summarised in Table 1. Of these, the 22nd February and 13th June 2011 earthquakes caused the most widespread damage with respect to the numbers of rockfalls triggered and areas affected. For a detailed description of the 2010/2011 Canterbury earthquakes refer to Webb et al. (2011). The severity of earthquakes is generally reported in terms of a magnitude, which is related to the energy released. However, of much greater importance in terms of damage to buildings or in particular (in this case) to cliffs and rock outcrops, is the shaking intensity (ground motion) felt at the surface.

The most commonly used measures of a particular ground motion are: a) Modified Mercalli Intensity (MMI[1]), an indirect measure of the effects of the earthquake on a scale from I (not felt) to XII (total destruction); and b) the peak horizontal acceleration (typically referred to simply as the peak ground acceleration or PGA), measured by strong motion instruments. However, the recent earthquakes have been notable for their high peak vertical accelerations, which have in the past received less attention in earthquake engineering than

[1] Modified Mercalli Intensity scale (MMI) is a measure of how ground shaking from an earthquake is perceived by people and how it affects the built environment at a particular location. In any given large earthquake, the Mercalli Intensity will depend on the location of the observer and will usually be greatest nearer to the earthquake source and diminish with distance away from it. This information is complementary to magnitude estimates, which describe the energy released at the earthquake source, rather than the ground shaking.

horizontal accelerations (Kramer, 1996). Typical scientific units used to express ground acceleration are either metres per second per second (m/s/s) or as a proportion of gravity, where the acceleration due to gravity is equal to 9.81 m/s/s (therefore 3.4 m/s/s is about 0.35 g).

In this study, measured peak ground acceleration has been used to characterise ground shaking. It is assumed that rockfalls require an instantaneous force exceeding a critical value to trigger them, rather than the multiple accelerations associated with longer duration shaking. These peak ground accelerations have been obtained from particular sites and are used only as an index of the likely accelerations experienced by the ground at the sources of the rockfalls. That is, the study assumes that when for example the Heathcote Valley Primary Schools strong-motion recorded experiences its maximum peak ground acceleration, nearby rockfall source areas also experience their maximum peak ground accelerations.

Although in this study, each earthquake has been characterised by a single peak ground acceleration value at a measurement site, in reality, the ground acceleration at that site is constantly changing, both in magnitude and direction, throughout the earthquake. It is impossible after the event to determine precisely when each rockfall initiated and so there is no means by which to determine either the magnitude or direction of each rockfall triggering ground acceleration. This is the reason for choosing a single-value index—peak ground acceleration. Because peak ground acceleration is used as an index of ground acceleration, and initial boulder acceleration, the terms *peak ground acceleration*, *PGA*, *ground acceleration*, and *acceleration* are used interchangeably in this report to assist readability where no confusion can arise.

Table 1 Summary of the 2010/2011 Canterbury earthquakes and their measured peak ground accelerations (PGA) from accelerometers located in the Port Hills, for the main earthquakes that have triggered rockfalls, cliff collapses and landslides. The listed stations are GeoNet strong-motion recording sites: CMHS - Cashmere High School; GODS - Godley Drive, Sumner; HVSC - Heathcote Valley Primary School; LPCC - Lyttelton Port Company; PARS - Panorama Road, Sumner (for locations see Figure 3).

Date (NZ time)	Magnitude	PGA horizontal[1] (g)	PGA vertical (g)	Strong motion station	Slope instability in Port Hills
4/09/2010 Darfield earthquake	7.1 (M_W)	0.3	0.3	CMHS	A few localised rockfalls and cliff collapses
		0.6	0.0	HVSC	
22/02/2011	6.2 (M_W)	0.5	0.9	CMHS	Many rockfalls, cliff collapses and landslides occurred widely in the Port Hills
		2.1	2.2	HVSC	
		1.3	0.5	LPCC	
16/04/2011	5.3 (M_L)	0.2	0.1	CMHS	Some localised rockfalls and cliff collapses
		0.8	0.4	PARS	
		0.2	0.1	LPCC	
13/06/2011	6.2 (M_W)	2.2	1.1	GODS	Rockfalls, cliff collapses and

Date (NZ time)	Magnitude	PGA horizontal[1] (g)	PGA vertical (g)	Strong motion station	Slope instability in Port Hills
		1.0	0.7	PARS	landslides in many areas of the Port Hills
		0.4	0.1	LPCC	

[1]Calculated from the maximum vector of both horizontal components

1.4.1 The 22nd February 2011 earthquake

The M_w[2]6.2 Christchurch earthquake of 22nd February 2011 was part of the aftershock sequence of the M_w7.1 Darfield earthquake of 4th September 2010 (Berryman, 2011) (Figure 4). The M_w6.2 earthquake occurred at 12:51 pm (UT + 13 hours), when about 50,000 people were in the inner city area and where 176 fatalities resulted from building failures. A further 5 fatalities occurred in the Port Hills area as result of rockfalls and cliff collapses.

The M_w6.2 22nd February 2011 earthquake was by far the most destructive of the 2010/2011 Canterbury earthquakes, with severe ground shaking occurring over much of the city. The earthquake occurred on a northeast-southwest oriented fault at shallow depth (Webb et al., 2011). Slip along the fault reached within ~1 km of the surface but did not break the surface. This fault was unknown prior to the 4th September 2010 Darfield earthquake, but had been marked by aftershock activity in the months prior to the Christchurch earthquake. The faulting movement for this earthquake was oblique-reverse (a combination of right-lateral strike-slip and thrust faulting) (Webb et al., 2011).

The main 22nd February 2011 earthquake was followed within the hour by a large aftershock that also triggered rockfalls. Rockfalls from earthquakes on 22nd February 2011 could not be differentiated, and have been treated in this report as if they all fell in the mainshock.

[2] Moment magnitude (M_w) is a measure of the final displacement of a fault after an earthquake. It is proportional to the average slip on the fault times the fault area. M_w is more complicated to determine than M_L (Richter magnitude), but is much more accurate, although the standard methods used to determine it are valid only for larger earthquakes (~M_w>4.0). M_w is a rough proxy for the amount of low-frequency energy radiated by an earthquake and is commonly used worldwide to characterise large earthquakes.

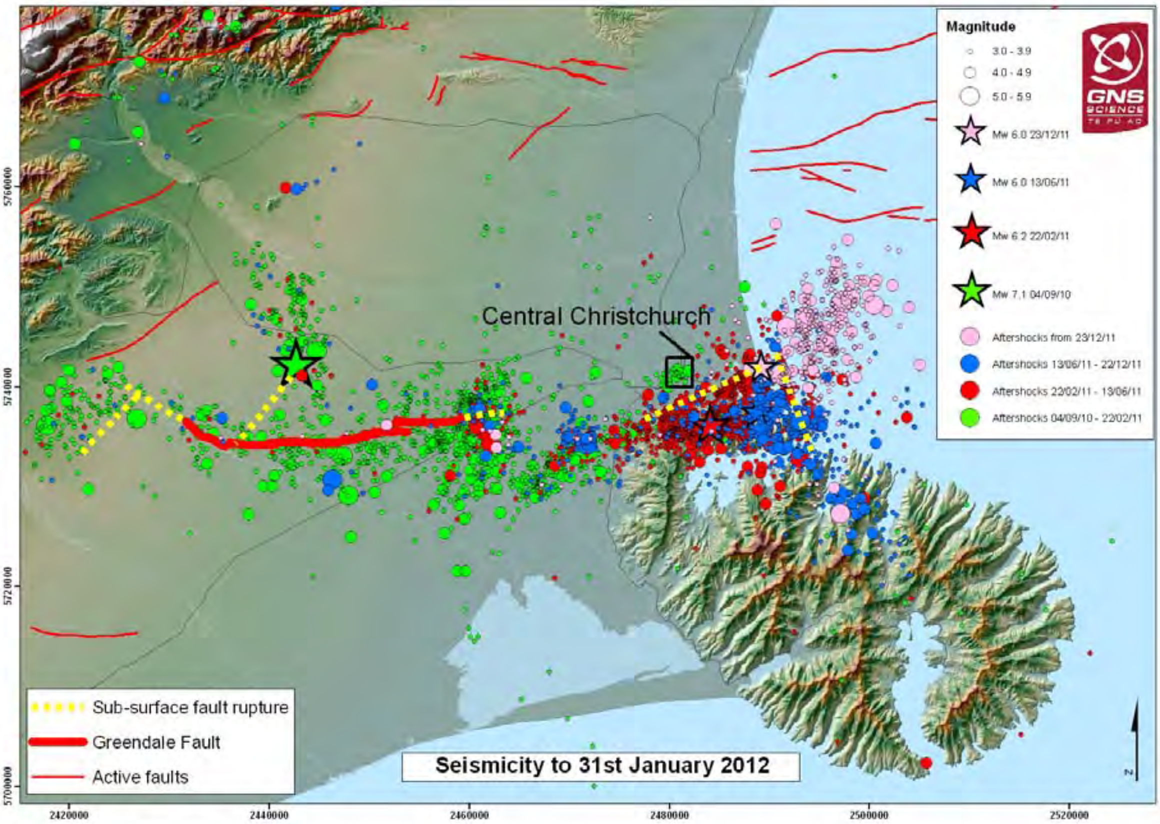

Figure 4 Sequence of aftershocks from the Darfield earthquake on 4th September 2010 up to 31st January 2012.

Ground accelerations in the main 22nd February 2011 earthquake were recorded at three strong-motion sites in the Port Hills (Figure 3); these sites are part of the GeoNet monitoring network. The peak (horizontal) ground accelerations recorded at these strong-motion recording sites (Cashmere High School (CMHS); Lyttelton Port Company (LPCC) and Heathcote Valley Primary School (HVSC), Figure 3) range from 0.5 g to 2.1 g (Table 2).

The 22nd February 2011 Christchurch earthquake and many of its aftershocks are notable in having unusually high peak vertical ground accelerations (Table 2 and Figure 5). The large vertical accelerations may be an additional reason why so many rockfalls were triggered by this earthquake, as rocks would have been thrown upward and outward from their source areas.

Table 2 Summary of strong motion records from GeoNet accelerometers located in the Port Hills for the earthquake at 12:51 pm on 22nd February 2011: CMHS - Cashmere High School, HVSC - Heathcote Valley Primary School, LPCC - Lyttelton Port Company (for locations see Figure 3).

Station	Peak horizontal acceleration (maximum vector of both horizontal components) (g)	Peak vertical acceleration (g)	Site Class (NZS1170)
CMHS	0.5	0.9	D (deep spoil)
HVSC	2.1	2.2	C (shallow soil)
LPCC	1.3	0.5	B (weak rock)

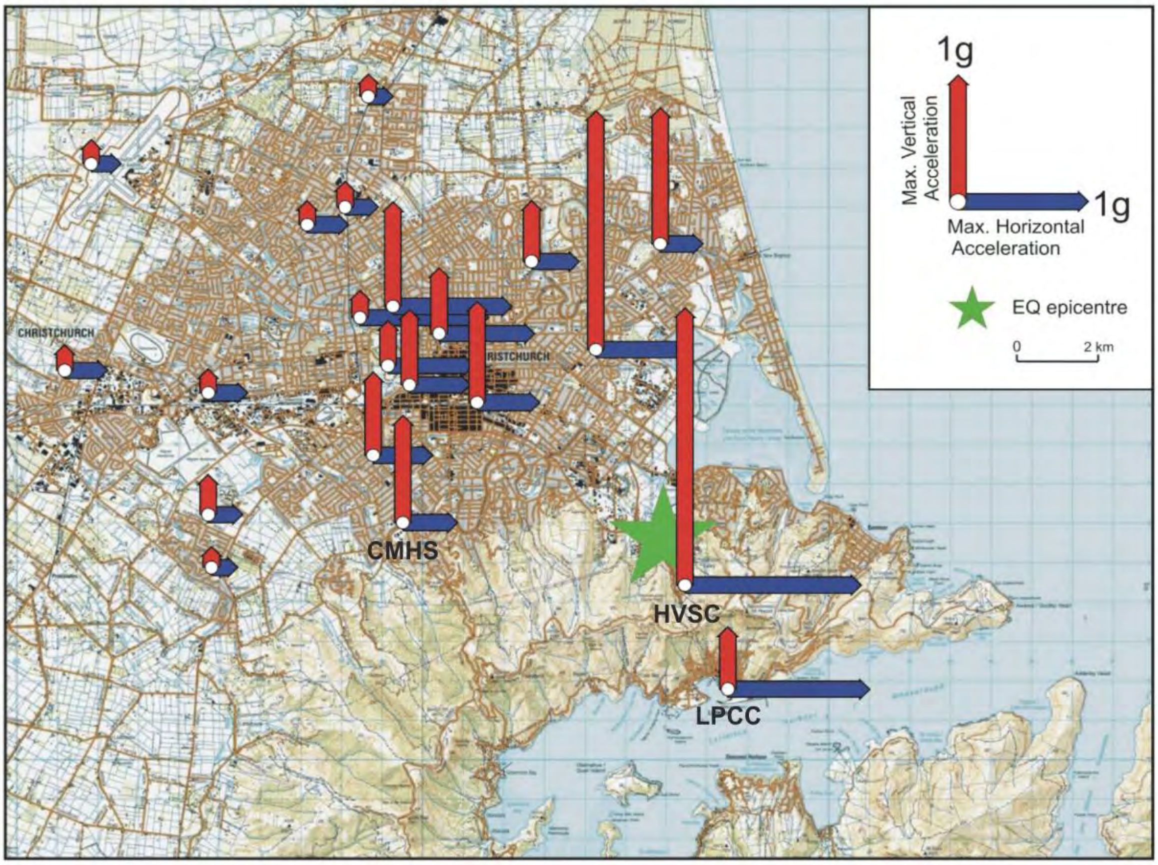

Figure 5 Maximum horizontal (single component only) and peak vertical ground accelerations recorded during the M_w6.2 22nd February 2011 earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network). Note: the arrows are not vectors and indicate component magnitudes but not direction.

A number of factors are thought to have contributed to the high accelerations experienced in Christchurch city during the main 22nd February 2011 earthquake (Fry et al., 2011; Reyners, 2011). Firstly, because the earthquake was close to the city and at a shallow depth, ground shaking was high compared to the 4th September 2010 Darfield earthquake, as the energy of seismic waves reduces very rapidly away from where the fault rupture occurred. Secondly, the energy magnitude (M_e)[3] of the Christchurch earthquake was 6.75 (compared to the Richter magnitude (M_L)[4] of 6.2), indicating that, like the 4th September 2010 Darfield earthquake, this was a high stress drop earthquake (stress drop is a measure of the energy released in relation to the rupture size—i.e. the sudden reduction of stress across a fault

[3] Energy magnitude (M_e) is a measure of the amount of energy released in an earthquake, so it is very useful for determining the potential of an earthquake to cause damage. M_e is determined from the amplitude of all frequencies of seismic waves as measured on seismographs (as opposed to just the peak amplitude used to determine the Richter magnitude M_L). It thus contains more information about the overall energy released in an earthquake and hence its destructive power.

[4] Richter magnitude (M_L) is the initial magnitude assigned to an earthquake with routine GeoNet processing. The GeoNet M_L is a modification of the original magnitude scale defined by C.F. Richter in 1935. M_L is derived from measurements of the peak amplitude on seismographs and is thus a preliminary estimate of the amount of energy released by the earthquake. It is measured on a logarithmic scale, so each magnitude increment of 1 represents an order of magnitude increase in the measured amplitude or about 30 times more energy released.

during rupture). This earthquake thus radiated more energy than average for an earthquake of this size. Thirdly, seismological and geodetic modelling shows that the maximum fault displacement was shallow and the direction of rupture was in a north-westward direction and upwards towards Christchurch city. Therefore stacking of energy in the direction of earthquake rupture (or directivity effects) is likely to have further enhanced ground motions within 10 km of the fault (Webb et al., 2011).

Other site-, basin- and topographical-effects will also have contributed to the strong ground shaking in Christchurch. Of particular note was that vertical accelerations were greater than horizontal accelerations near the fault source (Figure 5). As noted above, this can be partly attributed to the rupture directivity, but local site conditions are also thought to contribute. The local site condition effects are shown by the striking differences in the frequency characteristics of seismic waves in the horizontal and vertical directions were observed at many Christchurch stations. Vertical accelerations near the fault were high in high-frequency (short period) energy, in marked contrast to the dominant lower frequency energy (longer period) generally observed for the horizontal components. In addition, a 'trampoline' effect involving complex behaviour of near-surface unconsolidated soil may have increased accelerations in the 'upwards' direction at stations near the fault source (Fry et al., 2011). This effect has only previously been observed in a small number of earthquakes worldwide with very large accelerations (e.g. Aoi et al., 2008; Yamada et al., 2009; Webb et al., 2011).

1.4.2 13th June 2011 earthquake

The epicentre of the M_W6.0 earthquake on 13th June 2011 was located close to the eastern suburb of Sumner (Figure 4). The 13th June earthquake was preceded about an hour before by a significant M_L5.7 foreshock in a similar location.

The effects of the earthquake were most strongly felt in the southern and eastern suburbs, where Modified Mercalli Intensities were above MM8. Further damage to vulnerable structures occurred in the Central Business District (CBD), and there were further cliff collapses and rockfalls on slopes in the southern Port Hills. Liquefaction was once again widespread in the southern and eastern suburbs. As in the main 22nd February 2011 earthquake, accelerations in Christchurch were again very high during the 13th June 2011 earthquake (Table 3), reaching 2 g in Sumner and 0.4 g in the CBD (Figure 6). The energy magnitude (M_e) of 6.7 indicates that energy released during the 13th June 2011 earthquake was again high, as in the 4th September 2010 and 22nd February 2011 earthquakes, indicating a high stress drop and the radiation of higher-than-average levels of seismic energy. In contrast to the high vertical accelerations during the 22nd February 2011 earthquake, horizontal accelerations were dominant in the 13th June 2011 earthquake, particularly near the source fault in the Port Hills (Figure 6). It is likely that the different fault movement of the two earthquakes (strike-slip in June; oblique-reverse in February) contributed to the differences in the dominant acceleration directions. The extremely high accelerations at the Sumner station on Godley Drive (GODS, which is on rock) may also have been influenced by a degree of amplification of seismic waves due to the shape of the topography at the surface (Webb et al., 2011).

Table 3 Summary of strong motion records from GeoNet accelerometers located in the Port Hills for the 13th June 2011 earthquake. The listed stations are GeoNet strong-motion recording sites: CMHS - Cashmere High School, HVSC - Heathcote Valley Primary School, LPCC - Lyttelton Port Company, PARS - Panorama Road, Sumner, GODS - Godley Drive, Sumner; and D15C (for locations see Figure 3)

Station	Peak horizontal acceleration (vector of both horizontal components) (g)	Peak vertical acceleration (g)	Site Class (NZS1170)
CMHS	0.3	0.2	D (deep spoil)
HVSC	0.6	0.2	C (shallow soil)
LPCC	0.4	0.1	B (weak rock)
PARS	1.0	0.7	B (weak rock)
GODS	2.2	1.1	B (weak rock)
D15C	0.9	0.6	B (weak rock)

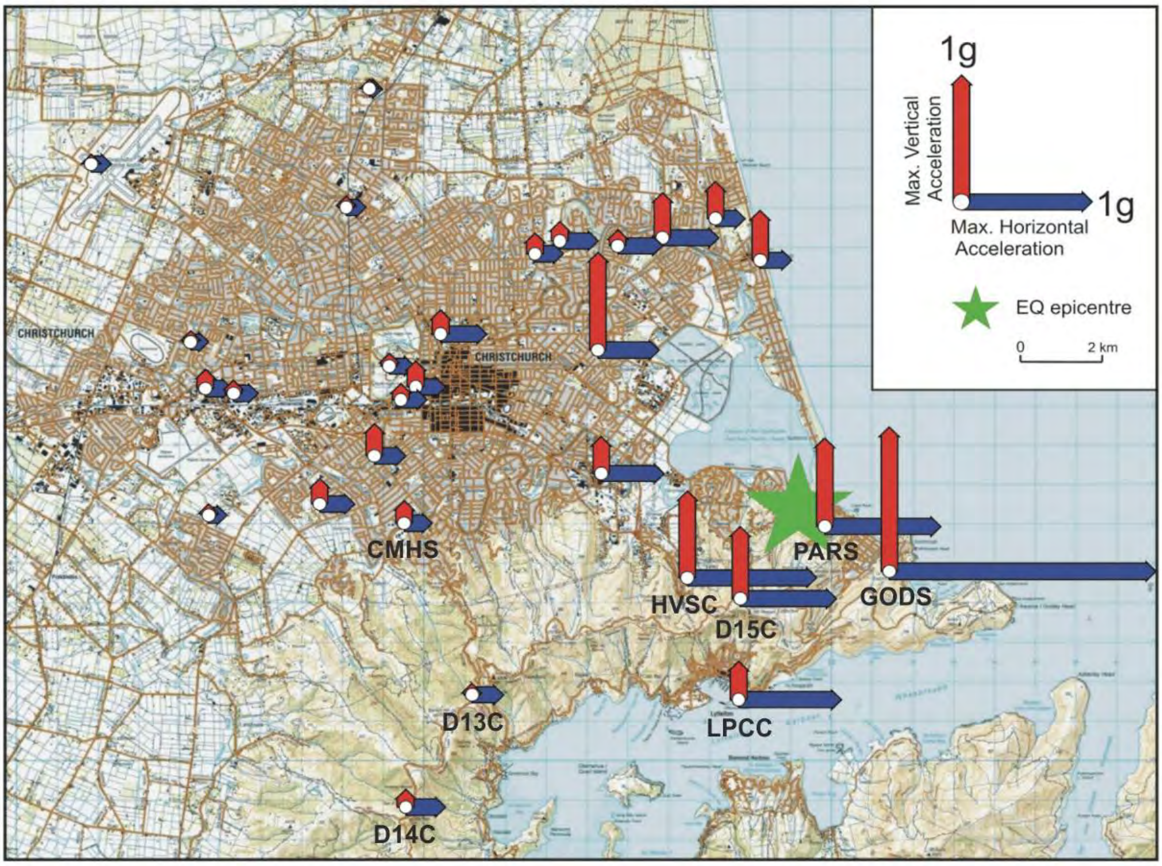

Figure 6 Maximum horizontal (single component) and vertical peak ground accelerations recorded during the 13th June 2011 earthquake at GeoNet stations and using temporary low-cost accelerometers (Quake-Catcher Network). Note: the arrows are not vectors and indicate component magnitudes but not direction.

1.4.3 Evidence of prehistoric earthquake-induced rockfalls

In many areas of the Port Hills, there are deposits from prehistoric rockfalls now partly or totally buried by loess and loess colluvium (loess that has subsequently been remobilised and moved downslope). Loess is a wind-blown yellow-brown silty deposit, locally with fine sand and clay, which is widespread on Banks Peninsula. The loess was largely deposited during the late Pleistocene, with most deposited before 11,500 years ago (Forsyth et al., 2008), but some deposition continues even today.

At Rapaki Bay and in Heathcote Valley, clusters of prehistoric rockfalls have been observed, either totally or partially buried in the loess, indicating that the rockfalls occurred while the loess was accumulating. Some of the loess deposits on the lower slopes of Banks Peninsula, however, have been reworked by mass-movement processes that still occur today. Removal of forest by fires over the last 1,000 years makes it likely that accessible boulders have been disturbed by post-rockfall mass-movement. Therefore, these boulders cannot be used in any quantitative assessment of risk. The data do, however, indicate past rockfall events.

There is archaeological evidence for substantial rockfalls in the Sumner-Redcliffs area some 500 years ago (e.g. Trotter, 1975). At Moncks Cave, a substantial rockfall deposit blocked the cave entrance about 500 years ago, preventing further occupation of the cave until the deposit was removed for road construction in the 1880s. Substantial rockfalls fell in Moa Bone Point Cave around the same time, and substantial rockfalls buried middens of around this age. Triggers for these rockfalls have not been discussed previously, but the 2010-2011 experience strongly suggests a local earthquake trigger.

2.0 DATA

Table 4 Summary of datasets used in the rockfall-risk analyses

Data	Description	Source	Date	Where used in the analysis
Post 22nd February 2011 earthquake digital aerial photographs	Aerial photographs were taken on 24/02/2011 by NZ Aerial Mapping and were orthorectified by GNS Science (10 cm ground resolution).	NZ Aerial Mapping	Last updated 24/02/2011	Used to identify rockfall end points, and travel paths for those rockfalls triggered by 22nd February 2011 earthquake
Light Detecting And Ranging (LiDAR) digital elevation model (DEM)	Digital elevation model derived from post 22nd February 2011 LiDAR survey re-sampled to 3 m ground resolution.	NZ Aerial Mapping	8-10/05/2011	Used as the base topography model, including development of the shadow angles, and profiles along selected rockfall trails.
Christchurch building footprints	Footprints are derived from aerial photographs. The data originate from 2006 but have been updated in the rockfall zones by Christchurch City Council staff using the post-earthquake aerial photographs.	Christchurch City Council	Unknown	Used to identify the locations of residential buildings in the rockfall zones and to proportion the population (from the 2006 census data).
Christchurch City Council rockfall database	The location, date and size of fallen rocks mapped in the field from the 22nd February and 13th June 2011, earthquakes	Engineering consultants working for Christchurch City Council. Data compiled by Christchurch City Council staff	Last updated 11/10/2011	Used to estimate the numbers of rockfalls produced at each location mainly by the 22nd February 2011 earthquakes, and the likelihood of a boulder striking a building or person at a particular location.
GNS Science rockfall database	Location, date and size of fallen boulders mapped from aerial photographs (utilising the NZ Aerial Mapping 26th February 10 cm ground resolution aerial photographs), and from field mapping.	GNS Science and Canterbury University	Last updated 8/05/2011	
Christchurch City Council recorded house hits	Data on the numbers of houses hit and penetrated by boulders triggered during the recent earthquakes	Engineering consultants working for Christchurch City Council.	Received 22/11/2011	Used to assess the vulnerability of people in the homes from rockfalls
GNS Science landslide database	Approximate location, date, and probably trigger of newsworthy landslides	GNS Science	Updated monthly	Used to estimate the likely numbers of rockfalls produced at each location from non-earthquake triggers
Earthquake Commission claims database	Location, date and brief cause of claims made in the Port Hills of Christchurch since 1993.	EQC	1993 to August 2010	Used to estimate the likely numbers of rockfalls produced at each location from non-earthquake triggers
Seismic records for the 22nd February 2011 earthquake and other earthquakes in the region	Seismic records from the GeoNet strong motion sites located in the Port Hills.	GeoNet	22nd February 2011	Used to estimate the frequency of a given peak ground acceleration.

3.0 METHODOLOGY

The methods for quantitative risk-estimation used for this work generally follow the Australian Geotechnical Society framework for landslide risk management (AGS, 2007) where this is possible and appropriate (Figure 7).

Using AGS 2007 (and the accompanying practice notes), for loss of life, the risk of loss-of-life to an individual is calculated from:

$$R_{(LOL)} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)} \quad [1]$$

where:

- $R_{(LoL)}$ is the risk (annual probability of loss of life (death) of a person) from rockfall;
- $P_{(H)}$ is the annual probability of a rockfall-initiating event;
- $P_{(S:H)}$ is the probability of a building or person, if present, being in the path of one or more boulders at a given location;
- $P_{(T:S)}$ is the probability that a person is present at that location; and
- $V_{(D:T)}$ is the vulnerability, or probability of a person being killed (or receiving injuries which prove fatal in the near aftermath of the event) by a rockfall.

A full landslide risk analysis involves considering all landslide hazards for the site (e.g. large, deep-seated landsliding, smaller slides, rockfalls, debris flows) from all landslide causes and of all the elements at risk. This report considers these other types of landslide, but in a necessarily simplistic way because the data are limited.

The steps in the rockfall risk analysis are laid out in Figure 7, and include the following key steps:

1) Risk analysis carried out as per the Australian Geomechanics Society (2007) method;

2) Two dimensional numerical rockfall modelling using the Rocscience® Rocfall™ programme. This was carried out to determine the likely distances rockfalls travel (runout) down a slope and was used to define the limits of rockfall runout;

3) Field verification (ground truthing) of the analysis results by the Port Hills Geotechnical Group; and

4) Updating of the risk analysis maps with the results from the field verification and two dimensional rockfall modelling.

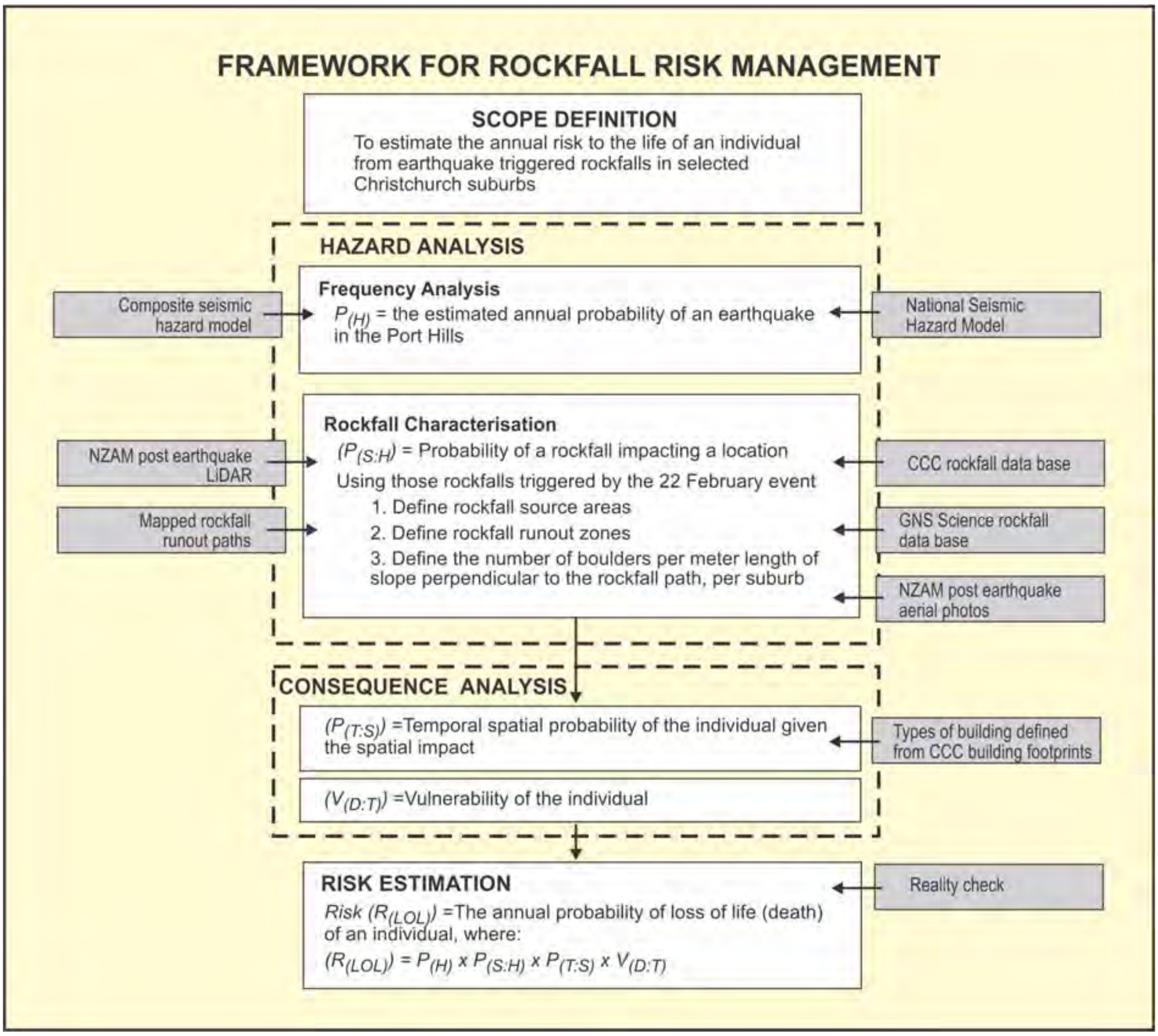

Figure 7 Framework used to assess the annual probability of loss of life (death) of an individual from rockfalls in the Port Hills that were triggered by the main 22nd February 2011earthquake. Modified after AGS (2007) *Guidelines for landslide risk management*.

4.0 CHARACTERISING ROCKFALLS

In the literature, a wide range of rockfall trigger mechanisms and conditions have been identified. These trigger mechanisms can be divided into rockfall-initiation factors (i.e. factors that prepare the slope for failure) and triggering events. However, in reality it is difficult to make a distinction between the two, since often one process both promotes weathering and causes rockfall, e.g. frost shattering (Dorren, 2003).

Events that trigger rockfalls are typically, in no particular order: 1) rainfall; 2) earthquake-induced ground accelerations; 3) frost shattering; 4) human activities, e.g. modification of slopes, and walkers and mountain bikers dislodging boulders; 5) animal activities; 6) vegetation changes; and 7) time, with no obvious trigger. In a review, Dorren (2003) found that various factors are often reported as triggers of rockfall but, in most cases, a combination of topographical, geological and climatological factors and time determine whether a rockfall occurs.

4.1 Earthquake triggers

Kanari (2008) reports that a sequence of earthquakes is required to trigger rockfall, rather than an isolated earthquake. Kanari (2008) suggests that strong ground acceleration is not the only variable in rockfall triggering, but a certain stage of maturity of fracture weakening (and/or deformation) of the rock mass must be reached in order to trigger rockfalls. Analysis of the 1987 South California earthquakes (Harp and Wilson, 1995) indicates two shaking velocity thresholds for the limits of rockfalls and slides. The sites with the lower velocity thresholds were those with large aperture fractures and loose rock (as would be caused by repeated earthquake shaking) and were therefore easier to dislodge at lower accelerations. Conversely earthquakes may remove those rocks more susceptible to failure, but in turn may reduce the stability of other rocks (through earthquake-induced fracture weakening and deformation of the rock mass), making them susceptible to failure during a subsequent earthquake. This appears to be the case in the Port Hills, as the 13th June 2011 aftershock (with peak ground accelerations of 1.0 – 2.0 g, and an epicentre near Wakefield Avenue in Sumner), triggered about 190 mapped rockfalls, a similar number to those triggered by the 22nd February 2011 earthquake in the same area only a few months before. Further studies (Harp and Jibson, 2002; Sepulveda et al., 2005) show that higher concentrations of rockfalls occur in areas where shaking is enhanced by local topographical amplification, complicating the relationship between ground acceleration and the number of boulders produced.

In this study, peak ground acceleration has been used to characterise ground shaking, as it is assumed rockfalls require an instantaneous force exceeding a critical value to trigger them, rather than the multiple accelerations associated with longer duration shaking. Observations on the ground suggest many boulders and large plant pots were thrown upwards and outwards in a single motion, as no evidence of “scuff” marks were apparent. Note however that the accelerations used in this study are those measured at named strong-motion recorder sites, they are not necessarily the accelerations experienced by the rockfall sources (which could be different due to local site condition effects). The acceleration value is used only to estimate the probability of occurrence of the rockfall trigger; it is not, and should not be, used in any dynamic analysis of rockfall triggering.

The relationship between earthquake magnitude and the maximum distance from the earthquake epicentre that landslides and rockfalls are triggered has been analysed in several studies. Keefer (1984) developed curves representing the upper limit of the maximum distance from the earthquake epicentre to different types of landslides for historic worldwide earthquakes of different magnitudes (Figure 8). Wieczorek and Jager (1996), studying rockfalls in Yosemite National Park, USA, used Keefer's procedure. The four main Canterbury earthquakes and the associated distribution of mapped rockfalls in the Port Hills triggered by these events are plotted with the Keefer (1984) and Wieczorek and Jager (1996) data (Figure 8). The Port Hills data plot below equivalent data from international events, i.e. the maximum distance from the epicentre for Port Hills rockfalls for a given earthquake magnitude was shorter. Some of this scatter is thought to reflect the depth of the earthquake, which is not taken into account, along with differences in factors such as geology and slope angle. The main reason why the New Zealand data plot below the international data is because of topographic constraints. Much of the area affected by the strong ground shaking in the 2010/2011 Canterbury earthquakes was flat land and sea, where rockfalls or landslides do not occur. However, the Keefer (1984) analyses indicate that rockfalls in the Port Hills could be triggered by earthquakes elsewhere in the Canterbury region, and not just by localised earthquakes near the Port Hills. This was demonstrated in the Port Hills in the earthquake of 1888.

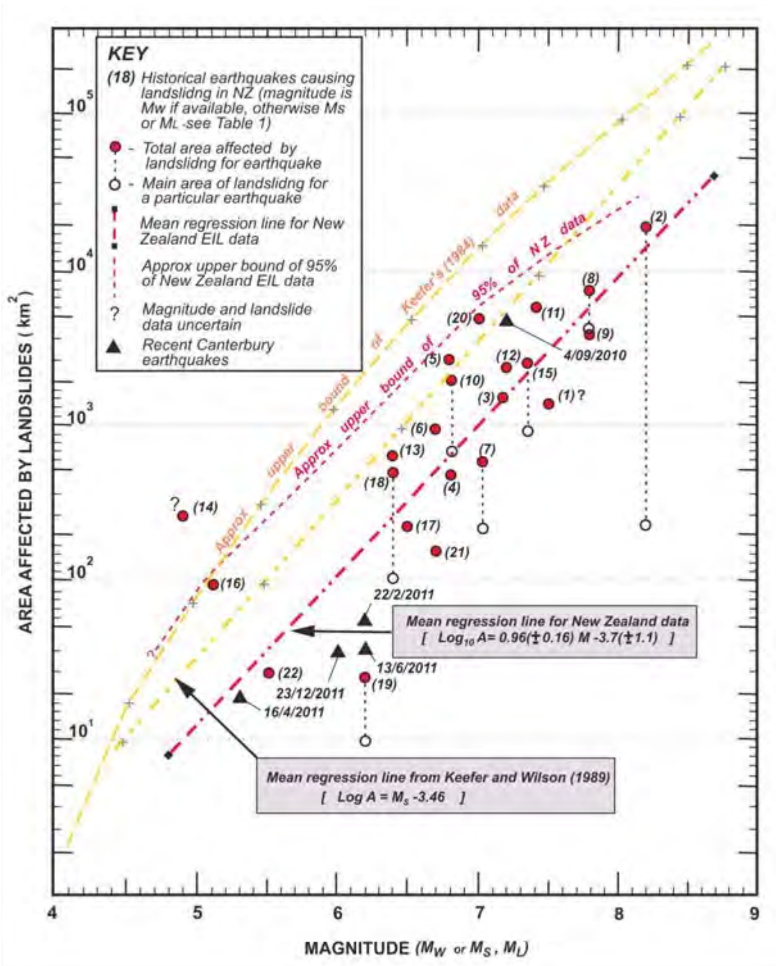

Figure 8 Relationship of the area affected by landslides during historical earthquakes of different magnitude in New Zealand and worldwide. The black triangles represent the main areas affected by the recent Canterbury earthquakes. Modified from Hancox et al. (2002).

4.1.1 Estimating the frequency of rockfall-triggering earthquakes

The number of rockfalls triggered by the 2010/2011 Canterbury earthquakes, mostly by the 22nd February 2011 earthquakes, and the peak ground accelerations that triggered them have been used to assess the probability ($P_{(H:PGA)}$) of rockfalls, given a range of ground accelerations. For ease of calculation of the area under the hazard curve of earthquake accelerations (to obtain annual probability of rockfall number exceedence) the range of accelerations likely to trigger rockfalls was divided into 4 bands (Table 5). The average consequences of the representative earthquake in each band were then estimated in terms of the number of boulders produced.

Table 5 Likely rockfalls triggered for different bands of peak ground acceleration

Acceleration Band (g)	Description of consequences
0.01 – 0.4	Rockfalls are minimal within this range of accelerations
0.4 – 1.0	Rockfalls occur at this range but they are of limited extent and local
1.0 – 2.0	This is the range of the 22nd February and 13th June earthquakes in which most rockfalls occurred.
2.0 – 5.0	Extremely rare, number of rockfalls expected to greatly exceed that triggered during the 22nd February 2011 earthquakes.

The frequency of a given acceleration band occurring is based on the New Zealand National Seismic Hazard Model (Stirling et al., 2012). In general, the hazard calculations within this model are based on time-independent (Poissonian) earthquake probabilities, which is standard practice for probabilistic hazard analysis for engineering design (pers. com. G. McVerry). Time-independent earthquake probabilities are based on the average rate of occurrence of earthquakes for a given source, but do not take account of the elapsed time since the last earthquake or the enhanced activity associated with the earthquake sequences that commonly follow major earthquakes. As noted earlier, due to the 4th September 2010 Darfield earthquake and its associated aftershock sequence, the current level of seismic activity in the Christchurch region is considerably higher than the long-term average, and is likely to remain enhanced for several decades (Webb et al., 2011). Given this current enhancement of seismicity, it is necessary to develop earthquake probabilities that change over time to represent the on-going earthquake sequence in the region.

This increased level of seismicity has been quantified using a modified form of the 2010 version of the National Seismic Hazard Model (Stirling et al., 2012), which incorporates the now-increased probabilities for major faults in the region (Gerstenberger et al., 2011). This is referred to as the composite seismic hazard model (CSHM) and is the same model used in the liquefaction susceptibility assessments for Christchurch (Webb et al., 2011, and Gerstenberger et al., 2011).

The diminishing frequency of earthquakes over time has been accommodated by estimating, for each location on a geographical grid, the earthquakes expected in a series of 0.2 magnitude intervals over each of the next 50 years, and then finding the average rates over the 50-year period. As the model is based on seismic activity that decreases with time, the annual probability of exceeding any ground-motion level is highest in the first year, gradually decreasing with time after that. Using the information in Webb et al. (2011) (which is based on data from before the 13th June 2011 earthquake), the annual probability of earthquakes is higher than the 50-year average in the first few years but drops below the 50-year average after about 9 to 10 years (illustrated for an earthquake of magnitude 6 to 7 in Figure 9).

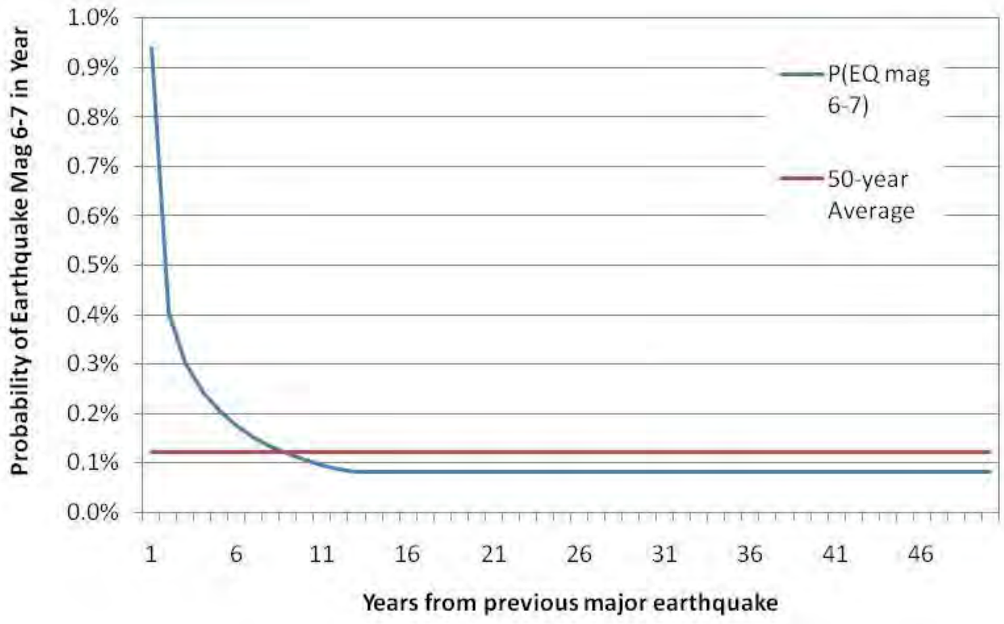

Figure 9 Estimated probability of an earthquake of magnitude 6 to 7 occurring in the next 50 year period. From Webb et al. (2011) (pre 13th June 2011 earthquake model).

For the composite seismic hazard model used for this work we consider that the most realistic representations of current seismicity and of longer term seismicity are provided by the 1-year (starting 1/01/2012) and 50-year average, respectively.

The peak ground acceleration hazard curves have been estimated using the McVerry et al. (2006) ground-motion prediction equations. These equations are used in the New Zealand National Seismic Hazard Model (Stirling et al., 2012) that underlies the hazard section of the structural design standard NZS1170.5:2004.

The peak ground acceleration (horizontal) hazard curves for the Heathcote Valley Primary School site, calculated using the composite seismic hazard model, show that the frequency of a given acceleration within the next 1year period is higher when compared to those over a 50-year period (Figure 10). As a result, there are two possible target periods for the risk calculation. One is the next 50 years, which is consistent with the design life used in typical seismic hazard analysis for building construction. However, unlike the usual National Seismic Hazard Model calculations, these forecasts are specific to the next 50-year period, rather than any 50-year period. The other is the immediate (and short-term) risk associated with the recognised higher frequency over the next year.

The composite seismic hazard model has been used to estimate the likelihood of a given ground acceleration occurring in the future. Values are calculated for the Heathcote Valley Primary School site, as the values for this site are representative of those estimated for other sites in the Port Hills (e.g. Lyttelton Port Company and Cashmere High School).

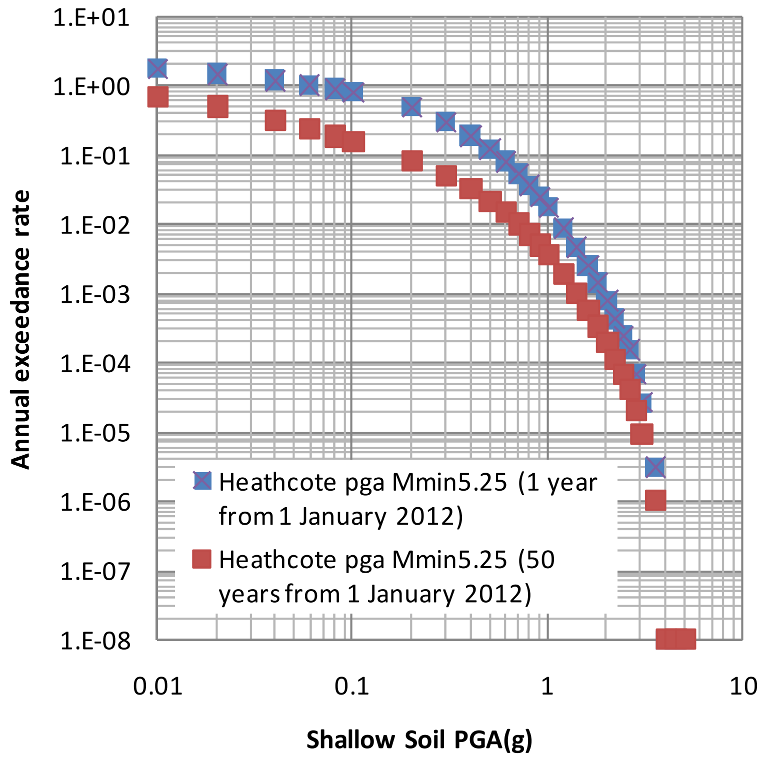

Figure 10 Peak ground acceleration hazard curves for the Heathcote Valley Primary School site in the Port Hills using the composite seismic hazard model for the next 1-year period and the next 50-year period, using a minimum earthquake magnitude (M_{min}) of M_W5.25. The Heathcote Valley site is classed as a shallow soil site (NZS 1170 site class C). These values do not include amplification effects induced in the rockfall source areas, or any magnitude weighting.

The model estimates the frequency with which a given ground acceleration will be exceeded at a point in the Port Hills by adding up the contributions from a large catalogue of likely future earthquakes of different magnitudes both close to and distant from the area. This catalogue is developed from: 1) known historical earthquakes; 2) expected rates of aftershocks and other triggered earthquakes; and 3) known active faults in the area. Thus the contributions from modest energy earthquakes close to the area and from higher energy earthquakes further away are both included. A minimum earthquake magnitude of M_W5.25 has been used in the model, as the composite seismic hazard model provides overly conservative values at magnitudes $<M_W5$, leading to large overestimates of the values generated (pers. com. T. Webb and G. McVerry).

For the assessments given in this report, the next 1-year and 50-year frequencies, for the period starting from 1/01/2012 at the Heathcote Valley Primary School site are used to estimate the likelihood of a given peak ground acceleration band occurring in the Port Hills (Table 6). Given that the decisions to be made about land use involve both immediate life safety and the longer-term viability of dwellings, there is scope for debate about whether to use the next 1-year or the next 50-year values as the base case for land-use decisions. Because the objective report is to provide estimates of fatality risk for management of life safety, and people may be reoccupying dwellings affected by rockfalls within the next year, when the risk of an earthquake triggering rockfalls is significantly higher, the seismic hazard averaged over the next year has been used in the assessment. Assessments were also made using a seismic hazard averaged over the next 50 years, but risk maps using a variety of lower risk scenarios are only presented for one location (Heberden Avenue) to illustrate the difference.

The Heathcote Valley Primary School ground acceleration hazard curves were used for all suburbs in our analyses; as this site is located in the central part of the Port Hills there is little difference between the ground acceleration hazard curves for Heathcote Valley Primary School and the other curves generated for the Lyttelton Port Company and Cashmere High School sites. Heathcote Valley Primary School is located on gently sloping ground in shallow soil (NZS 1170 Site Class C). Note that the frequencies of earthquakes used throughout this assessment are the frequencies of earthquakes at a particular measurement point—the frequency of an earthquake somewhere within the area being considered will be somewhat higher than that at any individual point within it.

Table 6 Peak ground acceleration bands and their annual frequency of occurrence estimated using the next 1-year and 50-year ground acceleration hazard model results for the Heathcote Valley Primary School site, using median values.

Acceleration Band (g)	Frequency – earthquakes per year		Description
	Current – within next 1 year	Over next 50 years	
0.1 – 0.4	0.6	0.12	Rockfalls tend to be minimal at this range of accelerations
0.4 – 1.0	0.17	0.03	Rockfalls occur at this range but their numbers tend to be limited and localised
1.0 – 2.0	0.016	0.003	This is the acceleration range of the 22nd February 2011 earthquake in which most rockfalls occurred
2.0 – 5.0	0.0008	0.0002	Rare earthquake, but will trigger significantly more rockfalls than the 22nd February 2011 earthquake

4.1.2 Estimating numbers of earthquake-triggered boulders

The numbers of rockfall boulders likely to be generated by an earthquake representative of each ground acceleration band were determined for each of the suburban areas. For these areas, the numbers of mapped rockfalls triggered in the 4th September 2010 Darfield earthquake and its aftershocks were plotted against the associated index peak ground acceleration recorded at the nearest strong motion station to that suburb; a total of eight strong motion sites are currently located in the Port Hills (Table 7).

These measured peak ground accelerations were from all eight of the stations in the Port Hills regardless of site class. The stations used are typically sited on classes B (rock) and C (shallow soil) (NZS1170.5:2004) and the recorded values do not represent the actual peak ground accelerations recorded at the rockfall source areas, which are likely to have been higher as a result of localised site effects.

The recorded peak ground accelerations have not been normalised to one particular site class and so the measured peak ground accelerations are being used as an index of what the range of peak ground accelerations were that triggered a particular number of recorded boulders.

Table 7 Number of mapped fallen rocks by suburb (main suburbs only) triggered by the recent Canterbury earthquakes and the maximum horizontal vector of ground acceleration recorded at the nearest strong motion station. The listed GeoNet strong-motion recording sites are: CMHS - Cashmere High School, HVSC - Heathcote Valley Primary School, LPCC - Lyttelton Port Company, PARS - Panorama Road, Sumner, GODS - Godley Drive, Sumner; and D15C (for locations see Figure 3). Note that the number of stations in the Port Hills was increased following the 22nd February 2011 earthquakes. Not shown are the many earthquakes that triggered no rockfalls.

Suburb*	Earthquake	PGA (g)	Strong motion site	Number of mapped fallen rocks	Comments
Heathcote*	4th Sept 2010	0.6	HVSC	~10	Estimated by consultants
	22nd Feb 2011	2.1	HVSC	2,465	Mapped by Christchurch City Council (CCC) and GNS Science
	13th Jun 2011	0.9	D15C	100	Mapped by CCC
Sumner (Heberden Avenue)	22nd Feb 2011	1.3	LPCC	176	Mapped by CCC and GNS Science
	16th Apr 2011	0.4	GODS	47	Mapped by CCC
	13th Jun 2011	0.8	PARS	184	Mapped by CCC
Sumner (Wakefield Avenue)	22nd Feb 2011	1.3	LPCC	766	Mapped by CCC and GNS Science
	13th Jun 2011	1.0	PARS	20	Estimated by consultants (limited area assessed)
Lyttelton	22nd Feb 2011	1.3	LPCC	453	Mapped by CCC and GNS Science
	13th Jun 2011	0.9	D15C	87	Mapped by CCC
Hillsborough (Vernon Terrace)	22nd Feb 2011	0.5	CMHS	46	Mapped by CCC and GNS Science
	13th Jun 2011	0.3	CMHS	7	Mapped by CCC
Avoca Valley1	22nd Feb 2011	1.3	LPCC	220	Mapped by CCC and GNS Science
	13th Jun 2011	0.9	D15C	17	Mapped by CCC
Rapaki Bay	22nd Feb 2011	1.3	LPCC	277	Mapped by CCC and GNS Science
	13th Jun 2011	0.9	D15C	33	Mapped by CCC and GNS Science
Bowenvale	22nd Feb 2011	1.3	LPCC	99	Mapped by CCC and GNS Science

* Castle Rock, Avoca Valley 2, 3 and 4 and Horotane Valley are not included in the analysis as their boulder data were not available at the time of writing.

A linearized power-law was fitted to the data in Table 7, of the form:

$$\log RF = a_i + b \log PGA \qquad [2]$$

where *RF* is the expected number of rockfalls, a_i is a site constant, *b* is constant over all sites and *PGA* is peak ground acceleration (g) measured at the strong motion sensor closest to the suburb . The fitted model allows for Poisson-distributed variability in the number of fallen rocks and has regard to all of the data in Table 7, including zero rockfall observations (Figure 11). The common slope constant *b* was estimated to be 3.7 ± 0.06 (1 standard deviation). There are several individual observations that are not well-fitted by the model, the residual deviance of 1007 on 88 degrees of freedom indicates that, overall, the data are more widely dispersed about the fitted model than expected under a Poisson distribution of variability. This over-dispersion relative to the assumed model is allowed for in the tolerance limits (Table 8) (pers. com. D. Rhoades).

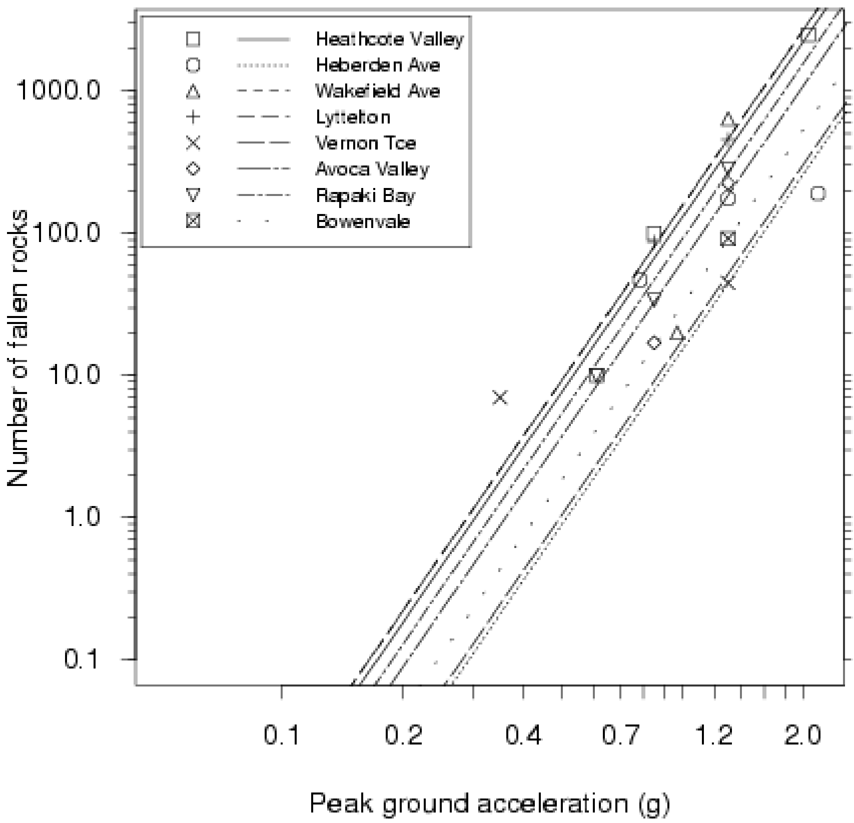

Figure 11 Expected number of fallen rocks (lines) by suburb (or by named streets for Sumner and Hillsborough) for the main suburbs, as a function of peak ground acceleration (g), as fitted by a generalized linear model [Eq. 2] to the data of Table 7, including those accelerations that did not trigger rockfalls (zero data values). The points on the graph show only the non-zero data values.

Table 8 Fitted site parameters a_i of model and their 95% confidence limits (main suburbs only).

Site	Fitted a_i	95% confidence limits
Heathcote Valley	5.12	(5.03 to 5.21)
Sumner (Heberden Avenue)	3.01	(2.88 to 3.14)
Sumner (Wakefield Avenue)	5.12	(5.04 to 5.20)
Lyttelton	5.12	(5.03 to 5.21)
Hillsborough (Vernon Terrace 1)	2.97	(2.69 to, 3.25)
Avoca Valley 1	4.15	(4.01 to 4.28)
Rapaki Bay	4.75	(4.64 to 4.86)
Bowenvale	3.54	(3.33 to 3.75)

The results suggest that a threshold for triggering rockfalls (i.e. the minimum peak ground acceleration required to trigger one rockfall) is about 0.3 to 0.4 g.

The above analysis treats each rockfall-triggering earthquake as independent of other earthquakes. The analysis does not directly take into account the geometry or size of the rockfall source areas. The correlation between numbers of boulders generated per square metre of source (per suburb) for a recorded ground acceleration is statistically poor and cannot be used in this analysis. The available data do not allow investigation of the possibility that the thresholds of rockfall triggering may be changing as a result of the earthquake sequence. Perhaps the continuing earthquakes are depleting the available supply of rockfall materials, or perhaps the ground shaking is renewing the supply faster than it is depleting it; there are not yet enough data to investigate these questions.

4.1.3 Expected numbers of rockfalls triggered in each peak ground acceleration band

The expected numbers of rockfalls triggered by an earthquake within the 0.4 – 1.0 g and the 1.0 – 2.0 g acceleration bands have been estimated from Figure 11 using Eq. 2 (Tables 9 and 10).

Table 9 Expected number of rockfalls and uncertainties from an earthquake within the 0.4 – 1.0 g acceleration band (main suburbs only). The tolerance limits are the uncertainty range on the actual number of rockfalls in a future occurrence of 0.7 g.

Suburb	Expected number of rockfalls*	95% tolerance limits
Heathcote Valley	45	(6 to328)
Sumner (Heberden Avenue)	5	(1 to 40)
Sumner (Wakefield Avenue)	45	(6 to 327)
Lyttelton	45	(6 to 327)
Hillsborough (Vernon Terrace 1)	5	(1 to 39)
Avoca Valley 1	17	(2 to 124)
Rapaki Bay	31	(4 to 227)
Bowenvale	9	(1 to 68)

*Note: the uncertainty ranges indicate that only the first digit of the expected number of rockfalls is significant

Table 10 Expected number of rockfalls and uncertainties from an earthquake within the 1.0 – 2.0 g band (main suburbs only). The tolerance limits are the uncertainties on the expected number of rockfalls in a future occurrence of accelerations of 1.5 g.

Suburb	Expected number of rockfalls*	95% tolerance limits
Heathcote Valley	749	(103 to 5468)
Sumner (Heberden Avenue)	91	(12 to 663)
Sumner (Wakefield Avenue)	749	(102 to 5471)
Lyttelton	749	(102 to 5475)
Hillsborough (Vernon Terrace 1)	87	(12 to 650)
Avoca Valley 1	283	(39 to 2076)
Rapaki Bay	518	(71 to 3791)
Bowenvale	155	(21 to 1141)

*Note: the uncertainty ranges indicate that only the first digit of the expected number of rockfalls is significant

For the 0.1 – 0.4 g ground acceleration band a small non-zero estimate of the expected number of rockfalls from a representative earthquake has been assumed (0.1 rockfall per suburb). This is consistent with the results from recent earthquakes in the Christchurch region where the minimum acceleration threshold for triggering rockfalls (the peak ground acceleration required to trigger 1 rockfall) is about 0.3 – 0.4 g. For the highest acceleration band of 2.0 – 5.0 g, the numbers of rockfalls triggered by a representative earthquake were estimated, per suburb, as being an order of magnitude larger than those triggered by the 22nd February 2011 earthquakes (Table 11).

For those suburbs where there are insufficient data (typically where the mapping of rockfalls has been limited and where there are no strong motion sensors close by), the numbers of rockfalls generated by each representative earthquake have been estimated. These numbers were estimated using data from geomorphologically similar suburban areas, the relationship in Figure 10 and judgement based on the mapped number of rockfalls triggered by the 22nd February 2011 earthquakes in that suburb.

Table 11 The estimated scale of rockfalls triggered by a representative earthquake within each peak ground acceleration band for all suburbs included in the assessment. These represent the estimated number of boulders leaving a source area (rock slope) for a particular earthquake (values in the table have been rounded to whole numbers).

Suburb	Estimated boulders leaving all source areas per acceleration band[1]			
	0.1 – 0.4 g	**0.4 – 1.0[2] g**	**1.0 – 2.0[2] g**	**2.0 – 5.0 g**
Lyttelton	0.1	45	749	7,500
Heathcote Valley	0.1	45	749	7,500
Avoca Valley 1	0.1	17	283	2,800
Avoca Valley 2	0.1	17	283	2,800
Avoca Valley 3*	0.1	2	38	380
Avoca Valley 4*	0.1	1	9	100
Horotane Valley**	0.1	17	283	2,800
Sumner (Heberden Avenue)	0.1	5	91	910
Sumner (Wakefield Avenue)	0.1	45	749	7,500
Hillsborough (Vernon Tce. 1)	0.1	5	87	870
Hillsborough (Vernon Tce. 2**)	0.1	5	87	870
Bowenvale	0.1	9	155	1,550
Rapaki Bay	0.1	31	518	5,200
Castle Rock**	0.1	17	283	2,800

*Note: only the first digit of the expected number of rockfalls is significant
[2]Estimated from Figure 11.
*Estimated using the numbers of mapped boulders triggered by 22nd February 2011 earthquakes, the modelled relationship between peak ground acceleration and numbers of rocks generated (Figure 12) and judgement.
**Estimated using those boulders from adjacent suburbs that are geomorphologically similar; Horotane Valley uses Avoca Valley 1 and 2, Vernon Terrace (Tce.) 2 uses Vernon Terrace 1 and Castle rock uses Avoca Valley 2.

4.1.4 Estimating the annual probability of rockfall initiating events

In the Australian Geotechnical Society framework for landslide risk management (AGS, 2007) $P_{(H)}$ is the annual probability of a rockfall initiating event. For this study the annual frequency, with corresponding units of "per year", has been used rather than probability, with units of "dimensionless probability of occurrence in one year". The use of "probability" invites confusion when events can occur several or more times in a year (Taig, 2011).

For this study $P_{(H)}$ is the annual frequency of a given number of rockfalls being triggered over a given period of time.

For earthquake triggers, $P_{(H)}$ is estimated using the composite seismic hazard model, where $P_{(H)}$ = the range of each ground acceleration band. For the 0.4 – 1.0 g band, the annual frequency of exceedence of these accelerations (estimated from the 50-year composite seismic hazard model) are 0.03 and 0.004 respectively (Table 12). Therefore the width of the band (the frequency of earthquakes within the band) is:

$$P_{(H)} = 0.03 - 0.004 = 0.026 \quad [3]$$

Table 12 Annual frequency of a given number of earthquake-triggered rockfalls occurring within a given time period; for all assessed areas using the next median 1-year seismic hazard model results.

Ground acceleration band	$P_{(H)}$ Frequency (earthquakes per year)[1]	Estimated number of rockfalls in band (all areas)[2]	Rockfall rate[3] (Number of rockfalls per year)
0.1 – 0.4 g	0.6	1.4	0.84
0.4 – 1.0 g	0.168	261	44
1.0 – 2.0 g	0.016	4,364	72
2.0 – 5.0 g	0.0008	43,580	33
		Total annual rockfall rate	**150**

[1]Derived from the composite seismic hazard model for Christchurch over the next 1 year.
[2] Note that only the first digit is significant
[3]Calculated by multiplying the estimated number of rockfalls per band by the annual frequency of the band occurring.

If the seismicity results for the next 50-years are used (median values), the total annual rockfall rate is about 31 boulders per year, compared to the 150 boulders per year estimated using the model results for the next 1 year. This consequence is not because there is less boulder risk per expected earthquake, but because there is more risk of earthquakes in the first year, and so there is a higher annual rate of rockfalls in the first year as compared to the average over 50 years.

4.2 Other rockfall triggers

To compare the risk from rockfalls triggered by the 22nd February 2011 earthquakes with the risk of rockfalls from other events such as high-intensity or long-duration rainfall, quantitative information is needed on rockfalls triggered by other events. For most locations on the Port Hills, quantitative data for other events is sparse; however, some data were available at the time of writing. The widespread use of belts of trees and engineered rockfall fences as rockfall mitigation below rocky bluffs in the region demonstrates that residents were aware of rockfall risk from causes other than earthquakes.

4.2.1 Estimating "other" triggers – rockfall boulder frequencies

A major source of data on the numbers of older rockfalls for the Port Hills is from historical records, mainly: 1) the GNS Science landslide database which is complete only since 1996; 2) insurance claims made to the Earthquake Commission (EQC) for landslides that are complete only since 1996; and 3) information from local consultants (e.g. M. Yetton, Geotechnical Consulting Ltd) which covers the period from 1992 to 2009 and relates to EQC insurance-claim assessments.

These data sources identify specific triggers and approximate triggering times. The GNS Science landslide database records 6 landslides that mainly affected roads in the region between 1996 and 2011, about 0.4 events per year. These are all recorded as being small (< 10 m^3) and mainly initiated by rainfall. The GNS Science landslide database records a home in Heberden Avenue destroyed by rockfall during rain on 24th October 2000, and two homes hit by rockfall in Wakefield Avenue during rain on 13–14th August 2006. These are the only rockfall-related events in the Port Hills in the GNS Science landslide database before 2010.

The EQC claims database contains 357 claims made for “Landslide, storm or flood”. These claims are for homes that are all located on sloping ground in the Port Hills suburbs covered by this assessment. About 68% of the reported claims (about 17 per year) relate to landslides. Between 1996 and 2010 (prior to the 4th September 2010 Darfield earthquake) EQC received about 26 landslide-related claims per year in the Port Hills. If it is assumed each claim relates to one event, then there have been 2 claims per suburb per year in the Port Hills. At the time of writing this report the detailed geotechnical information relating to these claims was not accessible, therefore it has not been possible to assess the nature of the event that triggered the claim.

Claims assessments carried out on behalf of the EQC by local consultants Geotechnical Consulting Ltd. have been summarised. Geotechnical Consulting Ltd. report that these claims mainly comprised small failures in loess and soil from cut (modified) slopes and from old coastal cliffs, and most were initiated by rain or snow melt. Between 1992 and 2006 there were 62 claims reported (about 4 per year); of these about 32% are related to rockfall and 68% to landslides in loess. These data suggest there are on average about 8 (32% of 26 claims per year) claims made to the EQC for rockfalls per year in the Port Hills.

Other information that may contain records of rockfalls in the Port Hills, e.g. Christchurch City Council files and reports, were not available at the time of writing. Knowledge held by other local geotechnical consultants indicates that rockfalls have occurred in the Port Hills over the past 30 years or more. Information in Bell (1992) indicates two failures of the rock slope at Redcliffs, the first in 1968 and the second in 1992; both are estimated to be about 50 m^3 in volume, and rainfall is reported as the trigger.

Archived newspaper accounts have also been reviewed; these report several rockfall events over the past ~100 years. One event occurred in 1907 at Peacock’s Gallop (Shag Rock Reserve) and involved the failure of about 1,500 to 2,000 m^3 of rock from the steep coastal cliff (Star newspaper issue 8891). A further failure from the same slope was also reported in 1912, involving about 150 m^3 of rock (Brown and Weeber, 1992). These can be associated with rainfall but they did not fall during rain. Earthquake triggering can be ruled out as no earthquakes were reported at these times.

The Star on 30 March 1907, in reporting on the “Great landslip” of the night before which blocked the Sumner Road and tramline at Clifton, remarked that “The cliffs on the Sumner Road have been a source of anxiety to the authorities and the public ever since the road was first opened by the Provincial Engineer, and periodically there have been falls of rock, more or less serious. The cliff, of course, is constantly “tailing” [ravelling].”

An additional source of information on unknown rockfall-triggering events has been obtained by GNS Science during geomorphology mapping in 2010 to 2012. Rockfalls triggered by events other than earthquakes have been identified in many of the Port Hills suburbs, e.g. Heathcote Valley, Lyttelton and Avoca Valley. In these three suburbs in particular, pre-Darfield earthquake (i.e. pre-4th September 2010) rockfalls are present on the slopes above many of the residential areas. Some of these rocks are partially buried in the colluvial loess, but a few are sitting on the surface, indicating they are relatively recent. None of these rockfalls can be related to any specific event or time, but they do indicate a past history of rockfall at these sites.

In view of the lack of detailed records, the rates of rockfall triggered by non-earthquake events were estimated based on the above very limited available data, discussion with local consultants, anecdotal evidence from residents, and judgement. These have been used to estimate the total risk contribution from non-earthquake rockfall-triggering events (Table 13).

Four representative time periods (in terms of resolution in time) have been used and the numbers of rockfalls triggered within these time periods have been estimated using a series of steps:

> Step 1 – Calculate the numbers of rockfalls that have accumulated over a given time period in each suburb using the available data. Four time-period bands have been used: 1) 1 – 15 years; 2) 15 – 100 years; 3) 100 – 1,000 years; and 4) >>1,000 (nominally 1,000 – 10,000 years) (Table 13).
>
> Step 2 – Estimate the annual accumulation rate of boulders per time-period band per suburb, allowing the contribution from each time-period band to be established.
>
> Step 3 – Assume a conservative value for the number of boulders per “typical” event in each band (same values used for all suburbs), using the available data.
>
> Step 4 – Calculate the corresponding event frequency for each given time-period band for each suburb so as to conserve the annual accumulation rate (Step 2). This represents the “effective” annual frequency of occurrence of the representative event per band.

Table 13 The annual frequency of an estimated number of rockfalls occurring, triggered by events "other" than earthquakes, for all areas assessed in the Port Hills.

Time period (years)	Type of events	Number of boulders per typical event in band	Description
<1 – 15	Rainstorms/frosts that occur frequently	1	Rockfalls tend to be minimal and localised. Estimated numbers of rockfalls derived using local geotechnical consultant files and the GNS Science landslide database.
15 – 100	Rainstorms with larger intensities and durations that occur about every 15 – 100 years	10	Rockfalls occur but their numbers tend to be limited and localised. Estimated numbers of rockfalls derived using historical (old newspapers and reports) and geomorphic evidence.
100 – 1,000	Rainstorms with very large intensities and durations that occur about every 100 – 1,000 years	50	Rockfalls will be widespread. Estimated numbers of rockfalls derived using geomorphic evidence only.
1,000 – 10,000	Rainstorms with extreme intensities and durations exceeding Cyclone Bola (1988) and the Manawatu storm (2004) that occur >1,000 years	100	These events might trigger a large number of rockfalls over a wide area and may be similar in number to those triggered by the 22nd February 2011 earthquakes. However, rockfall risk would be eclipsed by other risks (flooding, debris flows and debris avalanches).

For the purpose of analysis, about the same numbers of rockfalls triggered by the 1.0 – 2.0 g peak ground acceleration in each suburb have been used as an upper bound for those accumulated from non-earthquake events in the >>1,000 year frequency band. However, it is unlikely that a rainstorm will trigger a similar number of rockfalls over a given area to those produced by a large magnitude earthquake (typically $>M_W6$) as earthquake loading can "throw" rocks off slopes and generate cracks, while intense rain can only erode material from around rock blocks (making them unstable), and increase water pressures acting within joints. It is noted that there is only a sparse and very local geomorphological record of recently active rockfall talus fields in the Port Hills.

The expected numbers of rockfalls accumulated by events within the 100 – 1,000 year frequency band are estimated as being about half those accumulated during the >>1,000 year band, using the geomorphological evidence as a constraint. Accumulations of boulders within the 15 – 100 year frequency band are estimated from newspaper articles and the geomorphic record, while those accumulated within the 1 – 15 year frequency band are estimated using the EQC claims data and so are better constrained (Table 14).

Table 14 Example of the estimated numbers of boulders accumulated within each time-period band. These represent the estimated number of boulders leaving a source area (rock slope) over a given period of time (values in the table have been rounded to whole numbers).

Suburb	Estimated numbers of boulders accumulated from non-earthquake events in a given time period[1]			
	<1 – 15 years	**15 – 100 years**	**100 – 1,000 years**	**>> 1,000 years**
Lyttelton	30	100	375	749
Heathcote Valley	30	150	500	749
Avoca Valley 1	5	50	142	283
Avoca Valley 2	5	50	142	283
Avoca Valley 3	1	10	19	38
Avoca Valley 4	0.5	1	5	9
Horotane Valley	5	50	142	283
Sumner (Heberden Avenue)	2	20	46	91
Sumner (Wakefield Avenue)	10	50	375	749
Hillsborough (Vernon Tce. 1)	1	10	44	87
Hillsborough (Vernon Tce. 2)	1	5	44	87
Bowenvale 1	1	5	78	155
Rapaki Bay	5	50	259	518
Castle Rock	2	20	142	283
Estimated boulders accumulated per year, all areas	**7**	**6**	**2**	**0.4**

[1]Note that although up to three-digit numbers are given, only the first digit is significant

These assumptions suggest that there are about 15 rockfalls per year from other triggers, for all areas assessed in the Port Hills. The <1 – 15 year band is probably the best constrained band, as it is estimated from the EQC claims data and the GNS Science landslide database. However, the estimated accumulation rates from all events (Table 14) are higher. This is because the information in the EQC and GNS Science databases relates to rockfalls that have travelled into populated areas and been noticed. Therefore, they do not reflect the numbers of rocks derived from the cliffs that may not reach these areas and may not be noticed. The estimated numbers of rockfalls accumulated per band are thought to reasonably represent the overall rockfall rates determined from all available data sources prior to the 2010/2011 Canterbury earthquakes.

The estimated “effective” annual frequencies of the representative event per band for non-earthquake triggers are shown in Table 15.

Table 15 Annual frequency of a given number of rockfalls occurring within a given time period for all assessed areas from “other” (non-earthquake) events

Time-period band	**1 – 15 years**	**15 – 100 years**	**100 – 1,000 years**	**> 1,000 years**
Number of boulders per representative event	**1**	**10**	**50**	**100**
Suburb	**Effective annual frequencies of the representative event per band**			
Lyttelton	2.00	0.10	0.01	0.0007
Heathcote Valley	2.00	0.15	0.01	0.0007
Avoca Valley 1	0.33	0.05	0.003	0.0003
Avoca Valley 2	0.33	0.05	0.003	0.0003
Avoca Valley 3	0.07	0.01	0.0004	0.00004
Avoca Valley 4	0.03	0.001	0.0001	0.00001
Horotane Valley	0.33	0.05	0.003	0.0003
Sumner (Heberden Ave.)	0.13	0.02	0.001	0.0001
Sumner (Wakefield Ave.)	0.67	0.05	0.01	0.0007
Hillsborough (Vernon Tce. 1)	0.07	0.01	0.001	0.0001
Hillsborough (Vernon Tce. 2)	0.07	0.01	0.001	0.0001
Bowenvale	0.07	0.01	0.002	0.0002
Rapaki Bay	0.33	0.05	0.01	0.0005
Castle Rock	0.13	0.02	0.003	0.0003
All areas	**6.6**	**0.6**	**0.05**	**0.004**
Rockfall rate[1]	**6.6**	**5.7**	**2.3**	**0.4**
Total rockfall rate (Number of rockfalls per year) All bands				**15**

[1]The rockfall rate is the effective annual frequency of the representative event per band occurring, whilst making sure that the estimated rockfall accumulation rates are conserved.

The estimates of boulder accumulation rates from non-earthquake events were made from records that pre-date the recent earthquake sequence. The recent earthquakes have caused the rock masses forming the rockfall source areas to become more broken, open and dilated and therefore more susceptible to both earthquake and non-earthquake triggering events. It is therefore highly likely that rates of rockfall accumulation from other events are currently significantly elevated. The impacts of this increased frequency on the assessed risk are discussed later in the report.

4.2.2 Historical landslides other than rockfall

Rockfalls are not the only mass movement processes occurring in the Port Hills. Other types of mass movements such as landslides, e.g. debris flows and falls and translational slides (Cruden and Varnes, 1996), along with other erosion processes such as tunnel gullying and rilling also occur. Many of these tend to occur within the loess and reworked loess materials that are widespread across most of the Port Hills.

No systematic Port-Hills-wide risk assessments have been carried out for these landslide hazards in the past.

Harvey (1976) recorded 627 “soil slips” (landslides) in the Port Hills between Evans Pass and Dyers Pass from a major long-duration rain storm between 19–25th August 1975, which severely disrupted communications and transportation, and damaged housing and farms. Most of these landslides are described as mixed loess and colluvium and very few were basalt or basalt with <20% loess. Brown and Weeber (1992) report significant rockfalls on Scarborough Hill in 1968, 1970 and 1986.

Several of the recorded landslides (all data sources) have occurred within some of the areas affected by rockfalls that are assessed in this report. Historical local newspapers prior to 1930 available on-line have been searched for reports of landslide deaths in the Port Hills (E. McSaveney, pers. com.); among the many reports of landslide deaths in the early years of European settlement of New Zealand no deaths from landsliding appear to have been reported for the Port Hills area.

From this simple assessment of historical landslide data, of all the recorded mass movement processes operating in the Port Hills, earthquake triggered rockfalls appear to pose the highest risk to life. While this report is primarily concerned with assessing the life risks from rockfalls in the rockfall runout zones, it should be noted that other landslide types (such as debris flows and slides) can also occur within these same zones. Although these landslides may pose fatality risks, it is perceived, based on the precedent set in the Port Hills over the last 150 years, that they do not pose the same level of life risk as does rockfall.

4.3 Combining the triggers

The annual frequency of a given number of rockfalls occurring in each band for both earthquake triggers (using the next 50-year model results) and non-earthquake triggers can be summed for each suburb. The results, when plotted as a histogram, give an indication of the likely total numbers of rockfalls triggered over the considered period of time. These are usually referred to as magnitude-frequency plots (Figure 12). The average numbers of rockfalls triggered per year (or rockfall process rate) can be estimated as the area under the log-log histogram (Moon et al., 2005). This allows the relative importance of the different rockfall triggers to be assessed over time. These data show that:

1) Earthquakes contribute more to the overall numbers of boulders triggered than do other triggering events;
2) Other events (non-seismic) contribute significantly to boulder numbers in the bands of more frequently occurring smaller events but their boulder contribution is overwhelmed by the numbers falling in rare earthquakes (Figure 12); and

3) Earthquakes dominate the boulder-triggering events that occur every few hundred years, but other triggers dominate the boulder numbers for events that occur every few decades or less.

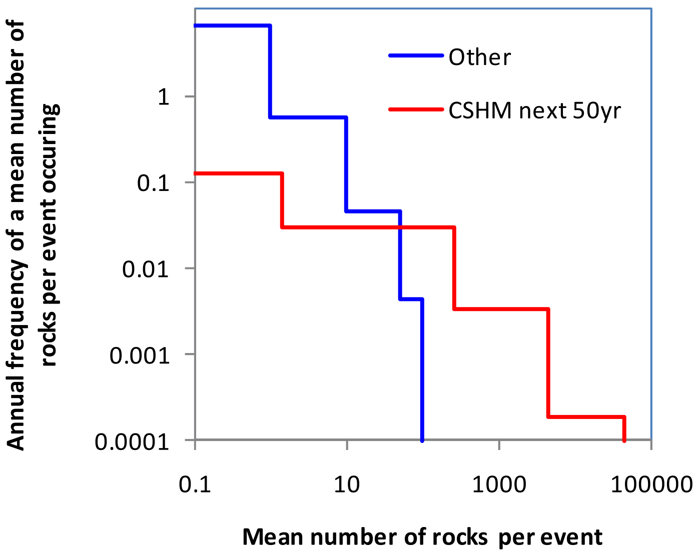

Figure 12 The rockfall frequency magnitude model developed for this study incorporating earthquake and other rockfall triggers. The frequency and magnitude of earthquake-triggered rockfalls shown are based on the next 50-year median from the composite seismic hazard model (CSHM).

The effects of using the next 1-year seismic hazard model results instead of the 50-year results are compared in Figure 13. The effect of using results for the next 1-year is a higher risk of a rockfall-triggering earthquake, and thereby a higher risk of a given number of rockfalls occurring.

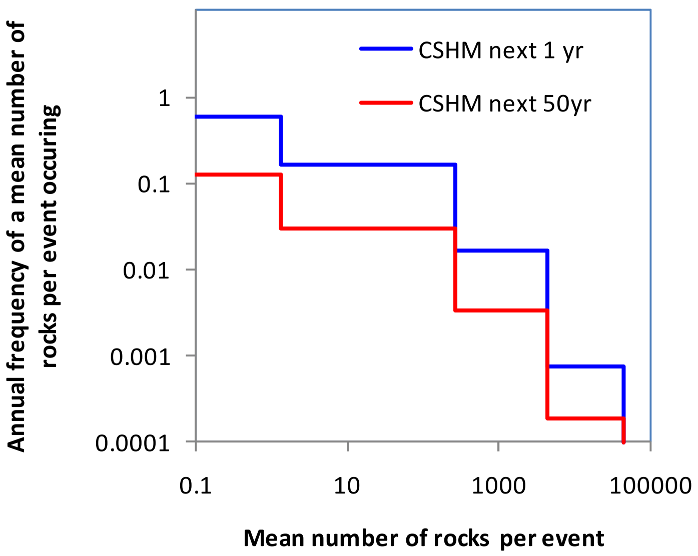

Figure 13 The rockfall frequency magnitude model developed for this study comparing results using the composite seismic hazard model (CSHM) for the next 1-year and the next 50-years. Plot is for all assessed suburban areas.

5.0 CONSEQUENCES OF ROCKFALLS

This analysis uses about 5,719 boulders (fallen rocks) that were mapped in the Port Hills area covered by this assessment (Appendix A). Of these, about 3,263 boulders come from the Christchurch City Council database (dated 11/10/2011) and about 2,456 boulders from the GNS Science database (Table 16). These boulders are assumed to have been triggered by the 22nd February 2011 earthquakes. For the same area, the Christchurch City Council and GNS Science databases contain about 398 and 36 mapped rockfalls respectively, which are attributed to the 13th June 2011 earthquakes. However, not all areas affected by the 13th June earthquakes have been re-mapped.

The GNS Science database contains boulders mapped in the more remote or difficult areas e.g. immediately below cliffs, on steep ground and in non-residential areas, detected on the post-22nd February 2011 earthquake digital aerial photographs, with some field verification. Those contained in the Christchurch City Council database were field mapped, primarily in the residential areas. Where overlaps between data sources occur only Christchurch City Council data has been used.

Table 16 Summary of mapped fallen rocks triggered by the 22nd February and 13th June 2011 earthquakes.

Number of fallen rocks attributed to the 22nd February 2011 earthquakes in the areas analysed in this project, from the Christchurch City Council database	3,263
Number of fallen rocks attributed to the 22nd February 2011 earthquakes in the areas analysed in this project, from the GNS Science database	2,456
Total number of fallen rocks attributed to the 22nd February 2011 earthquakes in the areas analysed in this project (the sum of both databases with no overlap)	5,719
Total number of fallen rocks attributed to the 13th June 2011 earthquake in the areas analysed in this project (the sum of both databases with no overlap)	434
Total number of individual fallen rocks (contained in both the CCC and GNS Science databases) with unique dimensions and volumes recorded	2,121

5.1 Characterising boulders and their sources

5.1.1 Rockfall source areas

The rockfall sources may be natural slopes or excavated faces, and are recognised by the steep topography and geology of the site. With respect to the topography, the slope angle must be steeper than about 37º in order to generate rockfalls, and the higher the slope the greater the velocity that rockfalls can attain (Wyllie, 2006). Rockfall source areas in the Port Hills typically are outcrops of basaltic lava flows. These tend to form steep (typically >40°) rocky bluffs. In some locations, only one particular rock outcrop is present (e.g. Castle Rock), in others, there are multiple rock outcrops present at different elevations (e.g. Heathcote Valley) separated by slopes at lower angles formed in weaker materials. The heights of the rock source areas also range from a few metres to tens of metres.

The stability of a rockfall source area is dependent on several geological factors: first is the rock material type—its strength and how it varies across the rock slope. Second is the orientation and spacing of rock discontinuities relative to the aspect and angle of the rock slope; they determine the likely failure mode of the rock blocks falling from the slope, e.g. toppling or sliding (Wyllie, 2006). Another factor is the state of the discontinuities, whether they are open, in-filled, weak, or strongly interlocking. The shape of the source area (its geometry in terms of slope angle, height and aspect) is another important factor, especially with respect to the earthquake triggering of rockfalls. Recent studies have shown that the slope gradient is the topographic attribute most sensitive to amplified seismic response, followed by the relative height of the slope (Muhammad et al., 2011). Topographic and geological factors can combine to cause localised amplification of ground shaking; these are typically referred to as "site effects" (Del Gaudio and Wasowski, 2010).

The relative stability of each rock slope was not assessed in this study. Given the magnitude of the 22nd February and the 13th June 2011 ground accelerations (both horizontal and vertical components), it is likely that many boulders were thrown from the slope rather than dislodged through sliding or toppling. The control of discontinuities on kinematic stability in the rockfall source areas was likely to have been minimal under such extreme dynamic conditions. These assumptions are supported by site observations made by residents in Port Hills at the time of these earthquakes.

Rockfall-source areas were mapped from the post-22nd February 2011 earthquake ortho-rectified aerial photographs, using a slope model (where slopes >35° were assumed to be rock) derived from the digital elevation model from LiDAR (Light Detection And Ranging) measurements collected after 22nd February 2011. The area of each source, within each suburb used in the risk assessment was calculated using the LiDAR digital elevation model, resampled to 3 m ground resolution. To reflect the steepness of the rock-slope source areas, the surface area and not plan area were used. These surface areas were compared to the number of boulders derived from them. These were calculated from the combined rockfall database, counting only the boulders within the areas used for the hazard analysis that passed the toe of the rock-slope source area (Figures 14 and 15).

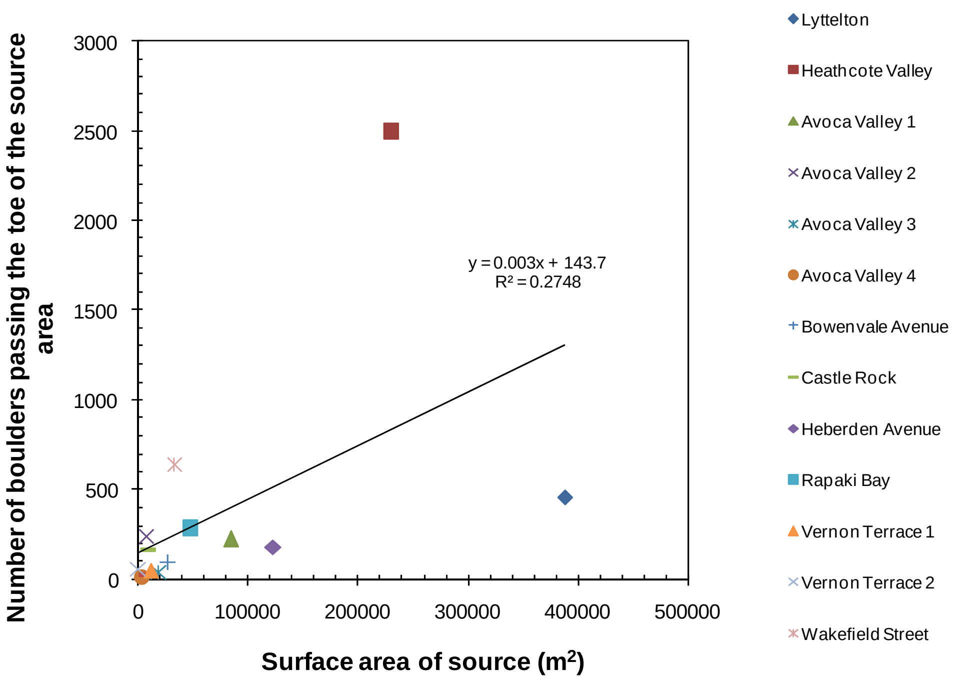

Figure 14 Surface area of rockfall sources, plotted against the number of boulders leaving the source, per listed area in the Port Hills using the mapped rockfalls triggered by the 22nd February 2011 earthquakes.

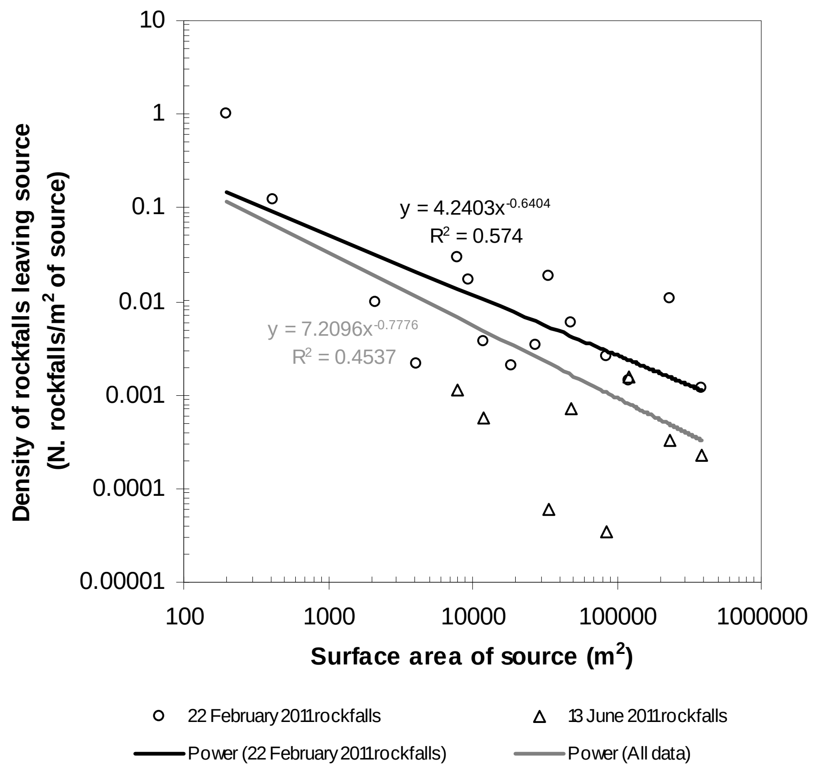

Figure 15 Surface areas of rockfall sources plotted against the density of rockfalls leaving the source, for all areas analysed in this report. Data relate to mapped rockfalls triggered by the 22nd February and 13th June 2011 earthquakes.

Results show a poor linear relation between source surface area and boulders passing the toe of the source. Linear regression gives a gradient of 0.003 (±0.001) boulders per m^2 of source (error at one standard deviation), which is about 1 boulder per 300 m^2 of source. However, the source areas are not uniformly distributed; they are clustered, with many boulders falling from unique sources. The poor relation may be due to other variables such as geology, local-scale topography, and the effects of these on locally amplifying the shaking.

5.1.2 Boulder size distribution

The size (magnitude) of a rockfall is a function of the persistence and spacing of discontinuities in the source area, and the number of fragments the fallen boulder breaks into as it travels down slope.

The frequency-magnitude distribution of the boulders that fell during the 22nd February and 13th June 2011 earthquakes were derived from the Christchurch City Council and GNS Science rockfall databases. These databases contain the location, dimensions (a, b and c axes) and shape of many boulders that fell. Volumes have been calculated by multiplying the a-, b- and c-axes, with the resulting volume reduced by 30% as an approximate adjustment for boulder shape.

Breakage of boulders as they travel from source is not relevant to this report as the assessed frequency-size distribution represents only “fallen” boulders, and not boulders still in the source area.

Out of the combined 5,719 mapped boulders, unique volumes have been recorded for about 2,121 boulders (Table 16). The magnitude- (volume) frequency (number of boulders) distribution of these rockfalls can be modelled with a power law over most of the range. The power law does not fit below at about 0.7 m^3 (Figure 16), indicating fewer and fewer boulders at increasingly smaller sizes. This is believed to arise largely from a sampling bias, arising from the difficulty of detecting all smaller boulders lying in long grass and scrubland.

Of the mapped rockfall particle size distribution, the 50th percentile (50% of the total population) is about 0.5 m^3 and the 95th percentile is 3 m^3. For the purpose of this study a design boulder size of 1.0 m (diameter) has been adopted.

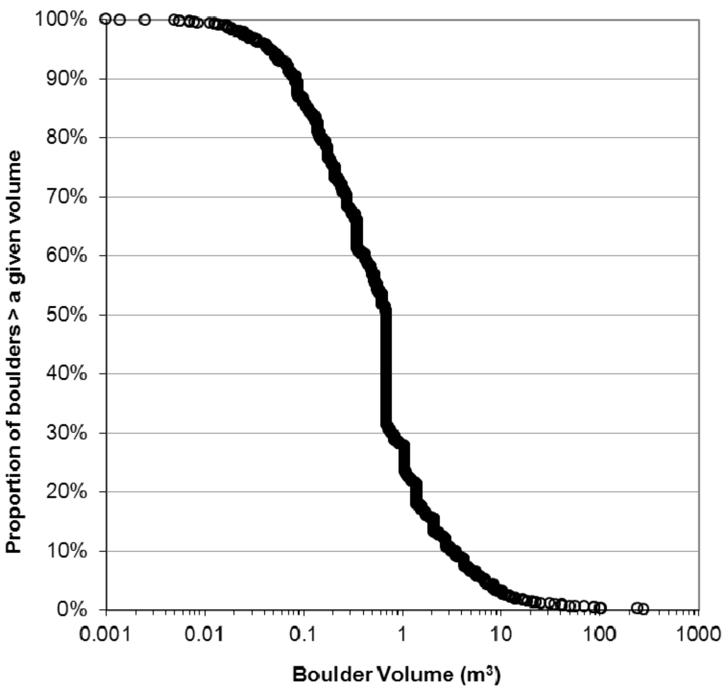

Figure 16 Rockfall size distribution as a proportion of boulders greater than a given size (n = 2,121) plotted in log-space. These data are of the mapped boulders with volumes recorded that fell on 22nd February and 13th June 2011.

The fallen boulders are predominantly tabular in shape, with one axis larger than the others. Most rockfalls begin to roll and bounce their way down slope, with the boulder gathering angular momentum. At fast rotations, only the corners along the longest perimeter make contact with the slope. Thereby the centre of gravity moves along an almost straight path, which is an efficient mode of motion with respect to energy loss. This combination of rolling and short bounces is one of the most economic displacement mechanisms (Dorren, 2003) and helps explain the long runout distances of rockfalls in the Port Hills.

5.2 Characterising boulder runout

5.2.1 Evidence from recent earthquakes

The probability of a boulder landing on an area of slope depends upon the distance the boulder can travel. The distance a boulder travels is termed the runout distance. Runout depends on: 1) the size of the boulder; 2) profile of the runout path; 3) the nature of the materials hit along the path; and 4) the mode of motion, which is strongly influenced by boulder shape, the slope and the materials forming the slope along the path.

The depositional patterns of rockfalls reflect certain regularities, such as gravity sorting by size, wherein the largest boulders tend to reach the base of the slope, and the frequency of boulders passing decreases with distance from the source area (Evans and Hungr, 1993).

The runout of boulders that fell around the 22nd February and 13th June 2011 were firstly assessed by comparing the distance of the mapped fallen boulders from their nearest likely source area (Figure 17), using those mapped fallen rocks from the main suburbs in the Port Hills. The plotted data appears to show a sample bias at distances below about 100 m; observer health and safety considerations often precluded boulder mapping closer to the source areas. The majority of the rockfalls that were mapped were located in the residential areas of housing, which in most cases tend to be located away from the source areas. There is also a problem in determining where the boulders came from; the analysis assumes that they came from the closest mapped source area, which we consider an appropriate assumption, but cannot be proven to be the case. In general, the number of boulders reaching a given distance decreases from the source, and can be modelled, in part, using a power law.

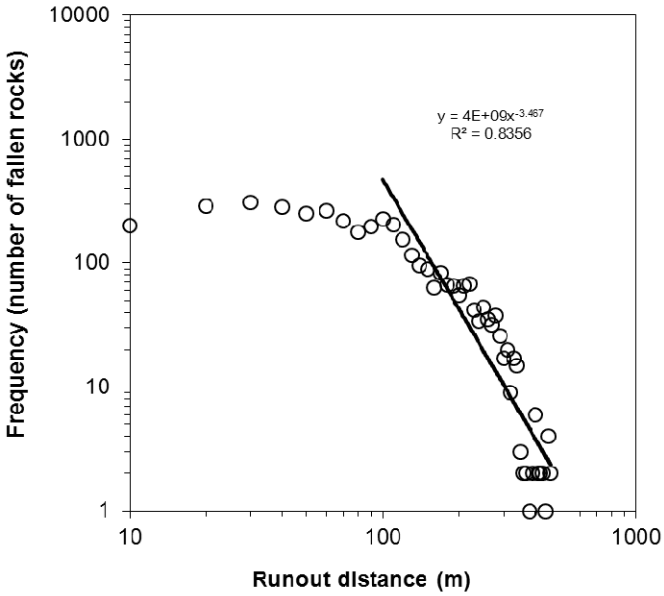

Figure 17 Frequency runout plot of boulders that fell on the 22nd February and 13th June 2011, mapped in the main suburbs. Distances are measured as plan distance from the mapped fallen boulder to the nearest upslope source area (n = 3,902). Bin size is 10 m.

The runout of rockfalls triggered by the 22nd February 2011 earthquakes have been assessed using empirical models, based on relationships between topographical factors and the lengths of runout of the boulders (Dorren, 2003). Sometimes these models are referred to as statistical models (Keylock and Domaas, 1999).

GNS Science mapped 66 selected trails left by boulders that fell during the 22nd February 2011 earthquakes. These trails were selected because it was possible to identify the rockfall end point, its likely source, and its trail, as marked by bounce marks left by the boulder as it travelled. Boulder trails were mapped in all of the main areas. In addition to field-mapped trails, additional trails were included where they could be clearly identified on post-earthquake New Zealand Aerial Mapping aerial photographs. To be “clearly identified”, the likely source area, trail (bounce marks or linear tracks through vegetation) and end point of the rockfall had to be apparent.

Trails were plotted using the New Zealand Aerial Mapping 10 cm ground resolution orthorectifed air photographs. Topographic profiles (sections) were generated for each mapped rockfall trail. The sections were generated from the 2011 post-earthquake LiDAR digital elevation model, resampled to 3 m ground resolution.

Data from the mapped trails were analysed using the following empirical models (Figure 18):

1) Fahrboeschung ("travel angle") method (Keylock and Domaas, 1999)

The Fahrboeschung is the slope of a straight line between the starting point and the stopping point for a given boulder (Figure 21). For the analysis presented here, where the starting point of the rockfall is not known, it was assumed to be the convex break in slope at the top of the highest (in elevation) rock slope;

2) Shadow-angle method (Lied, 1977; Evans and Hungr, 1993)

The shadow angle is the angle between a horizontal plane and a straight line from the toe of the source area (top of the talus slope) and the stopping point of the boulder, along the trail of the boulder;

3) Runout ratio method (Keylock and Domaas, 1999)

The runout ratio is the ratio between the horizontal length of the runout zone to the combined horizontal length of the talus slope and the free rock face (source area); and

4) Alpha (α) minus beta (β) method (Keylock and Domaas, 1999)

In the Alpha (α) minus beta (β) method, the average energy of a geological process (e.g. rockfall) can be approximated by the tangent of the α angle, which exhibits a correlation with the tangent of β, where β represents the energy line of a rockfall stopping at the foot of the talus.

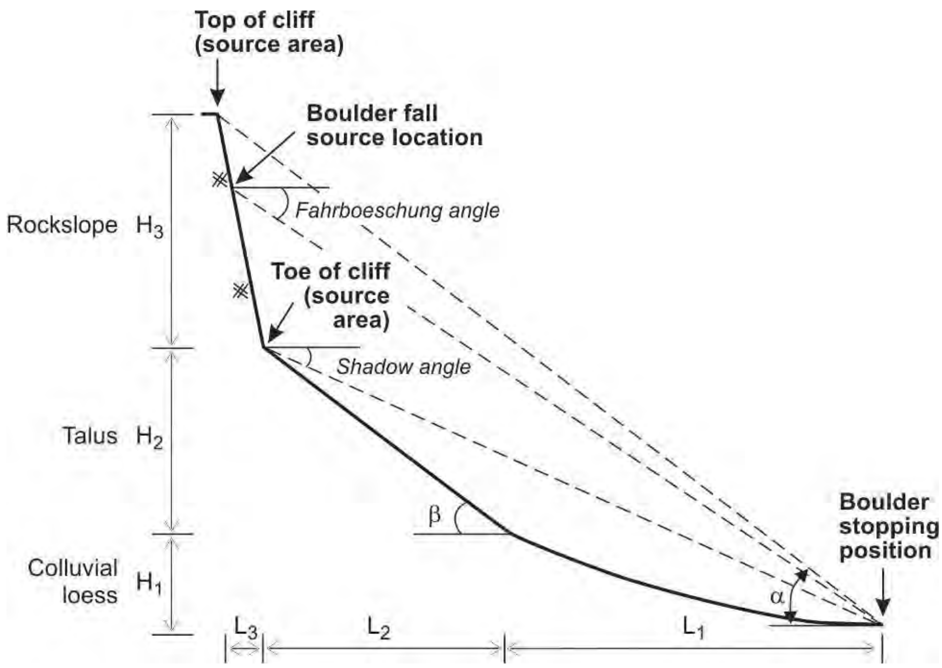

Figure 18 Schematic diagram illustrating the terrain parameters used in this study to assess empirical rockfall runout relations.

For each of the 66 mapped trails the boulder runout was analysed using:

1. Fahrboeschung;
2. Shadow angle;
3. Runout ratio model; and
4. Alpha (α) – Beta (β) model.

Linear regression was used to assess the relative performance of each statistical model (Figure 19).

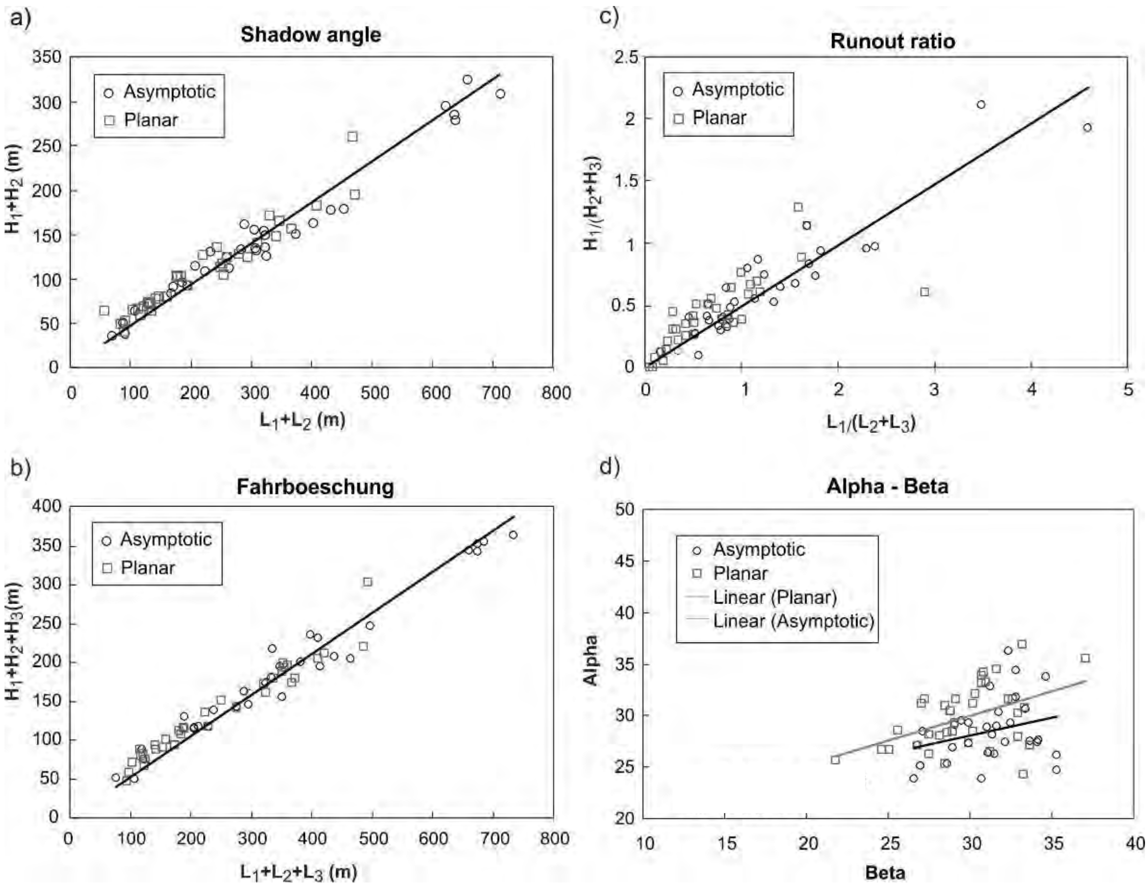

Figure 19 Rockfall runout for those boulders triggered by the 22nd February 2011 earthquakes (n = 66) plotted using empirically based runout models: A) Shadow angle model; B) Fahrboeschung; c) Runout ratio; and d) Alpha - Beta.

The Fahrboeschung and shadow-angle models performed well statistically (Appendix B), with little difference between the two. The runout ratio and Alpha – Beta models performed poorly, this was possibly due to a difficulty in defining loess and talus boundaries along the trails.

The purpose of the statistical analysis was to determine which model would provide the most reliable way of interpolating between and extrapolating from observed boulders to provide a “best estimate” of average runout to be expected across a wide spectrum of possible trigger events. The Fahrboeschung takes into account the height of the source area and therefore the potential energy of the rockfall, and assumes a rockfall from a high source area (steep rock slope) will travel further than one from a smaller less steep slope. The shadow angle assumes that the kinetic energy acquired by the boulder in the initial fall is largely lost (about 75-86%, Dorren, 2003) in the first impact on the talus surface near the toe of the rock-slope source. Thus, the height of the fall has little influence over the runout (Evans and Hungr, 1993). The shadow angle therefore represents the slope of the energy line, i.e. the rolling-friction gradient.

For rockfalls triggered on 22nd February 2011, the minimum mapped shadow angle was 21°, and the minimum Fahrboeschung is about 24°. The empirical relationships from the 66 trails shows there is no statistical difference between the two methods, they both performed equally well. However, if the height of the source area was a controlling factor on runout then the runout ratio model should perform the best statistically. Results from the 66 trails indicate this model performed poorly (Figure 19 and Appendix B). It has also been found in several studies that the Fahrboeschung overestimates the runout of rockfalls (e.g. Copons et al., 2009). These data suggest that the main control on rockfall runout in the Port Hills appears to be the morphology of the slope below the source and that the correlation with shadow angle rather than Fahrboeschung should provide the best estimate.

In some areas of the Port Hills there are steep rock cliffs that have essentially flat slopes at their toes. These are mostly now-abandoned relict sea cliffs. Where the larger of these cliffs collapsed in response to the recent earthquakes (e.g. Redcliffs, Wakefield Avenue and Shag Rock Reserve), the runout limits of the debris have been mapped. Empirical relationships between cliff height and debris runout such as the Fahrboeschung give minimum angles of about 31 degrees and suggest that cliff height is the main control on debris runout on flat ground.

However, when compared to steep rock slopes where there is sloping ground at the toes of bluffs, which allows debris to start rolling and bouncing (e.g. boulder roll), the minimum recorded Fahrboeschung is about 24°. The difference between the two scenarios (flat ground versus sloping ground at toe) suggests that for boulder rolls, the cliff height (or height of fall) is not as important as the slope angle of the ground below the toe of the cliff.

Locally some suburbs (e.g. Sumner (Heberden Avenue)) include minor (small in height) relict sea cliffs, or minor abandoned quarries, of limited length at the base of slopes that are subject to a risk of boulder roll from above. At such localities, the current report assesses the risk from boulder roll as if there were no cliff at the base, and as if the slope continued beyond. This is a limitation of the suburb-scale assessment, and is an important reason for recommending site-specific assessments which will be able to recognise specific additional hazards which contribute to the local risk.

Equally, locally where boulder rolls have run out far enough to reach essentially flat ground, the suburb-scale assessment that assumes sloping ground will overestimate the local risk. This recognised problem is known to apply locally in several of the suburbs assessed.

5.2.2 Estimating boulder runout from data

The risk to an individual on a slope susceptible to rockfalls results not only from boulders stopping at a location but also from those passing the location to stop further down slope (Evans and Hungr, 1993).

The numbers of boulders reaching or passing a given distance on a slope within a runout zone was estimated by:

$$P_{L1} = \frac{\left[\frac{(N - N_1)}{N}\right]}{L_1} \quad [4a]$$

$$N_{L1} = \frac{(N - N_1)}{L_1} \quad [4b]$$

where P_{L1} is the proportion, and N_{L1} the number of boulders (of a given size, i.e. the design boulder) reaching or passing a unit length of slope perpendicular to the runout path; L_1 is the unit length of slope perpendicular to the runout path within the entire runout zone (at given intervals down the slope); N is the total population of mapped fallen boulders within the runout zone; and N_1 is the upslope population of mapped boulders stopping before L_1 (Figure 20).

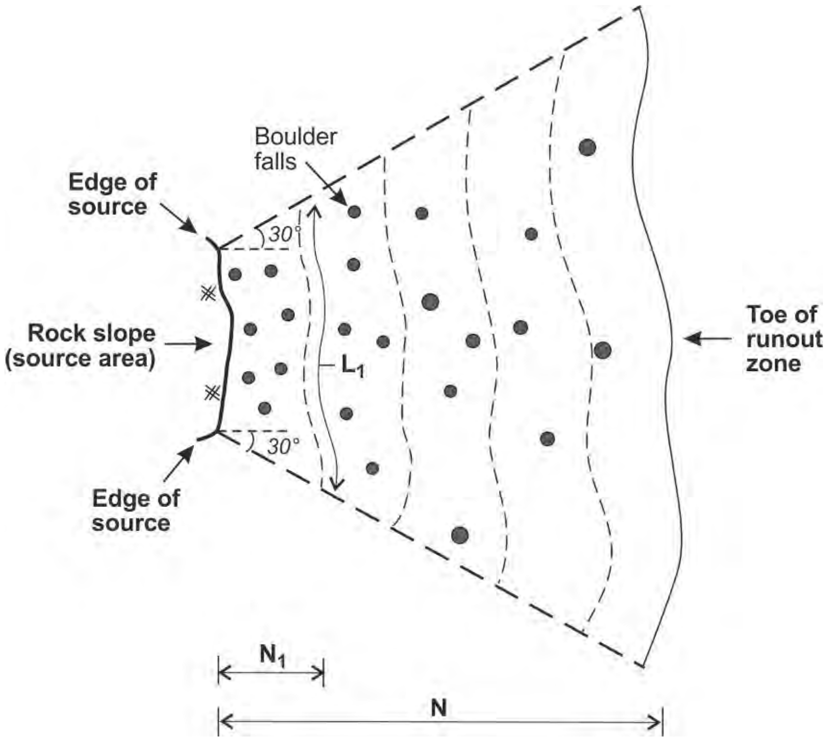

Figure 20 Diagram showing how the number of boulders reaching or passing a given location was calculated

The numbers of boulders reaching or passing a unit length of slope perpendicular to the runout path L have been calculated using the shadow angle approach. It should be noted that L in most cases is not a simple straight line but is instead a wavy line that meanders over the slope, thereby increasing the length of the line and therefore decreasing the probability of being in the path of a boulder on that line. This is an acknowledged shortcoming of this approach.

The number of boulders reaching or passing a given shadow angle per suburb have been used in the risk assessment. These numbers have been estimated, where possible, directly from the actual rockfall distributions recorded in each suburb. Rockfall shadow angle zones were generated for each suburb using the ArcGIS "visibility" tool. The runout zone is defined as the section of slope under a straight line, which is projected at an angle of 21° (the minimum recorded shadow angle) from the toe of the lowest (in elevation) rock slope (or apex of the talus) to intersect the ground surface.

The visibility tool works by assessing which areas can be seen or not seen from a particular location. In this case it was used to assess what areas of slope could be seen from the toe of the rockfall source areas (toe of the rock slopes), using the minimum rockfall shadow angle. Whether or not an area of slope can be seen (and is therefore within the minimum shadow angle) was determined using an elevation grid of 3 m resolution, derived from the post-earthquake LiDAR. The visibility of each grid cell (from a source area) was determined by comparing the altitude and angle of the grid cell with the altitude and angle of the local horizon. The local horizon is computed by considering the intervening terrain between the point of observation (each node on the line defining the toe of the rockfall source area) and the current grid cell. If the point lies above the local horizon, it is considered to be visible. The process was repeated for shadow angles of 22°, 23°, 24°, 25°, 27°, 29° and 31°. One degree shadow angles were used in the distal runout zones as these are more populated, whilst two degree angles were used in the upper, typically unpopulated, zones.

Once generated, the toe of each 21° visibility grid was digitised, and this formed the limit of the runout zone. In some cases, the toe of the visibility grid extended across drainage lines and up adjacent slopes. In such cases, the grids were clipped to the drainage lines, as it was deemed unlikely a rockfall would cross the drainage line. The edges of each runout zone were delineated by projecting a line perpendicular to the end point of the line delineating the lowest (in elevation) rock-slope toe. An angle of 30° was added to this line, which takes into account site observations where observed rockfall trails deviated up to about ±30° from the line of greatest slope.

5.2.3 Estimating limits of boulder runout beyond "tail" of the data

An important uncertainty in the risk assessment involves estimating the likelihood that future boulders might travel beyond the lowest shadow angles reached in the 22nd February and 13th June 2011 earthquakes. From the combined rockfall databases only 2 boulders travelled further than the 21° shadow angle, both of these are located in Avoca Valley.

The risk model assumes that the numbers of boulders reaching/passing a given shadow angle in any future earthquake will be in the same proportion as boulders generated by the 22nd February 2011 earthquakes for the specific suburb in question. A realistic assessment, however, also needs to consider the possibility, and estimate the probability, of boulders reaching further downslope than was observed on 22nd February 2011. This is particularly important for those areas located at some distance from the epicentres of the 22nd February and 13th June 2011 earthquakes, as these areas (mainly Cashmere and Bowenvale) did not experience the large ground accelerations that the other locations endured. If a future earthquake were to occur with an epicentre closer to Cashmere and Bowenvale, more boulders be expected to fall there and some of these would probably travel further than boulders did there in 2011. Also, account needs to be taken of those boulders that may pass the 23° shadow angle, but not reach the 22° shadow angle.

A simple statistical model was used to estimate the proportion of boulders that could travel further than those observed in February. This model assumes that the first shadow-angle zone that no boulders were observed to reach has a 50% chance of no boulders reaching it, and a 50% chance of at least one boulder reaching it. It then estimates the probability of an individual boulder transferring from the uphill shadow-angle zone passed this first boulder-free shadow angle. To do this, an attenuation factor *X* is calculated, where *X is* the proportion of boulders we would expect to reach the first zone with zero boulders, using the 22nd February 2011 boulder distributions., This attenuation factor is applied to the first zero-boulder shadow angle, with *X* such that the probability of no boulders in first zero-boulder zone is 50%.

$$P_0 = 1 - (1 - X)^N \quad [5a]$$

$$X = 1 - (1 - P_0)^{(1/N)} \quad [5b]$$

where: P_0 is the probability of zero boulders in a given zone (assumed to be 50%); *N* is the number of boulders that reached/passed the shadow angle zone immediately uphill from the first zero-boulder zone; and *X* is the attenuation factor.

As an example, for Vernon Terrace 1 the last shadow angle passed by boulders triggered by the 22nd February 2011 earthquakes was 24°. The number of boulders passing this line and entering the next zone (24° – 23° zone) was 1, about 2% (0.022) of the total number of boulders leaving the source. Using Eq. [5b] the attenuation factor (X) from 24° to 23° is 0.5, therefore the expected (modelled) proportion of boulders (as a proportion of those triggered by each earthquake) reaching the 23° shadow angle is about 1% (0.022 x 0.5 = 0.011).

At Avoca Valley 1, 19 boulders triggered by the 22nd February 2011 earthquakes passed the last shadow angle of 22°, but stopped in the 22° – 21° zone. This is proportion of 9% (0.086) of all those leaving the source area. The attenuation factor from 22° to 21° is 0.036 (using Eq. [5b]), therefore the modelled proportion of boulders reaching the 21° shadow angle is estimated as 0.3% (0.086 x 0.036 = 0.003).

This model does not model the true physical characteristics of the landscape. Features such as dips in the land, flat areas (roads), trees and other major obstructions such as houses may trap boulders in the last shadow-angle zone reached in the 2011 Canterbury earthquakes with no possibility of boulders travelling further. Or, on the other hand, features such as smooth, hard surfaces with a consistent or increasing slope might allow a proportion of boulders to travel beyond the limits reached in 2011. Such features alter the probability that a boulder could pass the next shadow angle. Perhaps it was just chance or the particular source or nature of a boulder that prevented it following a path that carried it further downslope. The simple model does take into account that, in areas such as Avoca Valley 1 where 19 boulders passed one shadow angle but not the next, that there may be some physical barrier preventing further travel.

Numerical rockfall models can take into account topography, the nature of the land surface and the characteristics of boulders to predict with greater detail the likely paths and distances travelled by boulders in rockfalls. These models are largely developmental and are time-consuming to use as they require collection and input of much local geographic data. It was not possible to apply them at a suburb-scale, but they have been used at specific sites where the simpler model produced risks that appeared anomalously high or low. These specific rockfall models were calibrated with the observed data.

5.2.4 Rockfalls reaching or passing each shadow line

The proportion of boulders triggered by the 22nd February 2011 earthquakes that left source areas and travelled a given distance downhill decreases with distance from the source area (Table 17). Therefore the probability of a rockfall boulder reaching or passing a given shadow angle decreases as the shadow angle decreases. To take this into account in the risk assessment, the number of boulders leaving a source and reaching or passing a shadow line of a given angle was calculated for each runout zone in each suburb. These steps in the analysis are shown in Figures 21 and 22, with the results shown in Figure 23. Boulders triggered by the 22nd February 2011 earthquakes as mapped for Christchurch City Council and GNS Science were used in the analysis. These proportions were used to apportion the numbers of boulders triggered by other events passing a given shadow angle.

For each suburb, modelled values were used only for the first shadow angle that no boulders reached or passed. That is, it was assumed that the proportion of boulders which would reach or pass the second and subsequent shadow angles where no boulders were observed in the 22nd February 2011 earthquakes was zero.

Table 17 Proportions of boulders passing specified shadow zones (as a percentage of the total number of boulders triggered) as used in the risk model (all suburbs) calculated using those rockfalls triggered by the 22nd February 2011 earthquakes. The highlighted proportions are those estimated using the statistical model.

Suburb	No. of Boulders	Source of Toe	31°	29°	27°	25°	24°	23°	22°	21°
Lyttelton	453	100%	52.8%	41.9%	28.5%	17.2%	11.9%	6.4%	2.4%	0.1%
Heathcote	2465	100%	69.4%	42.3%	15.9%	6.6%	4.0%	2.1%	0.8%	0.03%
Avoca 1	220	100%	80.9%	50.5%	42.3%	33.2%	28.2%	16.4%	8.6%	0.3%
Avoca 2	222	100%	90.6%	81.3%	67.9%	48.2%	40.6%	5.4%	1.8%	0.9%
Avoca 3	38	100%	13.2%	5.3%	2.6%	1.3%	0.0%	0.0%	0.0%	0.0%
Avoca 4	9	100%	88.9%	88.9%	55.6%	33.3%	11.1%	5.6%	0.0%	0.0%
Horotane	354	100%	94.6%	84.7%	62.7%	30.8%	17.2%	6.8%	0.2%	0.0%
Sumner (Heberden Ave.)	176	100%	40.9%	15.9%	2.8%	1.1%	0.0%	0.0%	0.0%	0.0%
Sumner (Wakefield Ave.)	766	100%	52.9%	16.3%	6.3%	3.1%	2.2%	0.4%	0.1%	0.0%
Hillsborough (Vernon Tce. 1)	46	100%	73.9%	39.1%	10.9%	2.2%	2.2%	1.1%	0.0%	0.0%
Hillsborough (Vernon Tce. 2)	52	100%	82.7%	63.5%	21.2%	1.9%	1.9%	1.9%	1.0%	0.0%
Bowenvale 1	99	100%	27.3%	13.1%	5.1%	2.0%	0.6%	0.0%	0.0%	0.0%
Rapaki	277	100%	50.5%	35.0%	20.6%	11.9%	7.6%	5.1%	0.7%	0.2%
Castle Rock	540	100%	80.6%	58.3%	10.0%	0.2%	0.1%	0.0%	0.0%	0.0%

Highlighted values are those modelled beyond the runout limits of the actual mapped rockfalls

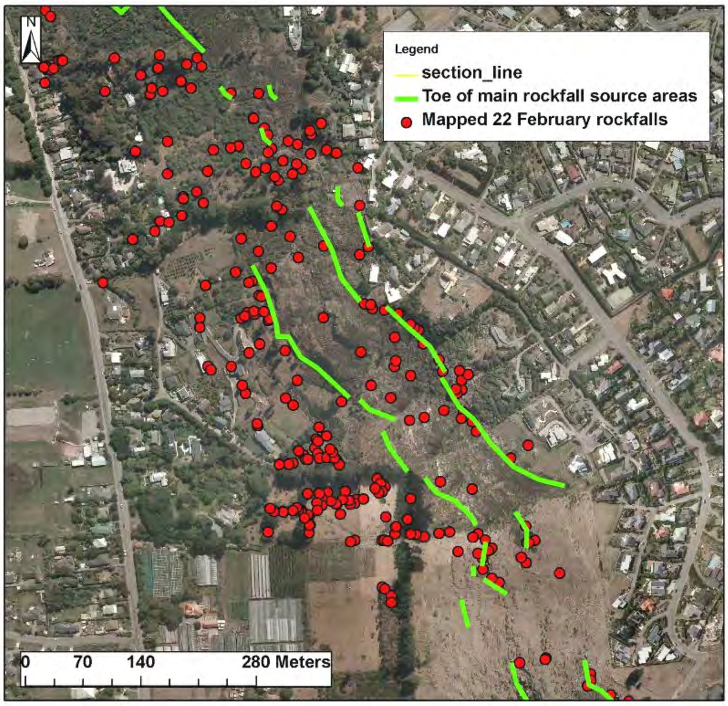

Figure 21 Example showing mapped rockfalls from the 22nd February 2011 earthquakes and the toe of the main source areas.

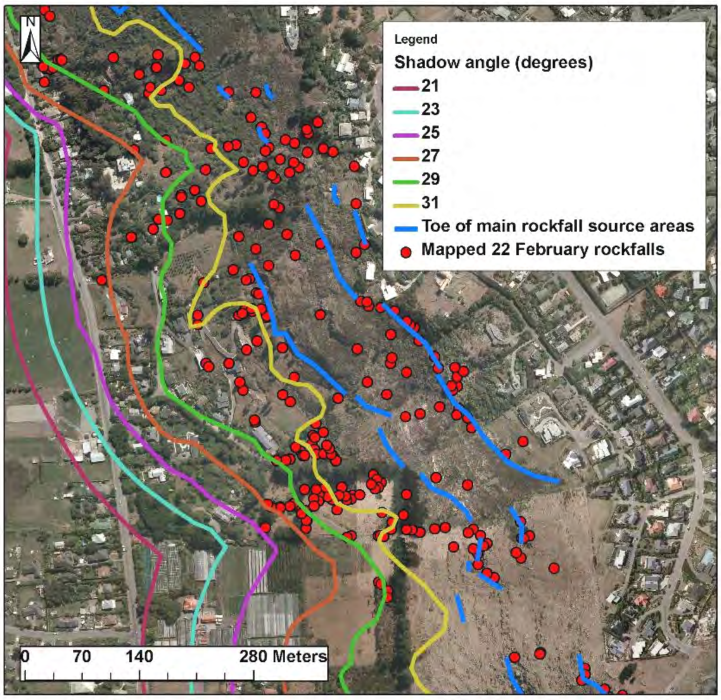

Figure 22 Example showing mapped rockfalls from the 22nd February 2011 earthquakes, the toe of the main source areas (rock cliffs) and the shadow angles projected from the toe of the lowest source areas.

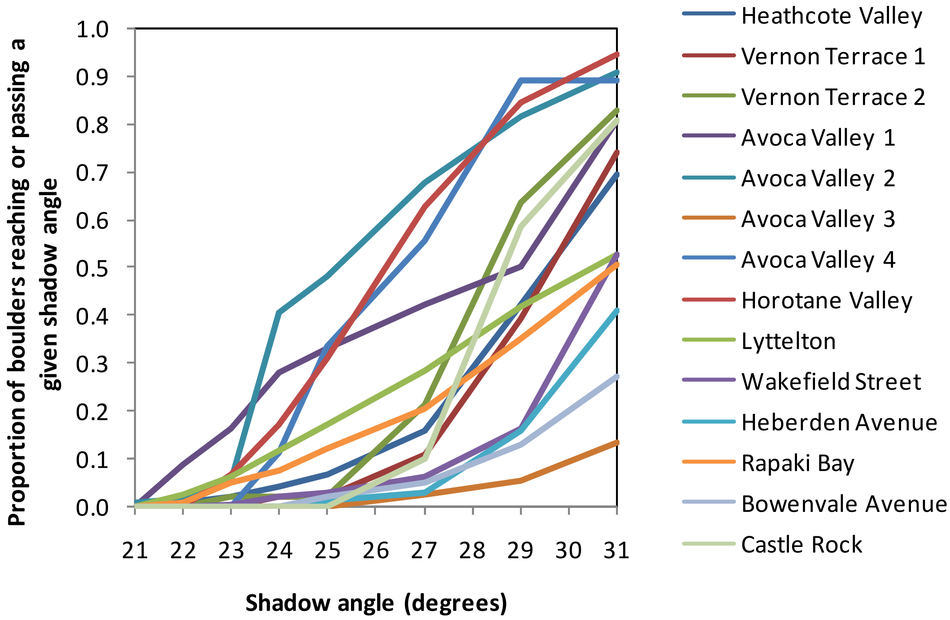

Figure 23 Proportion of rockfalls triggered by 22nd February 2011 earthquakes, reaching or passing a given shadow angle, for each suburb or given street within the suburb in the Port Hills, expressed as a proportion of all the boulders leaving the source area.

Variability in the number of rockfalls passing per linear metre of slope within a suburb was estimated from the standard deviation among suburbs. The 90% confidence limits of the mapped number of rockfalls passing a given shadow angle for each suburb was then determined by adding 1.65 times this standard deviation to the mean value for the suburb (Table 18). These data suggest significant variation exists among the suburbs and that the variations increase significantly in the distal runout zones.

Table 18 Estimated uncertainties on the numbers of rockfalls passing a given shadow angle line (all suburbs) calculated using those rockfalls triggered by the 22nd February 2011 earthquakes.

Shadow angle (°)	Mean % of boulders reaching or passing (all suburbs)	Standard deviation of mean (% passing) (all suburbs)	90% Limit (% passing) (all suburbs)
31	60.3%	6.3%	10.4%
29	42.4%	7.2%	11.9%
27	23.5%	6.1%	10.0%
25	12.8%	4.3%	7.0%
24	8.5%	3.3%	5.4%
23	3.0%	1.2%	2.0%
22	0.8%	0.6%	1.1%
21	0.1%	0.1%	0.1%

5.2.5 Topographic forcing

The adopted suburb-scale risk model assumes that the topography over which the boulders roll from their sources is uniform across the suburb and does not divert boulders into preferred pathways or deflect them from others. In reality, some parts of some slopes do modify the direction of boulder paths. This is called topographic forcing; it includes channelling (focusing) and deflection, which was beyond the scope of a suburb-scale assessment to consider, and was evaluated by site inspection.

Topographic focusing of rockfalls (channelling of rockfall paths by topography) has been noted for some localities and the risk maps modified to account for it. Topographic focusing is not always by a clearly defined channel, but more often by a subdued depression. Three sites were identified (Heathcote Valley, Avoca Valley and Lyttelton) where topographic focusing of rockfalls was particularly apparent in the mapped 22nd February 2011 earthquake-triggered rockfalls.

The areas of interest were first outlined by polygons following morphological boundaries that defined the depression/confined area. The number of boulders passing each of the shadow lines within each polygon was then calculated, and divided by the length of the shadow line within the polygon (to give the number of boulders passing per metre per shadow line).

These values for the depression/confined area were then compared to the open-slope values (number of boulders passing per metre per shadow line) to calculate the ratio (confined divided by open) and percentage change ((confined - open)/open).

Results show that the ratio between channelled versus open-slope settings of numbers of boulders passing per metre per shadow line ranges from 1.5 to 7, with a mean of 3.3. The distribution is approximately normal but the standard deviation is ±1.6 (on 15 degrees of freedom), which reflects the large variation in values.

The mean ratio increase is 3.3 ± 0.4 (1 standard error of the mean) or a conservative factor of 4 using the 90% probability limit. This suggested that where an area is affected by topographic focusing, the number of boulders passing a particular shadow angle should be increased. Topographic focusing was considered in site-specific assessments.

In addition to focussing of boulders, there is also topographic deflection of boulders which has also been identified at a few sites, and this too was considered in the site-specific assessments shown in the accompanying risk maps.

5.3 Probability an object is in the path of a boulder

$P_{(S:H)}$ is the probability of a rockfall hitting a portion of slope as it travels downhill from the source area. The probability of one boulder hitting an object when passing through a particular portion of the slope, perpendicular to the boulder path, is expressed as.

$$P_{1(S:H)} = \frac{(2D+d)}{L} \qquad [6a]$$

where D is the diameter of the design boulder (assumed to be 1.0 m) that travels along a path either side of d, within which the boulder cannot miss, where d is the diameter of an object such as a person or width of a building, and L is the unit length of slope perpendicular to the runout path.

The probability of hitting the same portion of slope increases with each successive boulder travelling down the slope. The probability of one boulder of the total number *N* boulders hitting an object when passing through that same portion of slope is then given, if all *N* of the boulders are randomly distributed across the slope, by:

$$P_{N(S:H)} = 1 - (1 - P_{1(S:H)})^{N} \quad [6b]$$

The probability of a person or dwelling that is present on a slope being hit by a boulder is therefore a function of:

1) The presence of a source from which boulders can fall, e.g. a rocky slope;
2) The stability of the source;
3) A credible pathway from the source along which a boulder can travel; and
4) Factors that control how far a boulder can travel (termed rockfall runout).

For the purposes of fatality risk estimation, it is necessary to have a quantitative measure of the size of a person. In this report, a “person” is assumed to be a cylinder of 1 m diameter and unspecified height (no specification of height is required in the model). The assumed value covers the order-of-magnitude range from about 0.3 m to about 3 m.

5.4 Probability a person is present

$P_{(T:S)}$ is the probability an individual is present in the portion of the slope when a boulder moves through it, and is a function of the proportion of time spent by a person at a particular location each day. A recent study carried out for the United Kingdom Health & Safety Executive (Hunt et al., 2010), identified several types of people – including the elderly, parents with young children, the very young, disabled and other vulnerable people – who may spend a very high proportion of their lives at home. The assumption used in the risk assessment for judging whether risk controls should be applied to individual homes was thus that more-exposed individuals at risk would be those who spend 100% of their time at home.

One possible reason why no one was killed by rockfalls in the residential areas included in this risk assessment on 22nd February 2011 is that the earthquake occurred during the day, when most, but not all people were away from home. There may have been a substantial number of household rockfall fatalities had the 22nd February 2011 earthquake occurred at night (when most people would have been at home), as over 200 homes suffered impacts from boulders of 1 m or more in diameter. The actual residency of homes thus varies widely, raising a question as to what residency should be assumed for the purposes of risk assessment.

The UK Health & Safety Executive recommend as a standard practice in risk assessments for the purpose of assessing tolerability of risk in support of planning issues to assume 100% residency for domestic dwellings so as to ensure that decisions are robust to any reasonable future use of the homes in question. This advice was followed in this report and $P_{(T:S)}$ was taken as 1.0, which is a reasonable approximation of any residency level greater than 0.5.

5.5 Probability of the person being killed if hit

$V_{(D:T)}$ is the probability of a person being killed (or receiving injuries which prove fatal in the near aftermath of the event) if present on the slope and in the path of a boulder. This probability is expressed as *vulnerability*, the term used to describe the amount of damage that results from a particular degree of hazard. Vulnerability ranges between 0 and 1 and for fatality risk represents the likelihood of an injury sustained by the individual being fatal (1) – vulnerability may also take into account the possibility of getting out of the way to avoid being struck although this logically is an influence on the probability of being struck.

Studies from Hong Kong (e.g. Finlay et al., 1999) summarised the vulnerability ranges and recommended values for death "if struck by rockfall". The vulnerability of an individual in open space if struck by a rockfall is given as 0.1 – 0.7, with recommended value of 0.5, assuming that it may be possible to get out of the way.

Using the recorded 22nd February 2011 rockfall consequences, out of about 65 houses hit by rocks, about 29 had boulders enter them (about 45%) (D. Macfarlane, pers. com. 2011). These statistics refer to houses hit, not to the numbers of boulders that hit and penetrated houses.

Although being in a house limits the ability to take evasive action, it offers protection from boulders that hit but do not enter homes, but still might be capable of inflicting a fatal injury to an unprotected person. It is also noted that people may spend considerable amounts of time outdoors at home, and therefore may not necessarily be protected by a house.

For this study $V_{(D:T)}$ is assumed to be about 0.5..

Although the modelled risks have assumed 100% residency and 50% personal vulnerability if hit by a rockfall, the calculated fatality risks are identical if it is assumed that the residency is 50% in combination with a vulnerability of 100%, or indeed any combination of the two whose product is 0.5.

6.0 RISK ANALYSIS RESULTS

The assessed annual individual fatality risk is the probability (likelihood) that a particular individual will be killed by a rockfall in any year at their place of residence. For most localities this probability is an imprecisely determined, very small number which is most conveniently expressed using the scientific number format rather than as a fraction or a decimal number. For example the number 10^{-4} ("10 to the power of minus 4") is the fraction 1/10,000, and the decimal number 0.0001; it may also be expressed as 0.01%. The units of risk are dimensionless probability per unit of time and the units of annual fatality risk are probability of fatality (death or loss of life) per year.

6.1 Risk analysis steps and illustrative example

The risk analysis consists of the following steps:

1. Consider the full possible range of rockfall triggering events, such as earthquakes or rain (following the method of Moon et al., 2005) in terms of a set of earthquake triggers and a set of "other" triggers;

2. Choose a small set of representative events for each type of trigger spanning the range of severity of events from the smallest to the largest;
3. For each representative event, estimate:
   a) the frequency of the event and the numbers of boulders produced ($P_{(H)}$),
   b) the proportion of boulders reaching/passing a given shadow angle (distance) down the slope and the probability of one of *N* boulders hitting a person at that location on the slope ($P_{(S:H)}$),
   c) the probability that a person is present on the slope as the boulder moves through it ($P_{(T:S)}$), and
   d) the probability that a person will be killed if present and hit by one or more boulders ($V_{(D:T)}$);
4. Combine 3(a) – (d) to estimate the annual individual fatality risk for individuals at different distances downslope contributed by each representative event;
5. Sum the risks from all events to estimate the overall risk; and
6. Enter the risk values at each shadow angle into a Geographic Information System and interpolate between shadow angles and provide contours of equal risk on a map.

An example from Heathcote Valley can be used to step through the analysis process. Consider the risk of rockfalls hitting and killing a person located on the 31° shadow line from rockfalls occurring within the 1.0 – 2.0 g band for peak ground acceleration. The estimated number of rockfalls generated in this band is about 749 (Table 10). About 70% of these boulders (about 520) would pass the 31° shadow line (Table 17).

Step 3a: Estimate the annual probability of the number of boulders occurring within the 1.0 – 2.0 g band for Heathcote Valley, where $P_{(H)}$ = 0.016 (about 1 in 60 years using the next 1-year seismic hazard model results).

Step 3b: Estimate the probability of one boulder hitting an individual (if present) in the portion of the slope when the boulder moves through it ($P_{1(S:H)}$) using Eq. [6a], where the design boulder diameter (*D*) = 1.0 m, the diameter of a person (*d*) = 1.0 m and the length of the 31° shadow line (*L*) = 4,065 m.

$$P_{1(S:H)} = \frac{(2\times1.0+1.0)}{4065} = 7.4\times10^{-4} \quad \text{[from Eq 6a]}$$

Estimate the probability of *N* boulders hitting an individual (if present) in the portion of slope (the 31° shadow line) when the boulders move through it, using Eq. [6b], where:

$$P_{N(S:H)} = 1-(1-7.4\times10^{-4})^{520} = 0.32 \quad \text{[from Eq 6b]}$$

Step 3c: Estimate the probability that the person is present and hit considering the time spent at home ($P_{(T:S)}$ = 1).

Step 3d: Estimate the probability of the person being killed if present and hit by a boulder ($V_{(D:T)}$ = 0.5).

Step 4: Multiply steps 3a, 3b, 3c and 3d to calculate the annual individual fatality risk.

Therefore the annual fatality risk ($R_{(BAND)}$) to an individual on/around the 31° shadow angle from rockfalls triggered by an earthquake in the 1.0 – 2.0 g ground acceleration band is:

$$R_{(BAND)} = 0.016 \times 0.32 \times 1.0 \times 0.5 = 2.6 \times 10^{-3} \qquad \text{[from Eq 1]}$$

Step 5: Repeat Steps 1 to 4 for each shadow line for each of the considered bands, and sum the results for each shadow line to estimate the total risk to the life of an individual on a given shadow line (Table 19).

Table 19 Example risk analysis values calculated or assumed for annual individual fatality risk for the 31° shadow angle in Heathcote Valley.

	Parameter estimated	EARTHQUAKES (1-year model results)					OTHER ROCKFALL EVENTS				
		0.1 – 0.4 g	**0.4 – 1 g**	**1 – 2 g**	**>2 g**	**ALL earthquakes**	**1 – 15 years**	**15 – 100 years**	**100 – 1000 years**	**>1000 years**	**ALL other events**
A	**$P_{(H)}$** Annual frequency of number of boulders leaving source (years)	0.60	0.17	0.02	0.001		2.0	0.2	0.010	0.001	
B	Expected number of boulders leaving source for representative event in band	0.1	45	749	7500		1	10	50	100	
C	Relative proportion of boulders passing shadow angle	0.69	0.69	0.69	0.69		0.69	0.69	0.69	0.69	
D	Expected number of boulders passing shadow angle for representative event in band (BxC)	0.1	31	520	5206		0.7	7	35	69	
E	Probability a person is within path of a single boulder	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}		7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}	
F	**$P_{(S:H)}$** Probability person is within path of one or more boulders given the number of boulders passing shadow angle for this event	5×10^{-5}	2×10^{-2}	3×10^{-1}	1		5×10^{-4}	5×10^{-3}	3×10^{-2}	5×10^{-2}	
G	**$P_{(T:S)}$** Probability of a person being present	1	1	1	1		1	1	1	1	
H	**$V_{(D:T)}$** Probability of a person being killed by a rockfall if present and hit	0.5	0.5	0.5	0.5		0.5	0.5	0.5	0.5	
R	**$R_{(LOL)}$** Annual risk (death) all bands for shadow angle (AxFxGxH)	2×10^{-5}	2×10^{-3}	3×10^{-3}	4×10^{-4}	**5×10^{-3}**	5×10^{-4}	4×10^{-4}	1×10^{-4}	2×10^{-5}	**1×10^{-3}**
	TOTAL RISK (ALL EVENTS)					**6×10^{-3}**					

Step 6: The annual individual fatality risk considering all events was calculated for each shadow angle within each suburb following the five steps outlined in the example (Figure 24). These values were then modelled using ArcGIS®. ArcGIS is used to interpolate between the risks calculated at given shadow angles so as to produce contours of equal risk. Contours were developed for logarithmic classes, e.g. 10^{-2} – 10^{-3}, 10^{-3} – 10^{-4}, of individual risk values. The building-footprint database was then overlaid on the risk model and the centroids of the buildings, within each property, were used to assign the risk value (Figure 25).

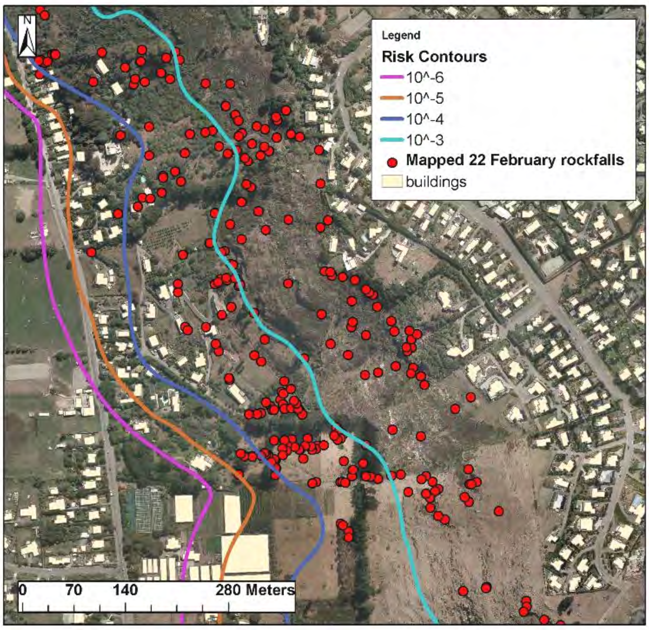

Figure 24 Illustrative example of the risk (annual individual fatality risk, considering all events) for a hypothetical suburb estimated for selected shadow angles.

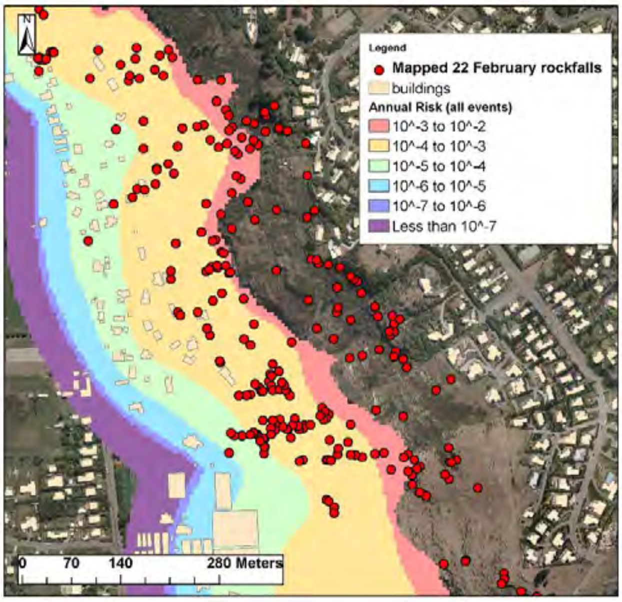

Figure 25 Illustrative example of the estimated risk (annual individual fatality risk) (considering all events) for a hypothetical suburb, with risk magnitudes interpolated from the values estimated for shadow angles.

6.2 Results

The results from the risk analysis for Heathcote Valley are summarised in Tables 20 and 21. The values of risk are the annual fatality risk of an individual located in the shadow zone used in the analyses, adopting seismic hazard model for the next 1-year. Heathcote Valley is representative of the results from the other suburbs.

Table 20 Contribution to annual individual fatality risk from rockfalls across each earthquake ground acceleration band (Heathcote Valley), using the 1-year seismic hazard model of 1 January 2012.

Shadow angle zone	Earthquake acceleration band				Total Earthquake individual risk
(º)	0.1 – 0.4 g	0.4 – 1 g	1 – 2 g	2 – 5 g	(loss of life)
Source toe	3 x10^{-5}	3 x10^{-3}	4 x10^{-3}	4 x10^{-4}	8 x10^{-3}
31	2 x10^{-5}	2 x10^{-3}	3 x10^{-3}	4 x10^{-4}	5 x10^{-3}
29	9x10^{-6}	1 x10^{-3}	2 x10^{-3}	3 x10^{-4}	3 x10^{-3}
27	3 x10^{-6}	4 x10^{-4}	7 x10^{-4}4	2 x10^{-4}	1 x10^{-3}
25	2 x10^{-6}	2 x10^{-4}	3 x10^{-4}	1 x10^{-4}	6 x10^{-4}
24	1 x10^{-6}	1 x10^{-4}	2 x10^{-4}	9 x10^{-5}	4 x10^{-4}
23	6 x10^{-7}	8 x10^{-5}	1 x10^{-4}	6 x10^{-5}	3 x10^{-4}
22	2 x10^{-7}	3 x10^{-5}	5 x10^{-5}	2 x10^{-5}	1 x10^{-4}
21	1x10^{-8}	1 x10^{-6}	2 x10^{-6}	1 x10^{-6}	4 x10^{-6}

Table 21 Contribution to annual individual fatality risk from other (non-earthquake) rockfall-triggering events (Heathcote Valley).

Shadow angle zone	Frequency band				Total Other individual risk (loss of life)
(º)	0 – 15 years	15 – 100 years	100 – 1,000 years	> 1,000 years	
Source toe	9 x10^{-4}	7 x10^{-4}	2 x10^{-4}	3 x10^{-5}	2 x10^{-3}
31	5 x10^{-4}	4 x10^{-4}	1 x10^{-4}	2 x10^{-5}	1 x10^{-3}
29	3 x10^{-4}	2 x10^{-4}	7 x10^{-5}	1 x10^{-5}	6 x10^{-4}
27	1 x10^{-4}	8 x10^{-5}	3 x10^{-5}	4 x10^{-6}	2 x10^{-4}
25	5 x10^{-5}	4 x10^{-5}	1 x10^{-5}	2 x10^{-6}	1 x10^{-4}
24	4 x10^{-5}	3 x10^{-5}	9 x10^{-6}	1 x10^{-6}	7 x10^{-5}
23	2 x10^{-5}	2 x10^{-5}	5 x10^{-6}	8 x10^{-7}	4 x10^{-5}
22	8 x10^{-6}	6 x10^{-6}	2 x10^{-6}	3 x10^{-7}	2 x10^{-5}
21	3 x10^{-7}	3 x10^{-7}	9 x10^{-8}	1 x10^{-8}	7 x10^{-7}

The results from the risk analysis for all suburbs are summarised in Tables 22 to 24, adopting residency of 1.0 and vulnerability of 0.5. For earthquakes the 1-year median seismic hazard model results have been used.

Table 22 Annual individual fatality risk from earthquake-triggered rockfalls (1-year seismicity, all suburbs).

Suburb	Source toe	Shadow angle							
		31°	29°	27°	25°	24°	23°	22°	21°
Lyttelton	5 x10^{-3}	4 x10^{-3}	3 x10^{-3}	3 x10^{-3}	1.6 10^{-3}	1 x10^{-3}	6 x 10^{-4}	3 x 10^{-4}	2 x 10^{-5}
Heathcote	8 x10^{-3}	5 x10^{-3}	3 x10^{-3}	1 x10^{-3}	6 x 10^{-4}	4 x 10^{-4}	3 x 10^{-4}	1 x 10^{-4}	4 x 10^{-6}
Avoca 1	6 x10^{-3}	3 x10^{-3}	2 x10^{-3}	2 x10^{-3}	2 x10^{-3}	2 x10^{-3}	9 x 10^{-4}	5 x 10^{-4}	2 x 10^{-5}
Avoca 2	1 x 10^{-2}	1 x10^{-1}	7 x10^{-3}	6 x10^{-3}	3 x10^{-3}	3 x10^{-3}	7 x 10^{-4}	3 x 10^{-4}	2 x 10^{-4}
Avoca 3	1 x 10^{-2}	1 x10^{-3}	4 x 10^{-4}	2 x 10^{-4}	2 x 10^{-4}	0	0	0	0
Avoca 4	2 x 10^{-2}	8 x10^{-3}	7 x10^{-3}	4 x10^{-3}	2 x10^{-3}	6 x 10^{-4}	2 x 10^{-4}	0	0
Horotane	9 x10^{-3}	7 x10^{-3}	5 x10^{-3}	5 x10^{-3}	3 x10^{-3}	2 x10^{-3}	1 x10^{-3}	7 x 10^{-5}	0
Sumner (Heberden Ave.)	2 x10^{-3}	7 x 10^{-4}	4 x 10^{-4}	7 x 10^{-5}	3 x 10^{-5}	8 x 10^{-6}	0	0	0
Sumner (Wakefield Ave.)	2 x 10^{-2}	9 x10^{-3}	4 x10^{-3}	2 x10^{-3}	8 X10^{-4}	6 x 10^{-4}	1 x 10^{-4}	2 x 10^{-5}	0
Hillsborough (Vernon Tce. 1)	6 x10^{-3}	3 x10^{-3}	1 x10^{-3}	4 x 10^{-4}	9 x 10^{-5}	1 x 10^{-4}	5 x 10^{-5}	0	0
Hillsborough (Vernon Tce. 2)	2 x 10^{-2}	1 x 10^{-2}	1 x 10^{-2}	4 x10^{-3}	3 x 10^{-4}	3 x 10^{-4}	3 x 10^{-4}	2 x 10^{-4}	0
Bowenvale	8 x10^{-3}	2 x10^{-3}	1 x10^{-3}	4 x 10^{-4}	2 x 10^{-4}	5 x 10^{-5}	0	0	0
Rapaki	2 x 10^{-2}	8 x10^{-3}	7 x10^{-3}	4 x10^{-3}	3 x10^{-3}	2 x10^{-3}	2 x10^{-3}	3 x 10^{-4}	8 x 10^{-5}
Castle Rock	2 x 10^{-2}	1 x 10^{-2}	8 x10^{-3}	1 x10^{-3}	4 x 10^{-5}	2 x 10^{-5}	0	0	0

Table 23 Annual individual fatality risk from other (non-earthquake) rockfall-triggering events.

Suburb	Source toe	Shadow angle							
		31°	**29°**	**27°**	**25°**	**24°**	**23°**	**22°**	**21°**
Lyttelton	9×10^{-4}	6×10^{-4}	5×10^{-4}	4×10^{-4}	2×10^{-4}	2×10^{-4}	1×10^{-4}	4×10^{-5}	$2 \times 1^{0-6}$
Heathcote	2×10^{-3}	1×10^{-3}	6×10^{-4}	2×10^{-4}	1×10^{-4}	7×10^{-5}	4×10^{-5}	3×10^{-5}	7×10^{-7}
Avoca 1	9×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}	2×10^{-4}	2×10^{-4}	1×10^{-4}	5×10^{-5}	2×10^{-6}
Avoca 2	2×10^{-3}	2×10^{-3}	1×10^{-3}	8×10^{-4}	4×10^{-4}	4×10^{-4}	8×10^{-5}	3×10^{-5}	2×10^{-5}
Avoca 3	2×10^{-3}	2×10^{-4}	6×10^{-5}	3×10^{-5}	2×10^{-5}	0	0	0	0
Avoca 4	3×10^{-3}	1×10^{-3}	1×10^{-3}	6×10^{-4}	3×10^{-4}	8×10^{-5}	2×10^{-5}	0	0
Horotane	2×10^{-3}	9×10^{-4}	7×10^{-4}	7×10^{-4}	4×10^{-4}	3×10^{-4}	1×10^{-4}	7×10^{-6}	0
Sumner (Heberden Ave.)	3×10^{-4}	1×10^{-4}	6×10^{-5}	8×10^{-6}	3×10^{-6}	1×10^{-6}	0	0	0
Sumner (Wakefield Ave.)	2×10^{-3}	9×10^{-4}	3×10^{-4}	3×10^{-5}	6×10^{-5}	4×10^{-5}	7×10^{-6}	2×10^{-6}	0
Hillsborough (Vernon Tce. 1)	5×10^{-4}	3×10^{-4}	9×10^{-5}		7×10^{-6}	8×10^{-6}	4×10^{-6}	0	0
Hillsborough (Vernon Tce. 2)	2×10^{-3}	1×10^{-3}	8×10^{-4}	2×10^{-4}	2×10^{-5}	2×10^{-5}	2×10^{-5}	9×10^{-6}	0
Bowenvale	4×10^{-4}	9×10^{-5}	4×10^{-5}	2×10^{-5}	7×10^{-6}	2×10^{-6}	0	0	0
Rapaki	2×10^{-3}	8×10^{-4}	7×10^{-4}	3×10^{-4}	2×10^{-4}	2×10^{-4}	1×10^{-4}	2×10^{-5}	5×10^{-6}
Castle Rock	2×10^{-3}	9×10^{-4}	6×10^{-4}	7×10^{-5}	2×10^{-6}	1×10^{-6}	0	0	0

Table 24 Annual individual fatality risk from all rockfalls (Tables 22 and 23 combined)

Suburb	Source toe	Shadow angle 31°	29°	27°	25°	24°	23°	22°	21°
Lyttelton	6×10^{-3}	4×10^{-3}	4×10^{-3}	3×10^{-3}	2×10^{-3}	1×10^{-3}	8×10^{-4}	3×10^{-4}	2×10^{-5}
Heathcote	9×10^{-3}	6×10^{-3}	4×10^{-3}	2×10^{-3}	7×10^{-4}	5×10^{-4}	3×10^{-4}	1×10^{-4}	5×10^{-6}
Avoca 1	7×10^{-3}	4×10^{-3}	2×10^{-3}	$2\ 1x0^{-3}$	2×10^{-3}	2×10^{-3}	1×10^{-3}	6×10^{-4}	2×10^{-5}
Avoca 2	2×10^{-2}	1×10^{-2}	8×10^{-3}	7×10^{-3}	4×10^{-3}	4×10^{-3}	8×10^{-4}	3×10^{-4}	2×10^{-4}
Avoca 3	2×10^{-2}	1×10^{-3}	5×10^{-4}	3×10^{-4}	2×10^{-4}	0	0	0	0
Avoca 4	2×10^{-2}	9×10^{-3}	8×10^{-3}	5×10^{-3}	2×10^{-3}	6×10^{-4}	2×10^{-4}	0	0
Horotane	1×10^{-2}	7×10^{-3}	6×10^{-3}	6×10^{-3}	4×10^{-3}	2×10^{-3}	1×10^{-3}	8×10^{-5}	0
Sumner (Heberden Ave.)	3×10^{-3}	8×10^{-4}	4×10^{-4}	8×10^{-5}	3×10^{-5}	9×10^{-6}	0	0	0
Sumner (Wakefield Ave.)	2×10^{-2}	1×10^{-2}	4×10^{-3}	2×10^{-3}	9×10^{-4}	7×10^{-4}	1×10^{-4}	3×10^{-5}	0
Hillsborough (Vernon Tce. 1)	6×10^{-3}	4×10^{-3}	1×10^{-3}	4×10^{-4}	1×10^{-4}	1×10^{-4}	5×10^{-5}	0	0
Vernon Tce. 2)	2×10^{-2}	2×10^{-2}	1×10^{-2}	4×10^{-3}	4×10^{-4}	4×10^{-4}	3×10^{-4}	2×10^{-4}	0
Bowenvale	8×10^{-3}	2×10^{-3}	1×10^{-3}	4×10^{-4}	2×10^{-4}	5×10^{-5}	0	0	0
Rapaki	2×10^{-2}	9×10^{-3}	8×10^{-3}	5×10^{-3}	3×10^{-3}	3×10^{-3}	2×10^{-3}	3×10^{-4}	8×10^{-5}
Castle Rock	3×10^{-2}	1×10^{-2}	8×10^{-3}	1×10^{-3}	4×10^{-5}	2×10^{-5}	0	0	0

6.3 Validation of estimates for house strikes

The expected number of house hits can be compared to the observed number of house hits recorded by the Port Hills Geotechnical Group. Observed house hits are defined as the number of individual boulders from the 22nd February 2011 earthquakes that hit a dwelling or accessory building. For observed house hits, if one boulder hits a dwelling it is counted as one hit, and if three boulders hit the same dwelling it is counted as three hits. Modelled house hits were calculated through equations [6a] and [6b] but with the mean width of a residential home (calculated per suburb; the mean width for all areas is about 16 m) substituted for the assumed width of a person. The expected numbers of houses hit for a given shadow line were estimated by multiplying the probability of a house being present and hit, by the number of homes in that shadow line using the 22nd February 2011 boulders (Table 25). Differences between the observed and estimated house hits are due to several factors; one is the way house-hit data were collected, where an observed house hit included hits of ancillary buildings such as a garage, shed or deck, thereby increasing the effective width of the house. Another factor is the variation in the numbers of boulders passing a given shadow line at a given location, i.e. focusing of rockfalls.

Table 25 Observed house hits per suburb compared with the expected house hits estimated from the analysis for the 22nd February 2011 earthquakes.

Suburb*	Observed house hits	Estimated hits	Factor of difference
Lyttelton	11	6.6	0.6
Heathcote	28	23.6	0.8
Avoca 1	12	15.5	1.3
Avoca 2	1	0.0	0.0
Avoca 3	13	1.4	0.1
Avoca 4	3	0.7	0.2
Horotane	2	2.0	1.0
Sumner (Heberden Ave.)	14	9.6	0.7
Sumner (Wakefield Ave.)	30	20.9	0.7
Hillsborough (Vernon Tce. 1)	1	0.3	0.3
Hillsborough (Vernon Tce. 2)	3	0.2	0.1
Rapaki	2	1.8	0.9
Castle Rock	0	0.1	1.0

*House-hit data were unavailable for Bowenvale at the time of writing.

These comparisons provide some confidence that the risk assessment is fit for purpose in predicting the consequences of rockfalls triggered by the 22nd February 2011 earthquakes.

6.4 Model sensitivities and uncertainties

We consider below how reliable the assessments are and the sensitivity of the model to key uncertainties (Sections 6.4.1 and 6.4.2), and then identify four particular sets of assumptions (or “scenarios”) which we consider particularly useful for Christchurch City Council to consider. They span the range of possibilities the Christchurch City Council would wish to consider in addressing this time-varying and uncertain risk (Section 6.4.3).

6.4.1 How reliable are the results?

Potentially significant uncertainties noted and their likely implications for risk are summarised in Table 26.

Table 26 Uncertainties and their implications for risk

	Issue	Direction & Scale of Uncertainty	Implications for Risk
a)	Under-prediction of annual frequency for a given peak ground acceleration by the composite seismic hazard model.	Upward, potentially considerable – but geomorphological evidence in the Port Hills suggests there is a sensible cap that can be placed on the upward uncertainty, which is about an order of magnitude.	Risk due to earthquakes could be systematically under-or over-estimated.
b)	Choice of whether to use average earthquake annual frequencies for next 50 years, or higher frequencies for next 1 year.	Use of 'next 1-years' figure builds in pessimistic factor of about 3 to 4 for longer term.	Longer term risk is potentially 3 to 4 times lower.
c)	Boulders produced in 0.4 – 1.0 g and 1.0 – 2.0 g earthquakes.	Factor of maybe 10 times uncertainty in either direction.	c) and d) combine to give a factor of about 4 uncertainty in the upward direction, but lower in the downward direction, about 0.3.
d)	Boulders produced by earthquakes in the > 2.0 g band.	Factor of maybe 10 times uncertainty in either direction.	
e)	Frequency of production of a number of boulders by other (non-earthquake) events.	Factors of 2 – 3+ uncertainty either way in the annual frequency, but constrained by the geomorphology, suggesting such extreme events (that dominate the risk) are at the medium and low frequency end. However, current frequency of boulder production is likely to be higher due to the disturbed nature of the rock masses. It may take many years for the frequency to drop back to pre-earthquake rates.	Factor of 1.1 – 1.2 uncertainty in the upward direction, but lower in the downward direction.
f)	Number of boulders travelling downslope and passing a given shadow angle.	Less than a factor of 2 uncertainty either way.	Factor of about 1.8 uncertainty in the upward direction, but lower in the downward direction.
g)	Boulders travelling further than those observed during the recent earthquakes.	Would increase the risk – In most suburbs that have experienced 1 – 2 g peak ground acceleration, the observed distances that boulders travelled are thought to be representative of the distances boulders triggered by future events could travel. However, there is a possibility that future boulders could go further. This is particularly relevant for those areas that did not experience 1 – 2 g peak ground acceleration. For these, it is expected that a future earthquake of this magnitude could generate many more boulders, some of which could travel further than those recently observed.	Would push the risk zones further downslope than the 21º shadow angle line, which is assumed to be the line below which the risk is negligible.
h)	Boulder distribution across slope, taking into account topographic channelling.	Factors of 3 – 10 difference either way at specific dwellings in number of boulders passing a given shadow line.	Similar differences in risk at individual dwellings.
i)	Local effects on rockfall runout.	The models are regional scale and cannot take into account local site effects that could either enhance or reduce the estimated risk. Impact not known.	Could increase or reduce the risk. Factor of uncertainty unknown and will depend upon the site specific assessments.
j)	Probability a person/home is struck, given the number of boulders passing their shadow line.	As (h) plus modest additional uncertainty related to bounce, ability to dodge etc.	Largely already incorporated via (g) and (h).
k)	Residency (proportion of time people are at home).	Assumption of 70% residency instead of 100% would modestly decrease estimated risk.	Would decrease by a factor of about 1.4.
l)	Probability a person is killed if struck.	Uncertainty potentially reducible but unlikely to make large difference – will always be fairly large. Houses do offer some protection from rockfall. However of those hit the shrapnel effects would effectively increase the probability of being hit if in the portion of house impacted.	A change in the residency from 50 to 70% would increase the risk by a factor of about 1.4.

The combined uncertainties in Table 26 are potentially significant in terms of:

1) Estimated absolute risk levels, which have potentially an order of magnitude uncertainty in either direction;
2) Estimated risk levels in comparison with levels considered tolerable or intolerable;
3) The relative contribution to risk of earthquakes in comparison with other triggers of rockfall; and
4) The relative contribution to risk by the annual frequencies of the different rockfall-triggering events.

Items (a) to (d) in Table 26

The least well determined parameters in the risk model used in this assessment are the probability-density distributions of the earthquake ground motions that: 1) caused the rockfalls that were used in the analysis; and 2) will cause future rockfalls. The uncertainty in the earthquake ground motions affects all studies, including the shadow zones in all of the Port Hills suburbs, as well as studies of liquefaction and building damage. Ongoing post-4th September 2010 seismic activity is continually changing the future probability-density distributions of rockfall-triggering events, and quite probably the number of rockfalls generated by each future event.

Item (e) in Table 26

There are very limited data on the probability-density distributions of other rockfall triggers. The little data available suggests that rockfall risk from other causes is less than or equal to the risk from earthquake-triggered rockfalls. The authors note that those suburbs where other triggers have been assessed as causing high risk are the suburbs where mitigation works were already in place. While the adequacy of the mitigation can be questioned, the presence of a risk was acknowledged.

There is a significant possibility that the future frequency of rockfalls triggered by other events will be higher than those previously experienced, as a result of the recent earthquakes damaging the rockfall source areas.

Items (f) – (h) in Table 26

The control on rockfall runout is the observed distribution of boulders within the suburb. In the critical areas of each suburb (where dwellings are located), it is assumed that only a few boulders from the 22nd February 2011 earthquakes have been missed. The fewer boulders there were in an area, the greater the effort put into the search to find them. At the upper end of the risk assessment, where there are many boulders in an area, it becomes more likely that some may not have been counted. Hence the areas assessed as having the highest relative risk, may actually have a slightly higher risk. The control on boulder mapping is the ability of the people mapping boulders to find all of them. The assessment is reliant on the mappers finding most of boulders among the homes and gardens. It is less sensitive to missing boulders close to the source areas, where some areas could not be mapped in detail for health and safety reasons. Such sample bias is apparent in the frequency runout plot (Figure 17), but in these areas there are very few if any dwellings.

Item (i) in Table 26

A potentially significant uncertainty in the model is defining the furthest limit of rockfall runout. The models developed here estimate the average risk for the suburb; they do not take into account local topographic effects and other effects such as roads, areas of flat ground or buildings that could locally limit rockfall runout.

Field verification (“ground-truthing”) was used to examine in more detail local topographic features and evidence of historic as well as recent rockfalls. This process was used to reduce the uncertainty in the risk assessment associated with the maximum runout of boulders.

Items (j – l) in Table 26

There is much uncertainty in the likely average dwelling residency rates (proportion of time individuals are at home) and in the likely average vulnerability (likelihood of dying if hit by a rockfall boulder). It should be noted that the assumed values of 100% residency and 50% vulnerability are multiplied together in the model, and so the same outcome would result from assuming 50% residency and 100% vulnerability, or any combination of residency and vulnerability that gave a product of 0.5.

Knowledge of other life risks

This study has assessed the range of annual individual fatality risks from rockfalls to individual residents on their properties in the Port Hills. This risk is only meaningful in relation to knowledge of all other fatality risks; these are discussed in Taig et al. (2012).

6.4.2 Sensitivity to key uncertainties

The estimated risk has been assessed in terms of its sensitivity to changes in:

1) Using the seismic hazard model results for the next 50-years instead of the next 1-year;

2) The numbers of boulders triggered by the representative events for both earthquake and non-earthquake triggers (i.e. using scale factors to increase the numbers of boulders);

   a. For earthquake triggered boulders this takes into account that some of the boulders that fell during the 2010/2011 earthquakes may not have been not mapped.

   b. For non-earthquake triggered boulders this scale factor takes into account a likely increased rate of rockfalls due to the now dilated and highly disturbed nature of the rockfall-source areas;

3) The probability of a person being present for 70 to 100% of the time;

4) Increasing the effective diameter of a person from 1 m to 2 m in order to take into account the shrapnel effects of boulders entering homes. This is also equivalent to increasing the boulder size; and

5) The vulnerability of a person if hit, from 0.5 to 0.7.

The risks have been calculated per shadow angle, per suburb for those suburbs included in the analysis, using the suburb-specific data. Details of seven different possible scenarios, their input parameters and the impacts on the estimated risk are shown in Table 27. The impact on the risk is calculated by comparing successive scenarios arranged in order of increasing risk.

Table 27 Seven selected risk scenarios and associated parameters used to examine model sensitivity. Note that the factors of increasing risk are cumulative down the table such that risk under scenario v is 3.1 times more than under scenario iv and the risk under scenario vi is 1.4 times that under scenario v. EQ is Earthquake.

	Seismic hazard model results[1]	EQ rockfall number scale factor	Other rockfall number scale factor	Probability person present	Vulnerability of a person if hit	Diameter of a person	Factor by which risk increases[2]
i	50-year	1	1	70%	50%	1 m	1
ii	50-year	1.5	1	70%	50%	1 m	1.2
iii	50-year	1.5	2	70%	50%	1 m	1.3
iv	50-year	1.5	2	70%	70%	1 m	1.4
v	1-year	1.5	2	70%	70%	1 m	3.1
vi	1-year	1.5	2	100%	70%	1 m	1.4
vii	1-year	1.5	2	100%	70%	2 m	1.3

[1]The seismic hazard model results used are the medians generated by the model.

[2]The scenarios are listed in order of increasing calculated risk

The results show that largest impact on the risk is from the time period selected for the seismic hazard model. The annual frequency of a rockfall-triggering earthquake occurring is expected to be much higher over the next few years than it will be in 50-years' time; the annual frequency is expected to decrease to about 25 – 33% of its 2012 value over the next ten years. All of the other parameters individually cause the risk to change by modest ratios of about 1.2 – 1.4. The risk that would be estimated using scenario vii (1-year model) is about 13 times greater (slightly larger than one order of magnitude) than that estimated using scenario i (50-year model).

6.4.3 Risk-assessment scenarios

The largest impact on the risk is from the choice of time-varying hazard model. To illustrate the effect on fatality risk of the time-varying seismic hazard, four particular risk assessment scenarios were developed, using the median base case (50^{th} percentile) and upper case (84^{th} percentile) estimates of seismic risk over the next 1-year and 50-year periods. The other parameters represent our "best" and "reasonable, but more conservative" estimates based on the range of uncertainties identified in the data available at the time of writing (Table 28).

The results for each scenario were modelled using the ArcGIS programme, as described in Section 6.1, to produce contoured fatality risk maps, and the numbers of homes falling into different risk bands (Table 29) were counted from these maps. Figure 26 is a graphical representation of the impact of the assessment selection, expressed as the estimated number of residential homes in each risk category, for each assessment scenario. For all assessment scenarios it has been assumed that the fatality risk from rockfalls downslope of (past) the 21° shadow angle is below the threshold of detection (annual individual fatality risk less than 10^{-6}), unless the 10^{-6} risk contour occurred at higher shadow angles.

Table 28 Approximations assumed for four risk scenarios considered to cover a likely range of possibilities.

Scenario	Seismic model results	EQ rockfall number scale factor	Other rockfall number scale factor	Probability person present	Vulnerability of a person if hit	Diameter of a person (assumed)
A	50-year base	1.5	2	100%	50%	1 m
B	50-year upper	2	3	100%	70%	2 m
C	1-year base	1.5	2	100%	50%	1 m
D	1-year upper	2	3	100%	70%	2 m

Table 29 Numbers of homes within each annual individual fatality risk category per risk scenario.

Scenario	Numbers of homes within each risk category			
	above 10^{-3}	10^{-3} to 10^{-4}	10^{-4} to 10^{-5}	below 10^{-5}
A	37	312	203	239
B	198	273	145	175
C	193	267	155	176
D	377	204	56	154

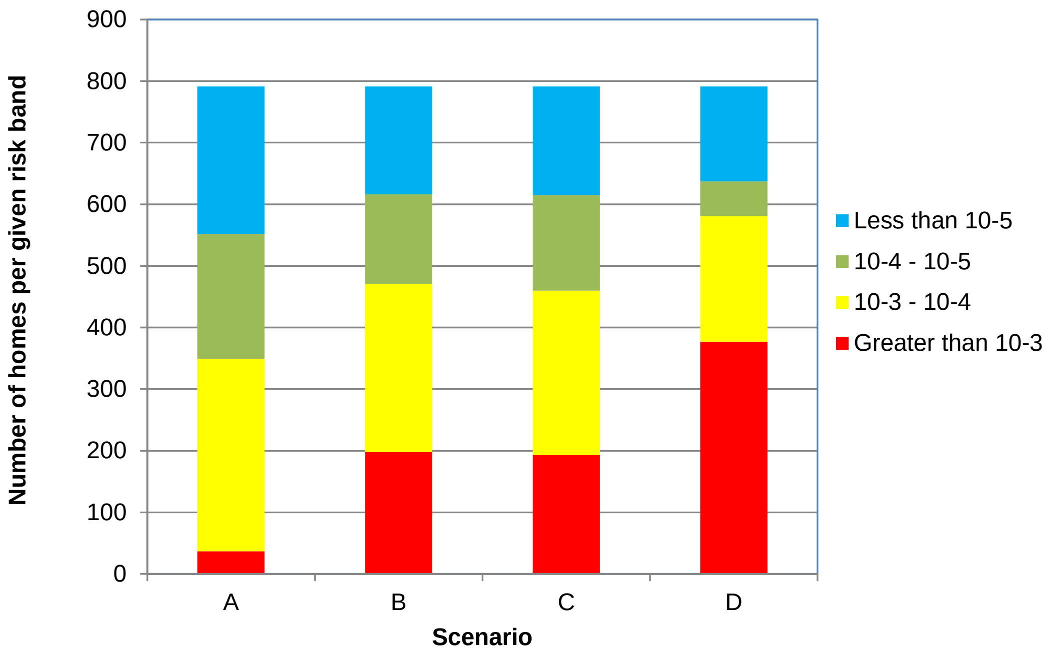

Figure 26 Numbers of homes within a given range of annual individual fatality risk for each of the different risk scenarios. The total number of homes in the areas analysed are 791.

The differences between the different assessment scenarios are shown graphically for Heberden Avenue, Sumner in Appendix C. The scenarios range from Scenario A, the most optimistic with regards to the number of homes in the higher risk categories, to Scenario D, the most pessimistic scenario assessed. Scenario D is considered to be overly pessimistic, but was included to illustrate the impact that increased levels of seismicity and conservative assumptions could realistically have. Scenario A is at the other end of the spectrum and is considered unreasonable for current use, considering the current increased levels of seismic activity. Scenarios B and C yield similar results to one another.

The most significant uncertainties identified in this assessment are those connected with the frequency of large earthquakes. It may be helpful in comparing these to appreciate the different return periods estimated for earthquakes generating peak ground accelerations of 1 – 2 g (the range experienced by most suburbs in the 2011 earthquakes that generated rockfalls) using the different seismicity assumptions:

1) Scenario A (50-year seismic model results median) about 300 years

2) Scenario B (50-year seismic model results 84th percentile[5]) about 200 years

3) Scenario C (1-year seismic model results median) about 60 years

4) Scenario D (1-year seismic model results 84th percentile) about 40 years

These numbers show that:

a) There is a significant increase in the expected likelihood of severe earthquakes now that seismic hazard models have been updated to include the earthquakes in 2010 and 2011 (prior to these earthquakes an earthquake ground motion on this scale would have been predicted to be a once-in-thousands-of-years event).

b) There is a substantial current elevation in seismic risk compared to the longer-term level to which that risk will decay to over the next 10 years or so (1-year versus 50-year comparisons).

c) It is important of consider the uncertainty in the frequency of earthquakes forecast using the best available models of seismicity.

[5] The seismic hazard models used take account of the variability in ground shaking for different earthquakes and can predict any required percentile of the statistical distribution of shaking expected from all the earthquakes included in the model. In other contexts, such as dam safety in New Zealand, a precedent has been established for using the median of these distributions (central estimate) as a basis for economic risk assessment, and using the 84th percentile (to provide a more precautionary, higher estimate of earthquake frequency) for life safety (fatality risk assessment).

7.0 DISCUSSION

7.1 Tolerability of risk

Taig et al. (2012) discuss what actions might be appropriate for what level of rockfall-related risk to homes in the Port Hills and suggest that these actions should be based on managing the annual individual fatality risk. The threshold above which annual individual fatality risk is considered intolerable should be set in the range 10^{-3} – 10^{-5} per year, with 10^{-4} (approximately 1 in 10,000) per year providing a suggested starting point for discussion. That report also discusses the use of a buffer zone or zones defined on a lower but significant level of risk, within which future development might be constrained so as to prevent an increase in the number of people at significant (but not intolerable) risk from these hazards in the future.

7.2 Societal risk

Societal risk is a measure of the combined risk associated with all individuals who may be exposed to the risk; it reflects the number of people exposed. The simplest measure of societal risk is the expected total number of fatalities and it is presented as the expected number of people killed in an event of a given frequency of occurrence (GEO, 1998).

The expected numbers of people killed as a result of the different representative earthquakes in each of the considered frequency bands in any scenario have been estimated. To do this, the 2006 census data (from Statistics New Zealand) were used to estimate the number of residents in at-risk dwellings in the Port Hills. Using these data, the mean number of people per dwelling in the Port Hills suburbs covered by this report is about 2.5, assuming night-time residency, and 0.4 people per dwelling assuming daytime residency. The numbers of dwellings in each risk category were estimated using the CCC building footprint data (Table 30).

Table 30 Estimates of societal risk from rockfalls from earthquakes in the assessed Port Hills suburban areas. PGA is peak ground acceleration.

Earthquake	Earthquake frequency (assuming the median 1-year seismic model)	Average expected number of fatalities*
22nd February 2011 earthquake day-time (equivalent to the representative earthquake in the 1.0 – 2.0 g PGA band)	0.016 or 1/63 per year	1 day-time
22nd February 2011 earthquake night-time (equivalent to the representative earthquake in the 1.0 – 2.0 g PGA band)	0.016 or 1/63 per year	20 night-time
Representative earthquake in the >2.0 g PGA band (night-time)	0.0008 or 1/1,250 per year	180 night-time
Representative earthquake in the 0.4 to 1.0 g PGA band	0.17 or 1/6 per year	2 night-time

*Assumes no homes have been evacuated

In the light of the 2010/2011 Canterbury earthquakes, the greatest contributions to societal risk are from larger earthquakes of longer return periods, which have the potential to cause many fatalities in a single event.

7.3 Selection of risk scenario for field verification

The risk model preferred by GNS Science (Scenario C, Table 28) is one which uses the higher risk 1-year base seismic model, and includes allowance for:

1) a modest number of unmapped boulders from the 22nd February 2011 earthquakes; and
2) an expected increase in the numbers of boulders generated from "other" (non-earthquake) events in the near future because the rockfall-source areas are now in a disturbed state.

This scenario provides a reasonably central estimate of the current, elevated level of risk. As time progresses, any decisions made on the basis of this scenario will become more defensible with respect to the uncertainties inherent in any assessment about future rockfall hazard.

Because each of the different scenarios were applied uniformly to each area, any one of them provides a sound basis for discussion of differences within and between suburbs. The two central scenarios (B and C) likely provide more accurate estimates of the actual numbers of homes at different levels of risk. Both provide mildly pessimistic estimates of the current risk, and will become more robust with respect to uncertainties as time moves on and the current elevated seismic hazard levels subside, however, scenario C is considered to more accurately represent the level of fatality risk likely to persist over the next 10 years or so.

Rather than seeing the model providing a risk estimate that will reduce with time, GNS Science suggests that it should be viewed as providing a risk estimate which allows for some uncertainty at the present time, and will allow for more uncertainty as time progresses over the next decade. In 10 years' time, both knowledge of the seismic risk, and the value of the seismic risk will have changed, and the fatality risk should be revised.

All other parameters used in the preferred model (scenario C) are central estimates for the most realistic values, based on the best evidence available to GNS Science.

7.4 Other matters and observations

7.4.1 Mitigation measures

The annual individual fatality risks estimated in this report are based around information on boulder distributions from the 22nd February 2011 earthquakes. As a result they include any influences of rockfall mitigation that were in effect at that time. The extant mitigation, deliberate and accidental, include set-backs below the more active pre-4th September 2010 rockfalls sources, shelter belts, forestry, other houses, and a variety of engineered protective measures such as scaling or pinning of loose rock, and rockfall fences. The GNS Science risk model did not differentiate between areas with known mitigation work and areas without, but this was considered in the individual site inspections.

To date, rockfall mitigation measures carried out in the Port Hills since the February earthquake have been aimed at stabilising "high risk" or "imminent risk" boulders, defined as boulders considered likely to move within the next 12 months. GNS Science obtained no data that would allow assessment of whether this work has significantly reduced the life risk in these areas, and so the work is not reflected in the risk assessments.

In many locations in the Port Hills, it is not possible to prevent every boulder from leaving a source area; for example, a source area may be too large to reasonably stabilise every boulder on it to an acceptable level of risk. In some such cases, alternative rockfall mitigation measures, ranging from land-use restrictions to extensive engineering works, may be considered to reduce the life risk.

7.4.2 Future planning processes

The principal goal of developing quantitative risk assessment methods is to make future planning processes simpler and more effective for managing risk. The key benefit is that having risk-based planning zones makes it simpler to decide whether, for example, a house can or cannot be built. Having to make a decision on a case-by-case basis in the absence of any risk criteria is protracted, difficult and ineffective in managing risk.

The quantitative assessment presented in this report reveals a widespread level of risk in the Port Hills that exceeded many people's expectations, notwithstanding their experiences in 2010 and 2011. Had people been aware of this risk in the past, it is likely that a number of these Port Hills suburbs would have developed differently. It is, however, notable that there were several areas in residential use in 2010 where in former times, rockfall shelter belts had been planted to protect grazing stock and orchards for falling rocks.

The annual individual fatality risk from rockfalls in those Port Hills areas assessed has now been quantified. The results from this analysis now allow comparison of these risks with many of life's other risks. This knowledge offers a powerful planning tool for the future of the Port Hills suburbs, and the wellbeing of their residents.

8.0 FIELD VERIFICATION OF FATALITY RISK

Consultants of the Port Hills Geotechnical Group, in collaboration with GNS Science, carried out 'ground truthing' verification of the fatality-risk zones generated using the fatality risk scenario C, to either:

1) Confirm for each dwelling that fatality risk was correctly defined in relation to the local rockfall source areas and local topography; or

2) Recommend changes to the risk-zone boundaries on the basis of site-specific ground conditions that were not considered in the suburb-scale assessments.

8.1 Assessment method

The field assessment methodology (Appendix E) is summarised below.

1) Initial office (desk top) assessment, including:

a. Generating base maps for field use

b. Identifying all properties (and dwellings) within the risk zones defined by this project

c. Reviewing all available relevant information;

2) Identification of dwellings/areas that appeared to be anomalous (for example where risk zones were defined but no boulders had fallen);

3) Two-dimensional rockfall modelling (using the RocScience program RocFall®) to check potential runout distances at specific locations to help define the furthest limit of detectable fatality risk (i.e. the rockfall limit line) before commencing field assessments. The modelling was carried out using the methodology in Appendix F; and

4) Field inspection of all houses within the risk zones defined by this project to determine whether the risk at each was judged to be consistent with, less than or greater than the risk assessed from the suburb-scale model. Field checking was carried out using a standard proforma to ensure consistency between the areas (Appendix F) and to document how particular decisions were reached. One proforma was completed for each residential property, including those properties without dwellings. These data are held by Christchurch City Council.

One factor in the fatality-risk assessment that was not amenable to field verification was the seismic hazard. The seismic hazard, which was applied uniformly across all areas was derived from the composite seismic hazard model, which is a statistical earthquake model (Gerstenberger et al., 2011).

8.2 Revising the risk maps

The risk maps generated using scenario C were revised in the following ways:

1) A line was drawn at the location where the assumed annual individual fatality risk was about 10^{-6} per year. The position of this line was largely determined from the assessed limit of rockfall-runout. This line was developed using the following data:

   a) Two-dimensional rockfall modelling which took account of local slope angle and shape;

   b) Geomorphological evidence of historic (post 1840 AD) and pre-historic rockfalls, derived from geomorphological mapping of the Port Hills (Townsend and Rosser, 2012); and

   c) Shadow angles and mapped 2010–2012 rockfall boulder distributions.

The position of the 10^{-6} per year line (contour) was then field checked against the extent of mapped historical and pre-historical boulders, the recently mapped fallen boulders and the location of the 21°shadow angle line. The position of the line demarking the assumed annual individual fatality risk of about 10^{-6} per year was drawn to incorporate these features. Rockfall fatality risks below this line have not been shown on the risk maps. A 10 m buffer was added to the line to take account of the probabilistic nature and inherent uncertainty in the modelling.

2) Local variations from the suburb-average risk were taken into account by showing on the maps those areas where:

   a) The risk was field assessed as greater than the suburb average, e.g. where the property is within a depression that directs boulders onto it, or where the source area (where the boulders originate) is larger or more disturbed than the suburb average; or

   b) The risk was field assessed as less than the suburb average, e.g. the property is sheltered by a local permanent topographic feature or where boulder runout is stopped by, for example, extensive natural or prepared flat ground (such as roads, tennis courts and large swimming pools). The presence of other buildings, fences (whether designed to stop boulders or not), and trees were not classed as sheltering features that would limit the runout of boulders as these are ephemeral features.

The field-verified risk maps generated using Scenario C are contained in Appendix G. These maps show those areas where the risk was field-assessed as greater and less than the suburb average.

8.3 Numbers of residential homes in each risk category

Using the revised "field verified" risk maps there are about 554 dwellings (including those classified as "unknown") located in the annual individual fatality risk zones. On the field verified maps (Appendix G), about 192 dwellings expose people to annual individual fatality risks estimated to be greater than 10^{-3}/year, 223 expose people to risks between 10^{-3} and 10^{-4}/year, 105 expose people to risks between 10^{-4} and 10^{-5}/year and 34 expose people to risks less than 10^{-5}/year.

9.0 CONCLUSIONS

1) Following the 4th September 2010 Darfield earthquake the levels of seismic activity in the Christchurch region are considerably higher than the long-term average, and are likely to remain enhanced for several decades. As a result the fatality risks from rockfall are now considerably higher than they were before September 2010. The risk from earthquake-induced rockfall is expected to decrease as the seismic hazard decreases.

2) It is feasible to estimate, quantitatively, the annual individual fatality risk from rockfalls triggered by earthquake and other non-seismic events, in the Port Hills area, albeit with uncertainty. A suburb-scale method has been presented that has been locally field verified.

3) This report provides information to support risk-based land-use decisions regarding the tolerability or otherwise of the annual individual fatality risk at dwellings in the Port Hills that are subject to the hazard of isolated boulders falling and rolling from the slopes above.

4) To take the time-varying seismic hazard into account, the next 1- and 50-year seismic hazard models (50 years being consistent with the design life used in typical seismic hazard analysis for residential building construction), have been compared in the risk calculations discussed in this report.

5) The number of dwellings exposed to a given annual individual fatality risk is very sensitive to the seismic hazard model used to estimate the annual frequencies of likely future ground accelerations.

6) When estimated using the 1-year seismic hazard model effective from the 1st January 2012, the annual individual fatality risk of a person residing in a residential property in any one of the Port Hills suburbs assessed in this report is significantly higher (by a factor of about 3 to 4) than when averaged over the next 50 years. The reduction in annual individual fatality risk over the next 10 years is not presented, because this reduction will depend on earthquakes that happen over the next 10 years.

7) The annual individual fatality risks from rockfalls triggered by non-seismic events have also been included in the risk analysis.

8) A range of risk parameters was tested to determine model sensitivity to the selected parameters. A model using reasonable input parameters and based on a seismic hazard model applicable for the next year was used in the preparation of risk maps. This model takes into account the currently elevated seismic hazard, and will become less vulnerable to other uncertainties when the seismic risk declines.

9) The results from the suburb-scale assessment were checked in the field to the extent possible by appropriately qualified members of the Port Hills Geotechnical Group of consultants. Each dwelling within the areas covered by this risk assessment has been visited and the risk maps accompanying this report take account of the results of these visits.

10) Using the revised "field verified" risk maps there are about 554 dwellings (including those classified as "unknown") located in the annual individual fatality risk zones. On the final field verified maps (shown in Appendix G), about 192 dwellings expose people to annual individual fatality risks estimated to be greater than 10^{-3}/year, 223 expose people to risks between 10^{-3} and 10^{-4}/year, 105 expose people to risks between 10^{-4} and 10^{-5}/year and 34 expose people to risks less than 10^{-5}/year.

10.0 SUGGESTED CHRISTCHURCH CITY COUNCIL ACTIONS

Once Christchuch City Council has decided what levels of individual fatality risk will be regarded as tolerable and how Council will manage risk on land where fatality risk is assessed to be at various levels of intolerability, it is suggested that:

1) Council accepts the information regarding annual individual fatality risk from rolling boulders presented in this report;
2) Council uses the information in reaching decisions about future risk management for rockfall-affected dwellings in the Port Hills;

3) Council monitors performance of the fatality risk model by continuing to monitor the state

of the catchments (where the rockfalls originate) above dwellings, in particular identifying any new rockfalls indicating the instability of the source areas; and

4) Council re-evaluates the fatality risks after a period of 10 years, to incorporate a seismic hazard model appropriate to the knowledge of that time, and incorporating knowledge about the post-2011 performance of rockfall sources in the Port Hills.

11.0 ACKNOWLEDGEMENTS

This work was funded by the New Zealand Public Good Science Fund via the Hazard Platform and Christchurch City Council. The authors acknowledge the advice and comments on this work provided by the Port Hills Geotechnical Group. This work would not have been possible without the data collected by them. The team comprises the following consultants: URS, OPUS, Geotechical consulting, Aurecon, GHD. The authors wish to acknowledge: T. Davies of Canterbury University, D. Macfarlane, M. Easton, M. Yetton, S. Bensberg and H. Grant ECAN, for their comments and guidance during this work; M. Gerstenberger and G. McVerry for providing the earthquake peak ground acceleration probabilities and D. Rhoades for carrying out the rockfall-ground-acceleration analysis. The authors also thank B. Lukovic and D Heron for all of the GIS modelling and map-preparation work, R. Buxton, G. McVerry and W. Smith for internally reviewing sections of this report and N. Litchfield, G. Dellow and T. Webb for internally reviewing the report. The report has been considerably enhanced by comments made by the independent peer reviewers. These were L. Richards regarding the mechanics of rockfalls, T. Taig regarding risk assessment methods and risk management criteria, and F.J. Baynes as the independent reviewer appointed by Christchurch City Council. The calculation procedures for the risk model were independently set up and checked by M. Hunt, TTAC Limited.

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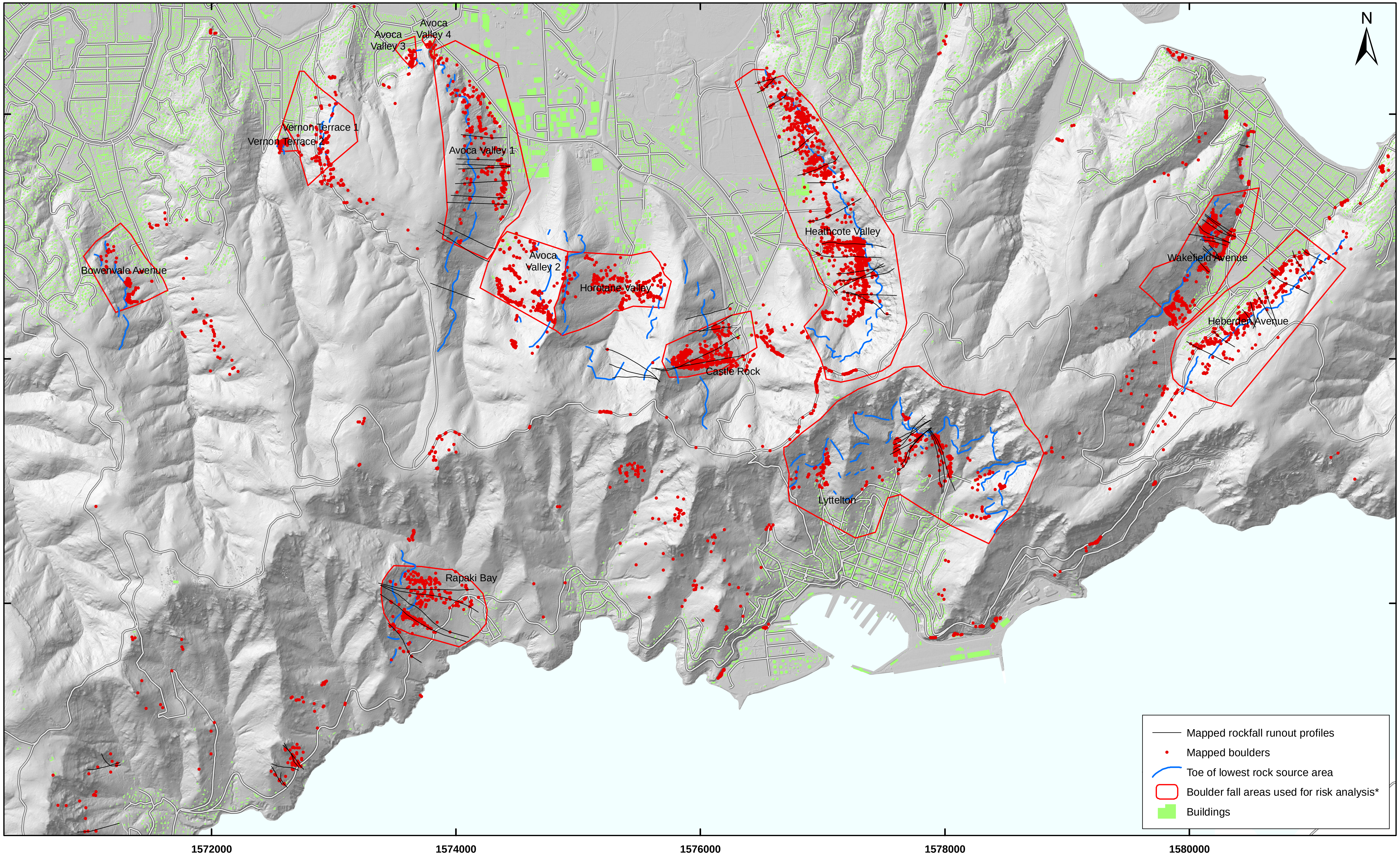
APPENDICES

APPENDIX A LOCATION MAP



SCALE BAR: 0 1 2 Km

EXPLANATION:

*Areas used to define the number of boulders passing each shadow line

Shade map derived from NZAM post earthquake 2011a (March 2011) LiDAR Survey resampled to a 3m ground resolution.

Roads and building footprints provided by Christchurch City Council.

DRW: BL

CHK: CM

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ROCKFALL LOCATION MAP

Areas included in the rockfall risk analysis

APPENDIX A

FINAL

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: Mar 2012

APPENDIX B   ROCKFALL RUNOUT ANALYSIS

B1.0 Rockfall runout

The runout of 66 boulders along their mapped rockfall trails (Table B1, locations shown in Appendix A) has been analysed. Profiles were drawn along each trail from the resampled post-22nd February 2011 LiDAR digital elevation model, resampled to 3 m ground resolution. The likely source area for the rockfall, and the nature of the substrate materials along the path were mapped from New Zealand Aerial Mapping aerial photographs, with limited field checking. The trail shapes, and therefore valley-side profiles in the Port Hills can be generalised into two main types: 1) planar; and 2) concave (almost asymptotic to a flat valley floor) (Figure B1).

Table B1 Location and number of mapped rockfall trails used in the runout analyses.

Location	Number of mapped trails
Castle Rock	5
Governors Bay Road	4
Heathcote Valley	14
Lyttelton	9
Rapaki Bay	5
Avoca Valley	10
Sumner (Wakefield Avenue)	11
Sumner (Heberden Avenu)e	8

Planar trails tend to be shorter, with smaller elevation differences between top and bottom than the concave trails. The planar slopes comprise areas of intermittent basalt rock outcrops of lava flows at different stratigraphic levels. Below the rock slopes are localised areas of rocky talus, which overlie pockets of loess colluvium (loess reworked through mass-movement processes). In some areas, the silty colluvium also contains reworked talus and isolated boulders. The rockfalls come from the rock outcrops. The planar slopes tend to end abruptly at sharp breaks in slope, which mark the boundary with flat basin/marine deposits. The concave (asymptotic) slope trails typically are derived from a single steep source area formed of multiple basaltic lava flows. Areas of mixed talus and loess colluvium extend from the toe of the rock slopes, and grade into loess colluvium with increasing distance from the toe of the rock outcrops.

In some areas, it is difficult to distinguish between rock at or near the surface with patchy thin talus cover from areas of predominantly talus. There is also an irregular and gradational boundary between the end of the talus and the beginning of the loess colluvium.

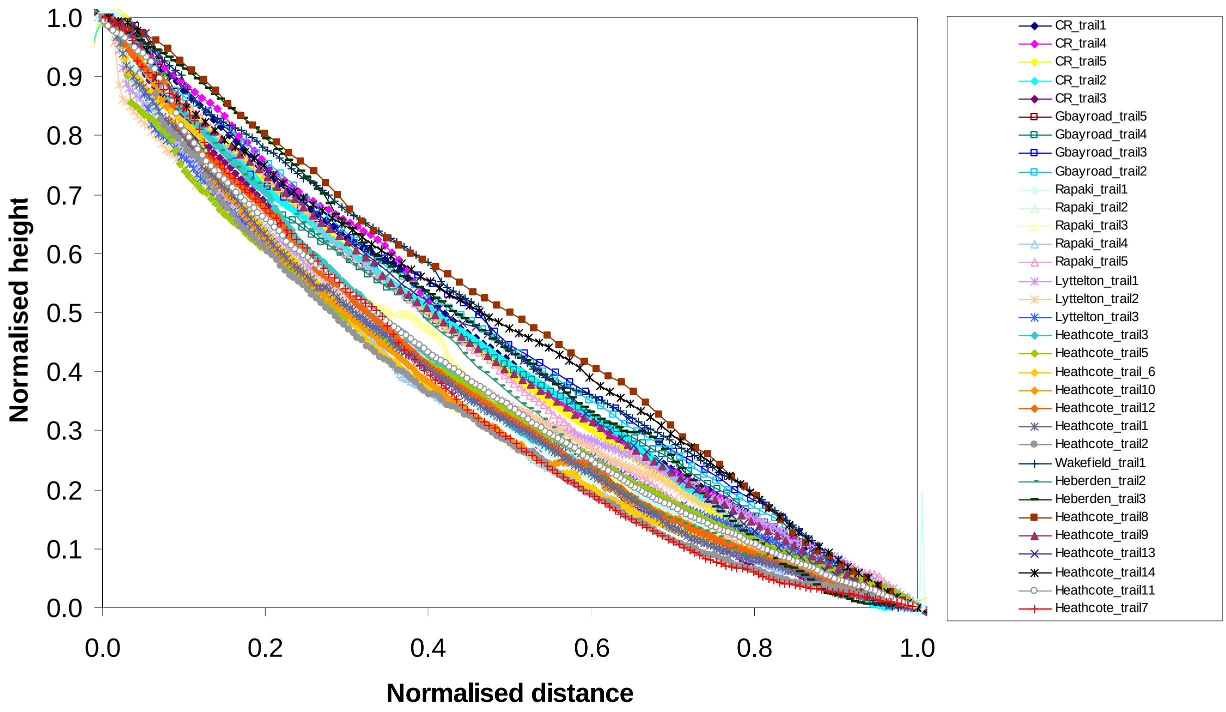


Figure B1 Selected rockfall trails for Castle Rock (CR), Governors Bay Road (Gbayroad), Rapaki Bay (Rapaki), Lyttelton, Heathcote Valley (Heathcote), Wakefield Avenue, Sumner (Wakefield) and Heberden Avenue, Sumner (Heberden).

For each of the 66 mapped trails the boulder runout was assessed using: 1) Fahrboeschung angle; 2) Shadow angle; 3) Runout ratio model; and 4) Alpha (α) – Beta (β) model. Linear regression was used to assess the relative performance of each statistical model (Table B2).

Table B2 Comparison of results from the different statistical runout models

Model	Gradient[1]	Error on the gradient[2]	R^2	No. records (trails)
Fahrboeschung angle	0.52	±0.01	0.96	64
Shadow angle	0.47	±0.01	0.95	64
Runout ratio	0.49	±0.02	0.76	64
Alpha – Beta	0.3	±0.1	0.10	64

[1]Calculated using the least-squares method
[2]Standard error on the gradient

The lowest Fahrboeschung angle for all 66 mapped trails was 24° and the lowest shadow angle was 21°. To assess the influence of slope profile on rockfall runout, the mapped rockfall trails were divided into planar and concave trails and the frequency distributions (using 1.5° bins) of each group assessed (Figures B2 and B3).

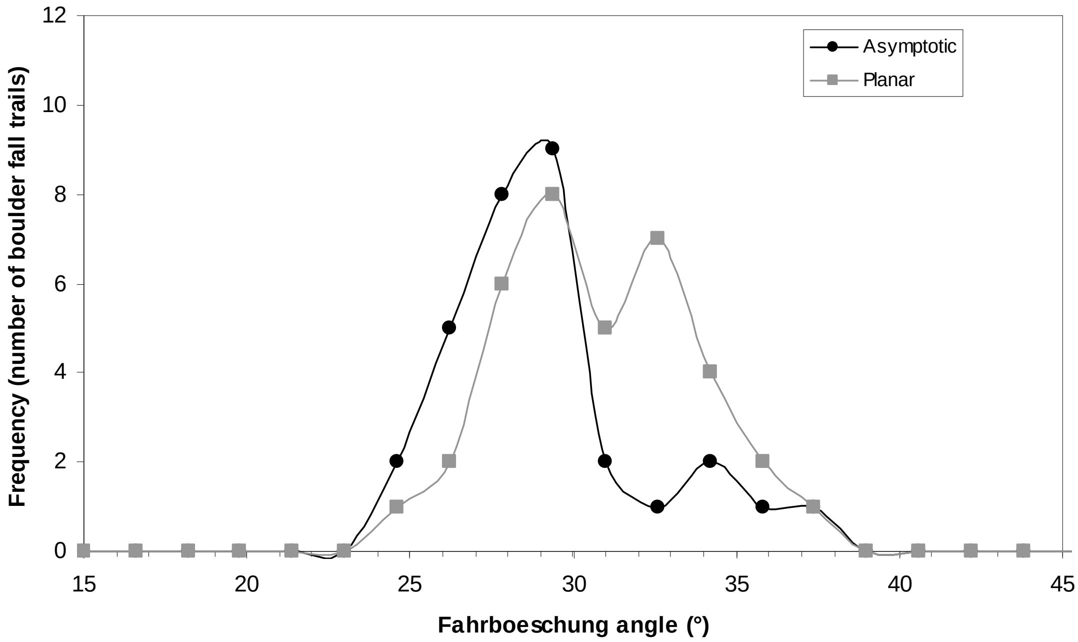


Figure B2 Fahrboeschung angle distribution (1.5° bins) for the mapped boulder trails (n = 66), divided into “asymptotic” (concave) and “planar” slope trails.

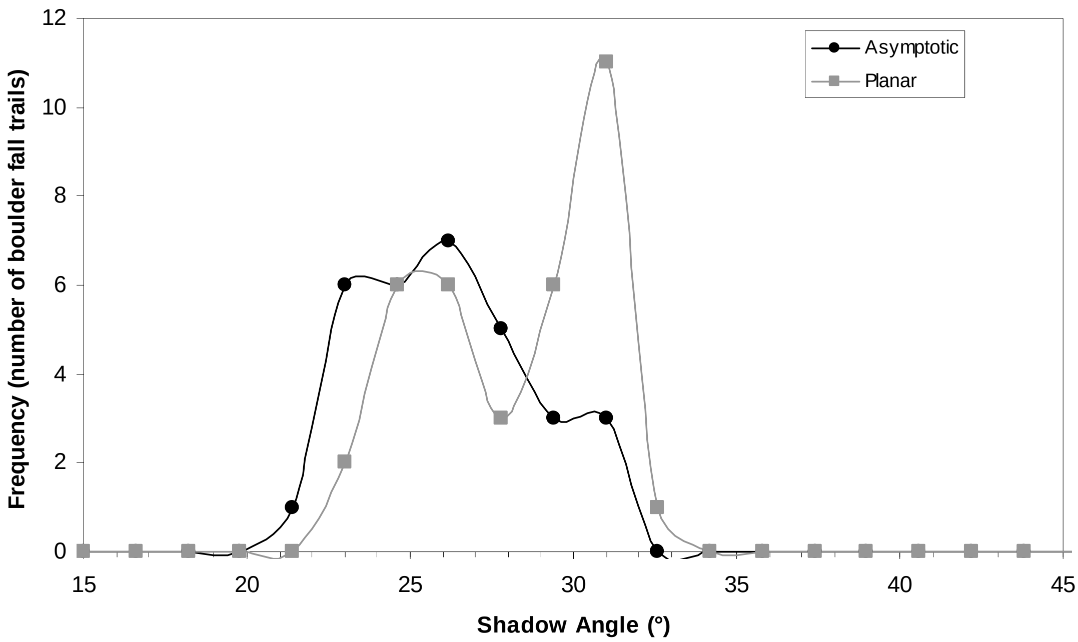
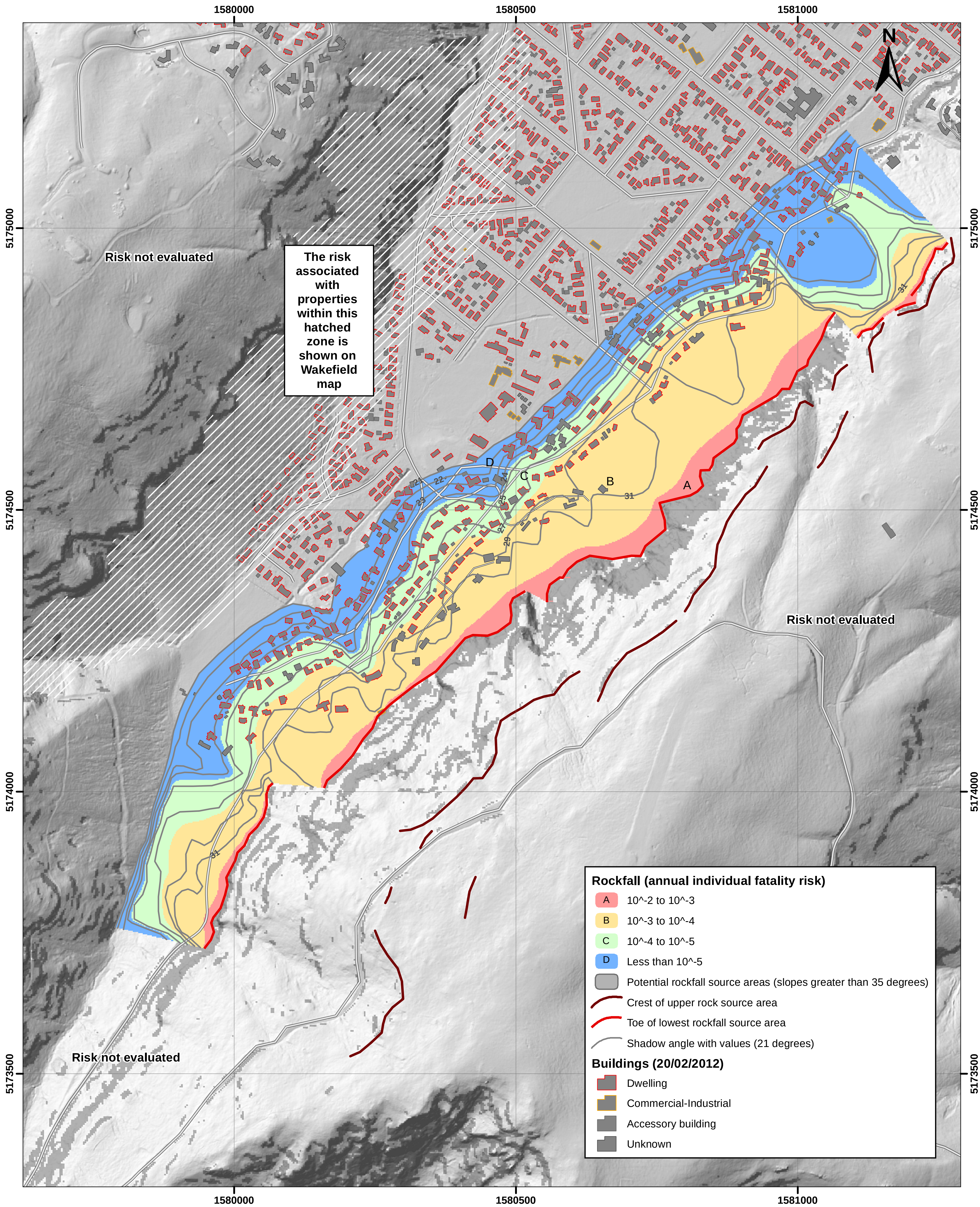


Figure B3 Shadow angle distribution (1.5° bins) for the mapped boulder trails (n = 66), divided into “asymptotic” (concave) and “planar” slope trails.

For asymptotic (concave) trails, the Fahrboeschung angle and shadow angle frequency distributions are bimodal. The shadow angle distribution has a smaller mode at 23° and a larger mode at 26°, while the Fahrboeschung angle distribution has a larger mode at 29.5° and a smaller mode at 34°. The frequency distributions for planar slopes are also bimodal but with the larger mode at 31° and the smaller mode at 25° for the shadow angles, and for the Fahrboeschung angle the larger mode is 32.5° and the smaller mode is 29.5°. These distributions show that planar trails have typically steeper Fahrboeschung and shadow angles than asymptotic slope trails, indicating that rockfalls on planar slopes do not travel as far. This is because in the Port Hills the planar slopes (e.g. Heberden and Wakefield Avenues, Sumner) tend to end abruptly at the margins of the flat sedimentary basins. However, the bimodal distributions suggest that there are other factors influencing rockfall runout currently not accounted for.

The shadow angle distribution of rockfalls triggered by this earthquake is at the lower end of those reported in the literature (e.g. 27.5°; Evans and Hungr, 1993). However, Dorren (2003) reports shadow angles of 22 – 30°, which are more similar to those recorded in the Port Hills. From field observations of Port Hills rockfalls, these longer runouts occur because the boulders roll, developing considerable angular momentum. This is in agreement with full-scale experimental observations and from field observations (e.g. Kirkby and Statham, 1975; Evans and Hungr, 1993). The kinetic energy acquired by the boulder in the initial fall is largely lost (about 75-86%; Dorren, 2003) in the first impact on the talus surface near the top of the slope. Thus, the height of the fall has little influence over the runout (Evans and Hungr, 1993). If the boulder starts to roll after its first impact, then its runout can be approximated by the minimum shadow angle. If the boulder starts to slide, then it tends to have limited runout. According to Evans and Hungr (1993), the shadow angle represents the slope of the energy line, i.e. the rolling-friction gradient. Although the Fahrboeschung angle ignores the marked asymmetry in energy expenditure and is dependent upon the height of fall (Evans and Hungr 1993), the results from this analysis suggest that it can still be a useful tool for investigating rockfall runout, possibly because the initial rockfall heights are relatively small in comparison to the total runout distance.

APPENDIX C RISK MODELS



SCALE BAR: 0 100 200 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK SCENARIO A

Heberden Avenue Christchurch

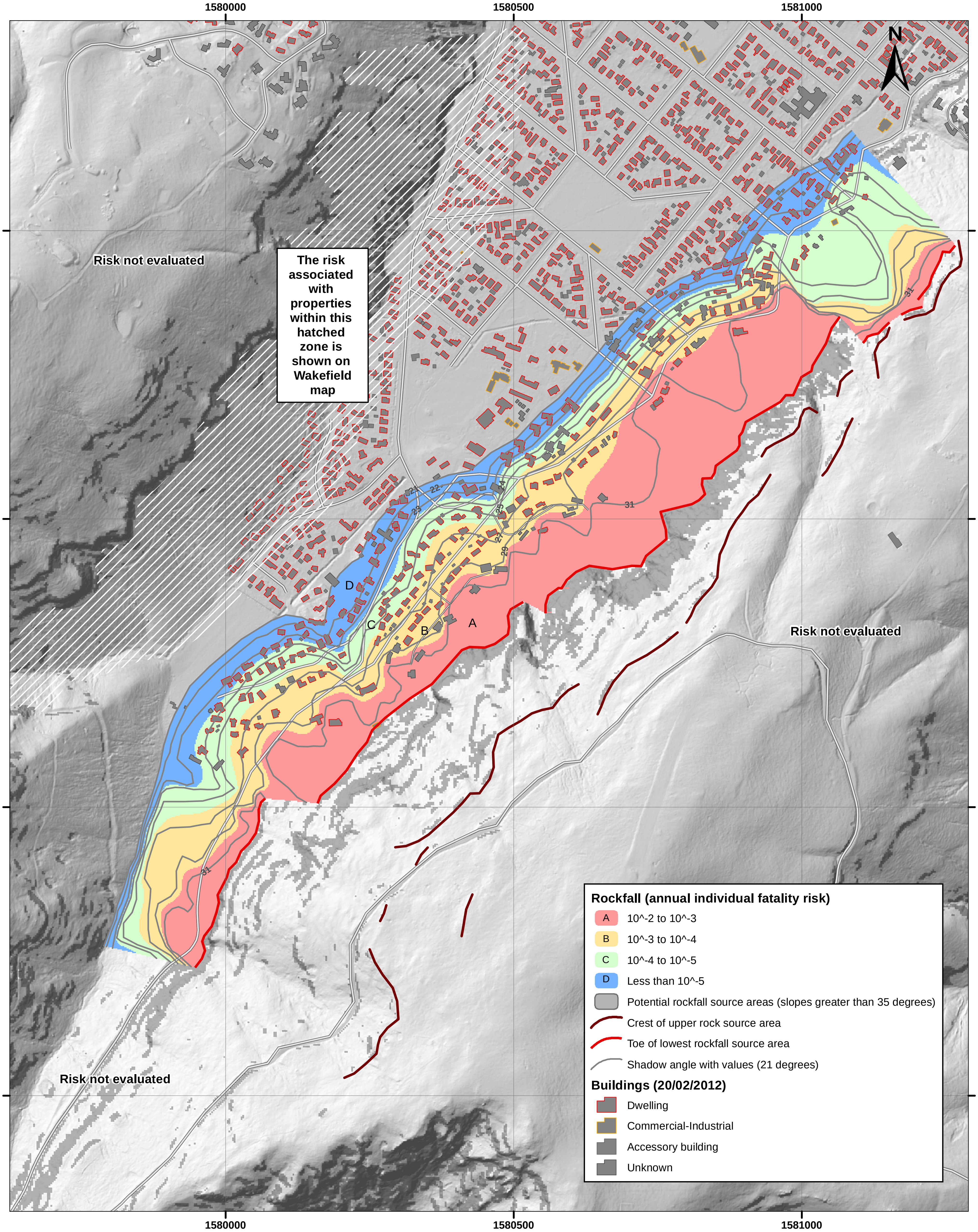
APPENDIX C

FINAL

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: Mar 2012



SCALE BAR: 0 100 200 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

DRW: DWH, BL

CHK: CM

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ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK SCENARIO B

Heberden Avenue Christchurch

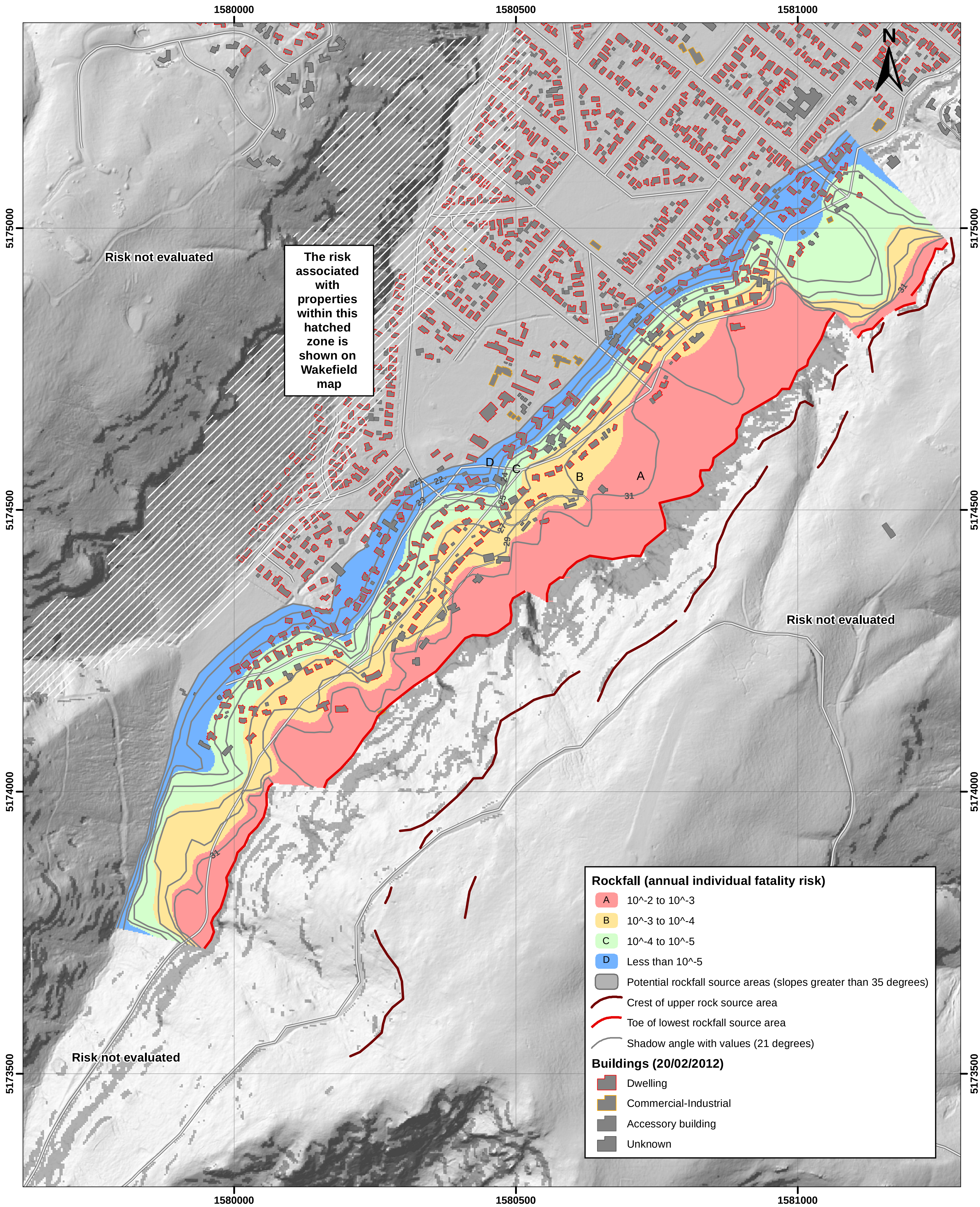
APPENDIX C

FINAL

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: Mar 2012



SCALE BAR: 0 100 200 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK SCENARIO C

Heberden Avenue Christchurch

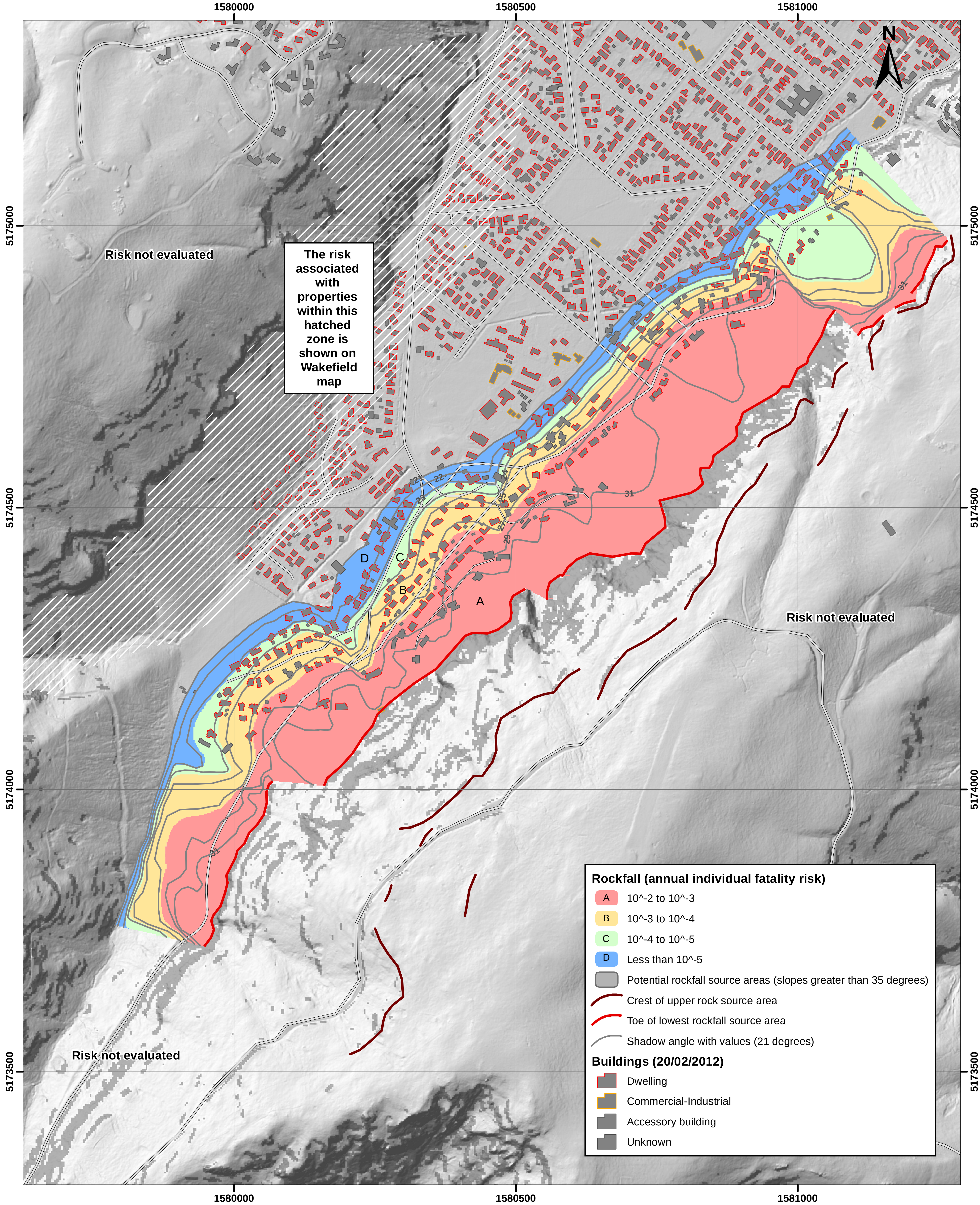
APPENDIX C

FINAL

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: Mar 2012



SCALE BAR: 0 100 200 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

DRW: DWH, BL

CHK: CM

GNS SCIENCE TE PŪ AO

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK SCENARIO D

Heberden Avenue Christchurch

APPENDIX C

FINAL

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: Mar 2012

APPENDIX D ROCKFALL MODELLING

D1.0 Rocfall™ modelling

Thirty three of the mapped rockfall trails have been back analysed using the Rocscience (2011) Rocfall™ programme. This programme is a process-based rockfall model, which simulates the models of motion of falling rocks over a slope surface. The results from this modelling provide a useful indicator of the likely rockfall bounce heights and kinetic energy, which are important factors to consider when designing rockfall retention structures, e.g. fences.

The Rocscience Rocfall™ programme, which is a lumped mass-modelling programme, was used for the analyses. Each rock block is considered to be a simple point with a mass and velocity. The point is then thrown down the slope along the mapped profile. The following parameters had to be derived for the analysis: 1) the size of the modelled rock blocks; 2) the initial conditions of the rock block (failure mechanism); 3) coefficients of restitution for the different materials forming the slopes along the path of the modelled rockfall; 4) angular velocity of the rock block; and 5) roughness of the slope along the path of the modelled rockfall.

In the Rocscience Rocfall™ programme, the block falls down the slope along the mapped trail. As the block makes contact with the slope surface, the velocities normal and tangential to the slope are reduced by the coefficients R_n (normal coefficient of restitution) and R_t (tangential coefficient of restitution). The Coefficient of Restitution (R) is the ratio of outgoing velocity to incoming velocity. The range of (R) values is between 0 and 1. If R is 0, the rock block will stop on impact (representing a perfectly inelastic material) and if R is 1, the block would have the same outgoing velocity as incoming velocity (representing a perfectly elastic material). The coefficients of restitution influence the travel distance and impact force of a rockfall, and are therefore dependent upon the material that forms the surface of the slope along which the blocks travel.

Three main materials form the slopes in the Port Hills: 1) Basalt lava flows, forming the rock slope source areas; 2) an area of rockfall debris (talus) immediately at the toe of the rock slopes; and 3) colluvial loess. The initial R values have been assumed from a review of available literature (Richards et al., 2001; Rocscience v4.0). For the back-analysis of the mapped 33 rockfall trails, slope profiles were generated from the post-earthquake New Zealand Aerial Mapping LiDAR survey, which was resampled to create a 3 m ground resolution digital elevation model. The slope profiles were then classified by material type, with the corresponding R values generated from the literature review.

D1.1 Angular velocity

Angular velocity is an optional parameter that can be considered in the Rocfall™ programme. If angular velocity is considered, then the rock block is allowed to rotate during its flight down slope. Angular velocity was considered in all analyses.

D1.2 Roughness of the slope

Slope roughness is used to model local variations in slope geometry. The Rocfall™ programme uses the angle of each slope segment (taken from the surveyed slope profile) to model roughness. Based on the field mapping, the slope surfaces of the rock slope and the slopes formed of talus were irregular, which was accommodated by applying a standard deviation value of 5° to the slope angle in the analyses.

D1.3 Results from the modelling

A sensitivity analysis of the various input parameters was carried out by varying the coefficients of restitution, friction and roughness for the different materials, to match the modelled rockfall end points with the mapped ones. Relatively high coefficients of restitution were needed for the loess in order to get the modelled end points to fit the actual end points. Changing the restitution coefficients of the rock and talus had little effect on the mapped end points.

All models used a zero slope roughness for the loess. Therefore slope roughness was assumed to be a function of the digital elevation model.

The sensitivity analysis showed that the modelled rockfall end points were most sensitive to the friction angle of the substrate material. This does not refer to the Mohr-Coulomb friction angle. The following is extracted from the Rocscience v4.0 user guide:

"*The friction angle is chosen based on the particle shape and the mode of movement. The value you should enter for the friction angle is the inclination of the segment such that a rock thrown onto this segment would continue to move downslope. In general, lower values are more conservative (i.e. the rocks will tend to move further downslope, and provide the "worst case" scenario. The "friction angle" depends on whether the rocks are all spherical shaped rocks, or if they are flat slabs. If the rocks are long flat slabs, then the mode of movement will be sliding, and the required friction value will be higher (much closer to a "standard" friction angle, as could be determined by a tilt test). If the rocks are all spherical, then the mode of movement will tend to be rolling, rather than sliding, and the value will be much lower (close to zero). If the rocks are somewhere between these two extremes (the most common situation) the value will also be somewhere between these two values, in proportion to the shape."*

This is slightly contradictory, as the majority of boulders were tabular-shaped (i.e. flat slabs), and during observed rockfalls the main movement mode was rolling, where the boulders rotated around their long axes.

Velocity scaling (*K*) was applied to the normal coefficient of restitution, so that the effective value of Rn reduces with higher velocities, reflecting increased fracturing of the rock and cratering of the slope surface at higher impact velocities. It was found that for most models the modelled end point distributions were not particular sensitive to changes in the *K* value. The reason for this is that the blocks are mostly rolling once they reach the loess and will continue doing so as long as the slope angle is greater than the rolling friction angle.

As the main mode of movement was rolling, low friction values were adopted (6 – 14°). However, the friction values adopted depend upon the slope roughness, as the slope roughness retards rolling. Where a 3 m digital elevation model was used, low friction angles were needed to get the modelled boulders to match the actual boulder end points. In contrast and as expected, higher friction values were needed for models using a 10 m digital elevation model.

Plots of bounce height and kinetic energy along each of the modelled trails suggest that for most trails the mean bounce heights are about 2.0 m (Figure D1). However these vary locally and can be in excess of 10 m. Field observations made of rockfalls from Castle Rock and Heathcote Valley indicates that bounces of >5 m in vertical height can occur. However the modelling shows that boulder bounce heights tend to decrease at distances of about 70% from the source areas, possibly representing a change from a bounding and rolling mechanism to more of a rolling one.

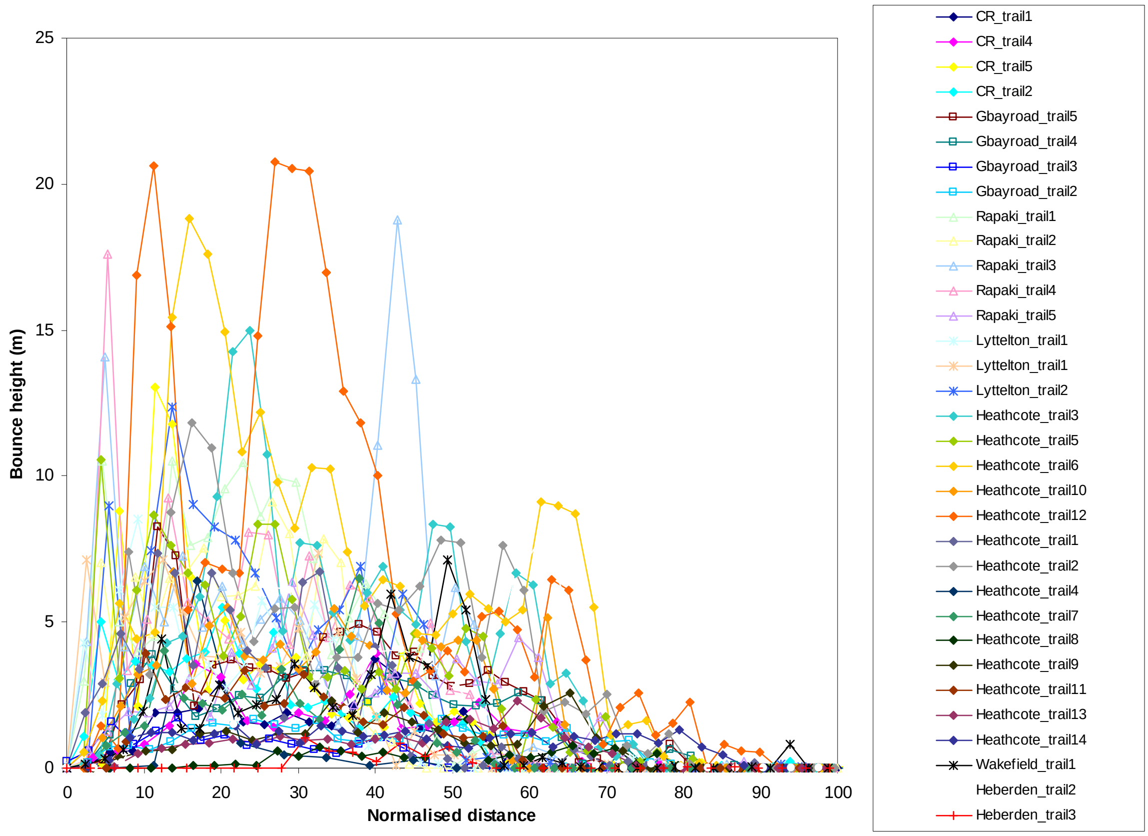


Figure D1 Bounce heights plotted along each trail derived from the Rocfall™ modelling of 33 mapped rockfall trails assuming a 1 m^3 boulder.

The kinetic energy is proportional to the size of the boulder. The kinetic energy distribution along each trail tends to be similar, where the central section's represent high kinetic energy values (Figure D2). In most cases the kinetic energy values tend to drop off at distance of about 70% from the source area, and may again represent a change in movement mechanism of the boulder. If the boulder size is increased by 2 m^3 (to a total volume of 3 m^3, the kinetic energy increases by about 66%. For a boulder size of 8 m^3, the corresponding kinetic energy would be about 7,000 kJ, which is well in excess of available fences (the maximum capacity of Geobrugg rockfall protection barriers is 5,000 kJ for example). It is likely that for some of the affected dwellings, it would not be economical to protect these with conventional rockfall fences, where the costs could be well in excess of ~$5,000 per metre for high capacity fences.

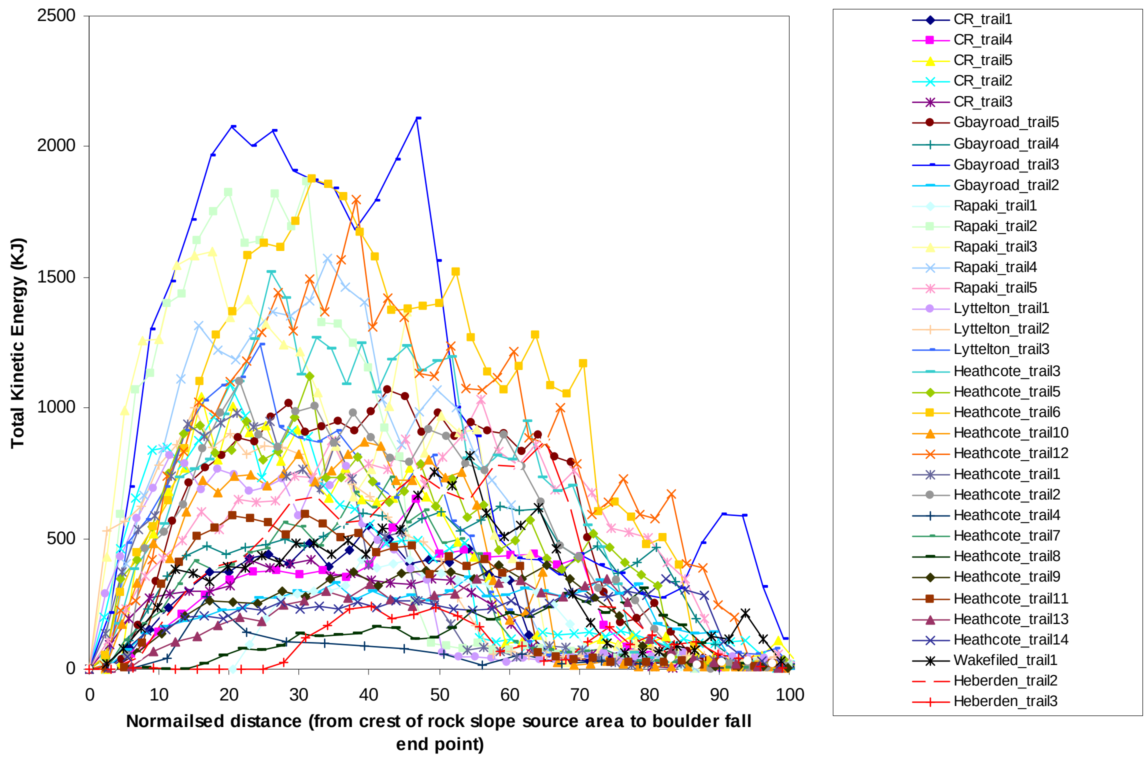


Figure D2 Kinetic energy plotted along each trail derived from the Rocfall™ modelling of 33 mapped rockfall trails assuming a 1 m^3 boulder.

APPENDIX E METHODOLOGY FOR FIELD VERIFYING BOULDER RISK ZONES

MEMORANDUM

Date	28 February 2012
To:	Karen McConachy, Ted Malan
From:	Don Macfarlane and Mark Yetton
Copies to:	Chris Massey, PHGG Sector Leaders
Subject:	**Methodology for Field Verifying (Ground-truthing) Rockfall Risk Zones**

Introduction

This memorandum is the finalised version of a document previously circulated in draft and incorporates revisions resulting from reviews of the draft and from the initial application of the methodology.

Preliminary Life Risk maps prepared by GNS Science for the Rockfall Risk Pilot Study have identified a series of Annualised Risk Zones (for individual loss of life) in areas subject to rockfall and boulder roll. About 800 homes are located within the risk zones defined by the pilot study. All are currently within the 'white zone' as defined by CERA, meaning that they are subject to further evaluation to determine whether they may continue to be occupied, cannot be occupied or can be occupied with conditions.

The Risk Zones are defined on the basis of a number of criteria and assumptions. PHGG, in collaboration with GNS Science, has been tasked with 'ground truthing' the risk zones to either

1. Confirm that they are correctly defined in relation to the known rockfall source areas, or
2. Recommend changes to the risk zone boundaries on the basis of site-specific ground conditions that are not considered in the suburb-scale assessments completed to date by GNS.

It is planned to complete the ground truthing of both the Pilot Study areas and the remaining areas of the Port Hills suburbs by the end of March, following which GNS Science will revise the risk maps and issue a set of FINAL, field verified maps

Proposed methodology and documentation

The PHGG assessment will consist of

1. an initial office assessment. This will include:
    a. generating base maps for field use by plotting the shape files onto air photo base plans (1:2000 or 1:2500 scale) that also show topographic details, fallen boulders, property boundaries, street numbers and s124 placarded properties
    b. identifying all properties (including dwellings) within the GNS risk zones
    c. reviewing all available relevant information including:
        i. geomorphic mapping (completed by GNS)
        ii. mapped boulder roll limits
        iii. boulder distribution (concentrations or not)
        iv. known or potential rockfall sources
2. identification of properties/areas that appear anomalous (for example where risk zones are defined but no boulders have fallen)
3. identifying cross sections for rockfall modelling and undertaking 2D modelling (using the RocScience program RocFall) to check potential runout distances at locations specified by the sector leader to help define the outer limits of the risk zones (maximum boulder runout distance) BEFORE commencing field assessments
    a. to confirm/otherwise that the mapped boulder limits are consistent with model expectations
    b. to confirm/adjust the 'negligible risk' line

It is expected that the initial cross sections for modelling will be spaced at approximately 100m intervals and/or at locations requested by the Sector Leader on the basis of site-specific knowledge, along the pilot study area and that the sections will be generated in the week prior to field review of a particular area

4. field checking of **all** houses within the pilot study risk zones to determine whether the risk at each is judged to be consistent with, less then or greater than assessed by GNS on the basis of suburb-scale application of criteria
5. site-specific assessment of those properties within the $>10^{-3}$ risk zone that do not currently have an s124 notice (see below). This will be used to determine whether such properties should be subject to an s124 Dangerous Building Notice, do not need an s124 Notice on technical grounds, or require further assessment
6. regular review of progress and results with GNS Science personnel

Properties within the 21° Shadow Angle line:

GNS have indicated that the 21° Shadow Angle represents the maximum observed runout distance for boulders below an asymptotic slope.

Properties within the areas defined by the 21° Shadow Angle line are assessed to be at varying levels of risk from boulder roll. The attached check sheet "Assessment of GNS Model Applicability for Individual Site" will be used to determine whether the site-specific life-safety risk is consistent with, greater than or less than the suburb-wide level of risk shown on the relevant drawings provided by GNS Science Consultancy Report 2011/311 (Rev 10 draft) dated 14 December 2011.

The assessment is to be completed for EVERY residential property within the life safety risk zones defined by the GNS pilot study report. All properties are to be inspected as part of the field review.

Where possible, this assessment will be used to determine whether or not those properties in the high risk zones ($>10^{-4}$) that do not currently have an s124 Dangerous Building Notice need one to be applied on **technical grounds** or whether additional evaluation is required to determine this.

Field Maps

Maps for validation and ground checking will be generated at a scale of 1:2000 and will include at least the following:

- GNS Life Risk zones (from GNS rev 10 draft report dated December 2011)
- PHGG mapped fallen boulders and known source areas
- Map showing slope areas of >35deg and >40deg slopes (rock bluffs/outcrops) (potential source areas)
- Contours (Lidar data)
- Geomorphological information (from GNS mapping)
- Street names
- Property boundaries and numbers
- House footprints
- S124 properties

[NOTE – may need to generate more than 1 set of base maps to show all base data listed]

Quality Assurance

To ensure consistency in all procedures so far as possible, we will

1. Use only dedicated, specifically trained personnel for all RocFall modelling. Training and verification will be provided by GNS Science, and
2. Provide a dedicated Team Leader (Mark Yetton) to oversee and manage the field aspects of the ground truthing

3. Undertake weekly reviews of progress and methodology with GNS Science and CCC

Deliverables

Regular reporting

- A Friday pm operational debrief will be held with GNS and CCC personnel each week
- Weekly updates will be provided to CCC in a spreadsheet each Friday listing the properties inspected in each Sector and the outcome
- Copies of the completed check sheets and marked up field maps will be provided to GNS at an agreed frequency, but no later than the following Friday.
- Additional supporting documentation (as below) will be provided as finalised.

Documentation to be provided for each property:

- Completed flow chart check sheet including explanatory notes (where applicable)
- Photos of the house and rocks that may be near it, including shadow angle measurements and F angle measurements where these can be measured to illustrate the context of the property and hazard source(s).

Additional reporting

- Any newly identified potential rockfall sources from field work or review of GNS geomorphic maps that could affect future development/planning will be identified as polygons and added to the GIS database (it is expected that any such potential sources will be outside the pilot study areas)
- Areas that are judged suitable for protective works such as bunds and/or rockfall catch fences will be identified, perhaps as an item at each weeks debrief while possibilities are fresh in the minds of the field team.

Final Report (per Pilot study area)

Brief (1-2 page) summary including

- when and where the inspections were carried out
- by whom
- summary of methodology [standard text]
- key outcomes
- A1 map of the whole study area annotated to show key outcomes of ground truthing and RocFall model sections
- GIS formatted digital copy of the "negligible rockfall risk line"

Plus Appendices

A. Table listing properties inspected and summarising key information and inspection outcomes (see attached example). This will be the final version of the weekly update.
B. Geocoded GIS version of the summary table
C. Property-specific package for each property inspected that includes the following information:
    a. Completed proforma
    b. Photograph(s) of house showing setting and area up slope
    c. Photograph(s) documenting shadow and Fahrboeschung angles at property (where possible)
    d. Photograph(s) of boulders that came to rest in the vicinity of the house
D. Copy of annotated A3 field maps
E. Rockfall modelling results, comprising a summary spread sheet and figures of the sections analysed showing the agreed outputs from the model

F. Ipad calibration photographs
G. Areas judged suitable for protective works

Field data should be given to GNS once each area within each sector has been completed.

Assessment Teams

Each assessment team will consist of two appropriately trained geotechnical personnel.

In order to ensure consistency across all Sectors we propose to form the evaluation teams primarily from Sector Leaders, but may also include other experienced field personnel with good knowledge of the Port Hills issues. Those undertaking evaluations will undergo an appropriate training session, including field calibration.

We further propose that in order to retain objectivity, individual site assessments within a sector will be completed by a Sector Leader (or other qualified person) who has not been working in that sector. They will be accompanied by the Sector Leader (or other qualified person) for that sector so as to provide any necessary background information.

At this stage it is anticipated that up to five teams will be available depending on the prioritisation of other tasks required of the PHGG team. However, initially we plan to have only one team operating, adding others as the sector leaders gain experience and are freed up as sectors are progressively completed.

The RocFall modelling will be undertaken by a small team of dedicated personnel to ensure consistency of modelling. A training workshop with GNS will be conducted prior to commencing the modelling.

GNS will provide support personnel in Christchurch for the duration of the ground-truthing exercise. GNS will not fully participate in the ground truthing but will provide advice as required and will undertake consistency checks by reviewing the field data. It is anticipated that GNS will participate in weekly field reviews (Friday am).

Prioritisation

Our proposed programme and time line are shown as Attachment A. The first priority was to test the process by assessing the Sector 2 pilot study area (Wakefield Avenue/Sumnervale) which has a full range of ground conditions and for which some preliminary RocFall modelling was available. This work commenced in the week beginning 23 Jan 2012 and allowed us to determine the time frame required for each property to be assessed and provided a basis for developing a forward programme and assessing resource requirements.

Further Assessment

One possible outcome of the review is that the property will be identified as requiring a more detailed evaluation.

The methodology for this has yet to be confirmed but is likely to be based on the s124 review process previously developed to draft stage.

A second possible follow up task is to undertake preliminary (conceptual) design of protective works in those areas for which such works are identified as potentially able to allow dwellings to be reoccupied or to remain occupied. Conceptual designs will NOT be initiated unless specifically requested by CCC.

Attachment A

Programme and Timeline

The following table summarises our proposed programme. This will be reviewed weekly and revised if necessary to reflect actual progress or changes in priority.

Initial Programme

Week	Commencing	Planned Activities
1	16 Jan	Finalise ground truthing methodology for CCC signoff. Conduct RocFall training workshop (GNS)
2	23 Jan	Commence ground truthing in Sector 2 Adjust methodology as appropriate.
3	30 Jan	Continue Sector 2
4	6 Feb	Complete Sector 2 Commence Sector 1 (Heberden Av)
5	13 Feb	Continue Sector 1
6	20 Feb	Complete Sector 1 Morgans Valley (Sector 5)
7	27 Feb	Bridle Path Road (Sector 4) Start Lyttelton
8	5 Mar	Continue Lyttelton
9	12 Mar	Complete Lyttelton. Avoca Valley 1 (main valley)
10	19 Mar	Horotane Valley, Castle Rock, Rapaki Bay, Avoca Valley 2, 3 4
11	26 Mar	Vernon Terrace, Bowenvale

Updated Programme (as at 24 February)

The following table summarises our proposed programme (Revision 3). It reflects progress to date (shaded yellow) and our anticipated forward programme, including ground truthing of the cliff collapse areas.

The revised objective is to complete the ground truthing of the GNS Pilot Study areas and the cliff collapse areas by 16 March 2012. However, we have delayed the start of the Lyttelton field work to 12 March to give time for the Geovert/Freefall team to undertake 3D modelling of this area. The ground truthing (field work) for Lyttelton may not be completed until 31 March.

This programme will continue to be reviewed weekly and revised if necessary to reflect actual progress or changes in priority.

Week	Commencing	Planned Activities	
1	16 Jan	Finalise ground truthing methodology for CCC signoff. Conduct RocFall training workshop (GNS)	
2	23 Jan	Commence ground truthing in Sector 2 Adjust methodology as appropriate.	
3	30 Jan	Continue Sector 2	
4	6 Feb	Continue Sector 2	Commence Sector 1 (Heberden Av)
5	13 Feb	Continue Sector 1	Complete Sector 2 (issued)
6	20 Feb	Complete Sector 1 MY/RG	Start Morgans Valley (Sector 5) MY/ME
7	27 Feb	Complete Morgans Valley (Sector 5) MY/ME/KW Bridle Path Road (Sector 4) ME/RG	Avoca Valley 1 MY/JM Cliff collapse (MY)/AB/CG *Sector 3, Sector 2*
8	5 Mar	Vernon Terrace, Bowenvale MY/JM	Cliff collapse AB/CG/SB/RG *Sector 1, Sector 2*
9	12 Mar	Horotane Valley, Castle Rock, Rapaki Bay, Avoca Valley 2, 3 4 ME/JM/AB	Start Lyttelton MY/KW
10	19 Mar		Continue Lyttelton MY/KW
11	26 Mar		Complete Lyttelton. MY/KW

Additional teams may be available for Lyttelton from 19 March

APPENDIX F ROCKFALL MODELLING METHODOLOGY FOR FIELD VERIFICATION

Rockfall modelling methodology

This rockfall modelling methodology forms one part of the “Methodology for Ground-truthing Boulder Risk Zones” (developed by the Port Hill Geotechnical Group (PHGG) and GNS Science). This methodology was produced by GNS Science.

The rockfall modelling was carried out by a group of modellers working for the different consultants that comprise the Port Hills Geotechnical Group. This report, along with the workshops, were used to provide consistency between the modellers.

Purpose of the modelling

To better define the “rockfall limit line” using two dimensional physically-based rockfall modelling software. The rockfall limit line is defined as the line beyond which rockfalls are unlikely pass, i.e. the limit of rockfall runout.

The modelling was also used to provide supporting evidence for the decisions made by the Sector leaders during the field verification exercise.

Rockfall modelling methodology

The methodology comprises the following main steps:

A) Back analysis of fallen rocks
   1. Define sections for analysis
   2. Generating the cross sections
   3. Setting up the Rocscience® rockfall model
   4. Running the analysis and assessing the results
B) Forecasting rockfall runout
   1. Identify sections to model
   2. Parameters to model
   3. Checking of model results
C) Defining the modelled rockfall limit line
   1. Plotting the results
D) Checking of results
   1. Cross checking of results
   2. GNS Science checking
E) Reporting
   1. Figures
   2. Summary table

This methodology was developed by GNS Science and PHGG consultants during workshops carried out on:

- 20th December, 2012 – 08:30 to 12:30, Opus offices, Christchurch

- 23rd December, 2012 – 10:30 to 14:00, Aurecon offices, Christchurch
- 24th December, 2012 – 14:00 to 15:00, Aurecon offices, Christchurch
- 9th February, 2012 – 10:30 to 12:30, Opus offices, Christchurch

A) Back analysis of fallen rocks

1. Define sections for analysis
   a. Sections to be used in the analysis should be chosen by the representative Modeller and appropriate Section Leader.
   b. Sections should be chosen that best represent the unhindered travel distance (runout) of the boulders that fell during the recent earthquake sequence, mainly those triggered by the 22nd February 2011 earthquakes. Unhindered refers to those boulders that were not prematurely stopped by temporal factors such as shelter belts, trees, houses, fences (whether engineered or not). Boulders that travelled the furthest distance down slope from a source area should be the ones selected for back analysis.
   c. Sections should be selected every about 100 m or less along the slope, taking into account such factors as changing topography e.g. fan, gully, and height of rockfall source area etc.
   d. The chosen section should be representative of the conditions (materials and topography) within the general area of slope
   e. Sections do not have to be straight lines but can follow the topography e.g. following a drainage line

2. Generating the cross sections
   a. All cross sections used for analysis should be generated by the Port Hills GIS team.
   b. Cross section locations should be provided to the GIS team as either polylines in ArcGIS shape file format or clearly marked on a map for inclusion into the GIS.
   c. Cross sections should be generated using the post 24th February LiDAR NZAM data set (2011a), resampled to provide a 1 metre grid.
   d. Cross sections should extend from the ridge crest to 50 m downslope of the 21 degree shadow angle line (where possible).
   e. Sections will be exported from ArcGIS in Excel format for inclusion into the Rocscience® rockfall program.

Note: the Excel output file should include a node (point) about every 1 m (i.e. a 200 m long section would have about 200 nodes). To get the Excel point data into the Rocfall program requires a "work around" by either importing the coordinate data (from the Excel file) into the Rocscience program Slide and then exporting the section in dxf. file format, or by using some other means e.g. AutoCad dxf. conversion programs.

   f. The nature of the materials along the section line should be determined from the GNS Science Geomorphology "materials" GIS layer (GNS Science Report CR 2012-015). This was done by hand using ArcGIS and printed maps.

3. Setting up the Rocscience® rockfall model

   a. Check that the most current version of the rockfall software is installed (it should be Version 4.054 or later), as earlier versions do not allow the mass of the modelled boulder to be included.

   b. Import the dxf. file of the section to be modelled

   c. Import the basic material parameters using the "material" file generated during the workshop on the 20th December 2011.

Note: during the workshop it was agreed that materials shown on the geomorphology maps can be simplified for the modelling (Table 1), to take into account that many of the materials are likely to have similar parameters. For rock outcrops (rockfall source areas) the GNS Science "Source toe" and "Source crest" shape files were used to define their extents, as these were not differentiated from the more general "rock at/near surface" materials included in the Geomorphology maps (CR2012-015). In some areas the scale of the geomorphological mapping did not adequately represent the complexity of the ground, in such cases the distribution of materials along the section lines were modified.

Note: The rockfall source areas (called "seeders" in the Rocfall programme), were defined using the geomorphological material type called "rock at/near surface" and in some cases "talus" may have been included as a seeder.

d. Check that the section has been correctly partitioned into the different material types, using the geomorphology maps and local knowledge of the slopes.

e. It was agreed that the Numbers of boulders modelled should be 2,000 and that the unit weight of basalt/Trachyte should be about 27 kN/m^3. The modelled boulder size should be the 95th percentile of the total distribution of fallen boulders in the Pilot study areas, about 3 m^3 with a mass of about 8,250 kg.

Note: the boulder size and mass has no effect on the modelled runout limits of boulders as the option "scale Rn by velocity" is being used. If the option "Scale Rn by mass" is used some difference in the boulder runout limits would be expected for different sizes of boulder.

Table 1 Materials and their associated parameters for use in the modelling

Material type (mainly from CR2012-015)	**Parameters to adopt (from Table 1)**	**Comments**
Rock outcrop (rock at/near surface)	Clean hard bedrock (basalt/trachyte)	Extents derived using the GNS Science Source toe and Source crest GIS shape files
Rock at/near surface or Talus	Talus with vegetation	Could also use Colluvial loess parameters depends on nature of material between rock outcrops
Colluvium Landslide debris Colluvial loess	Colluvial loess with vegetation (rough) Colluvial loess with vegetation (smooth)	These materials tend to all be variations of loess with boulders. In some cases boulders may give higher values of restitution
Loess Fan/debris fan	Colluvial loess with vegetation (smooth)	
Disturbed ground Valley floor/alluvium Swamp Dune	Colluvial loess with vegetation	
Asphalt		Use Rocfall® default parameters for Asphalt

4. Running the analysis and assessing the results
    a. Run the analysis and compare the modelled results (modelled boulder end points) with the actual field results, i.e. where the actual mapped boulders stopped (using the CCC fallen boulder database), with reference to those boulders nearest the modelled section.
    b. The modelled results should be within 10 m (downslope) of the actual fallen boulder being back analysed.
    c. If the initial modelled results do not match the actual back analysed boulder end point then change the model input parameters. The models are most sensitive to the "Roughness" and "Friction" parameters adopted for the different materials. These parameters should be changed until the modelled end points are similar to the actual end points being back analysed, (note: try to keep within the ranges discussed).
    d. If the modelled results still do not match the actual end points then start changing the coefficients of restitution adopted for the materials along the section. In some locations the standard coefficients of restitution may not apply, e.g. areas defined as rock at/near surface (from the geomorphology mapping) may actually comprise outcrops of clean hard bedrock separated by larger accumulations of talus or loess, and so the adopted parameters may need to be changed to reflect this.
    e. Check the modelled bounce heights to see whether they are realistic, taking into account that the observed bounce heights (impact marks on trees and other static features) are typically in the range of 1 to 4 m above ground level in the central part of the rockfall runout zones (recorded by GNS Science and PHGG). These bounce heights tend to decrease in the distal runout zones, where the boulders tend to roll and skip across the surface.

Forecasting rockfall runout

1. Identify sections to model
    a. The sections should correspond to locations where: a) no fallen boulders have been mapped; b) where boulders have been prematurely stopped by temporal objects (e.g. houses, fences and trees etc.); c) objects where the influence of topography on the runout needs to be assessed (e.g. the influence of a flat surface such as a road has on rockfall runout); and d) where the field assessor requires some verification to justify a decision made during the field verification.

2. Parameters to model
    a. ALL parameters used in the forecasting of rockfall rounout have been derived from the back analysis of boulders that fell during the recent earthquakes. These parameters have been fixed and cannot be changed by the modeller (Table 2).

Table 2 Final back analysed parameters for use in the rockfall modelling

Parameter	Assumed value
Initial conditions of boulder (source)	
No. boulders modelled	2,000
Individual rockfall volume	3.0 m^3 representing the 95th percentile of the mapped distribution of fallen boulders in the Pilot study areas
Boulder unit weight	27 kN/m^3
Boulder mass	8,250 kg
Assuming seismic loading	
Horizontal velocity	1.5 m/s
Vertical velocity	1.0 m/s
Project settings	
Velocity cut off	0.1 m/s
RN scaling	Velocity. K = 9.144 m/s.
Random number generation	Pseudo-random
Friction angle (Phi)	From material editor
Angular velocity	Consider
Materials (refer to GNS Science report CR 2012-015 for material boundaries). These parameters are based on the back analysis of boulders that fell during the recent earthquakes.	
1) Clean hard bedrock and rock at/near surface (e.g. basalt, trachyte rockfall source areas)	Rn = 0.53 ±(0.04), Rt = 0.99 ±(0.04) Phi = 40° ±(2) Roughness = 5
2) Talus with vegetation, 3) Rock at/near surface, when the rock is covered in parts by talus etc.	Rn = 0.5 ±(0.04), Rt = 0.85 ±(0.04) Phi = 20° ±(2) Roughness = 5
4) Colluvial loess with vegetation (rough)	Rn = 0.3 ±(0.03), Rt = 0.85 ±(0.03) Phi = 8° (±2) Roughness = 11
5) Colluvial loess with vegetation (smooth)	Rn = 0.3 ±(0.03), Rt = 0.85 ±(0.03) Phi = 4° (±2) Roughness = 0 (assumed roughness is equivalent to the 1m DEM used in the analysis)

3. Checking of model results
   a. Check the modelled end points against the fallen boulder distributions from elsewhere in the same area to make sure the results are realistic. Another check is to compare the modelled end points against the geomorphology maps, as in many

locations there are older (pre the recent earthquake sequence) collections of boulders present on the slopes, do the modelled end points coincide with areas where older fallen boulders have been mapped.

b. Identify areas where the modelled runout is less than the extent of older boulders shown on the Geomorphology “Process” maps. In these situations the Sector leader needs to verify the extents in the field and the GNS Science representative needs to be notified.

Cautionary note: results from the modelling showed that in a few locations e.g. Rapaki, the modelling under estimated the runout of the actual mapped boulders. This was due to the roughness of the digital elevation model (DEM) used in the modelling. When a smoother DEM was used (2 m grid size rather than the 1 metre grid size) the modelled end points were found to match the actual end points. It was generally found that the modelled bounce heights did not tend to match the field observed bounce heights, especially in the distal rockfall runout zones.

Defining the modelled rockfall limit line

1. Plotting the results
   a. Plot on the map the modelled boulder end points for each section including sections that were used for back analysis and forecasting.
   b. Sector leader with the modeller should draw a thick “smudgey” (dashed) line (10 m at a scale of 1:2,000) that links all of the modelled end points, this line is the “modelled rockfall limit line. This line should be drawn in ArcGIS as a polyline.
   c. Digitise the line and pass to Aurecon GIS for compilation into the geodatabase. The lines should be labelled “Modelled rockfall limit line” and the attributes should include the Sector and surburb and who drew it.
   d. Aurecon GIS to include the “rockfall limit line” on the maps used by the sector leaders in the field. *(Note: the modelling should be carried out in advance of the field verification program to ensure the appropriate limit lines are includes on the maps in time for the ground trothing teams.)*

Note: the “Modelled rockfall limit line” will eventually be used along with other information such as: 1) the geomorphology maps, 2) the shadow angle lines and 3) the extent of the recently mapped (and historic and prehistoric) to define the limits of rockfall runout per area. This will be done by GNS Science in conjunction with the Sector leaders once field verification is complete.

Checking of results

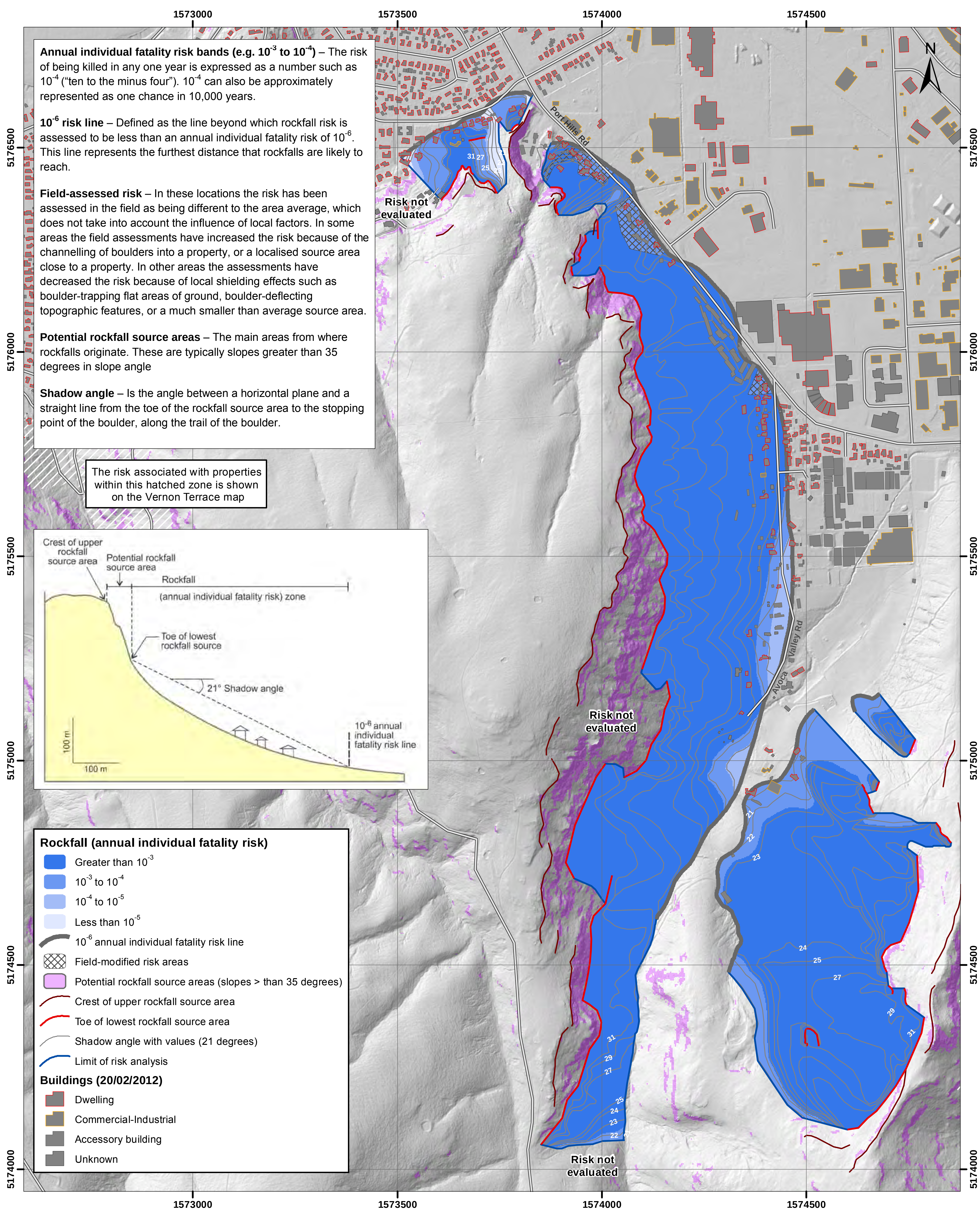
1. Cross checking of results
   a. For a few sectors each consultant “modeller” should pass their results to another consultant “modeller” to check.
2. GNS Science checking
   a. GNS Science will be available to check results and provide advice as requested.

Reporting

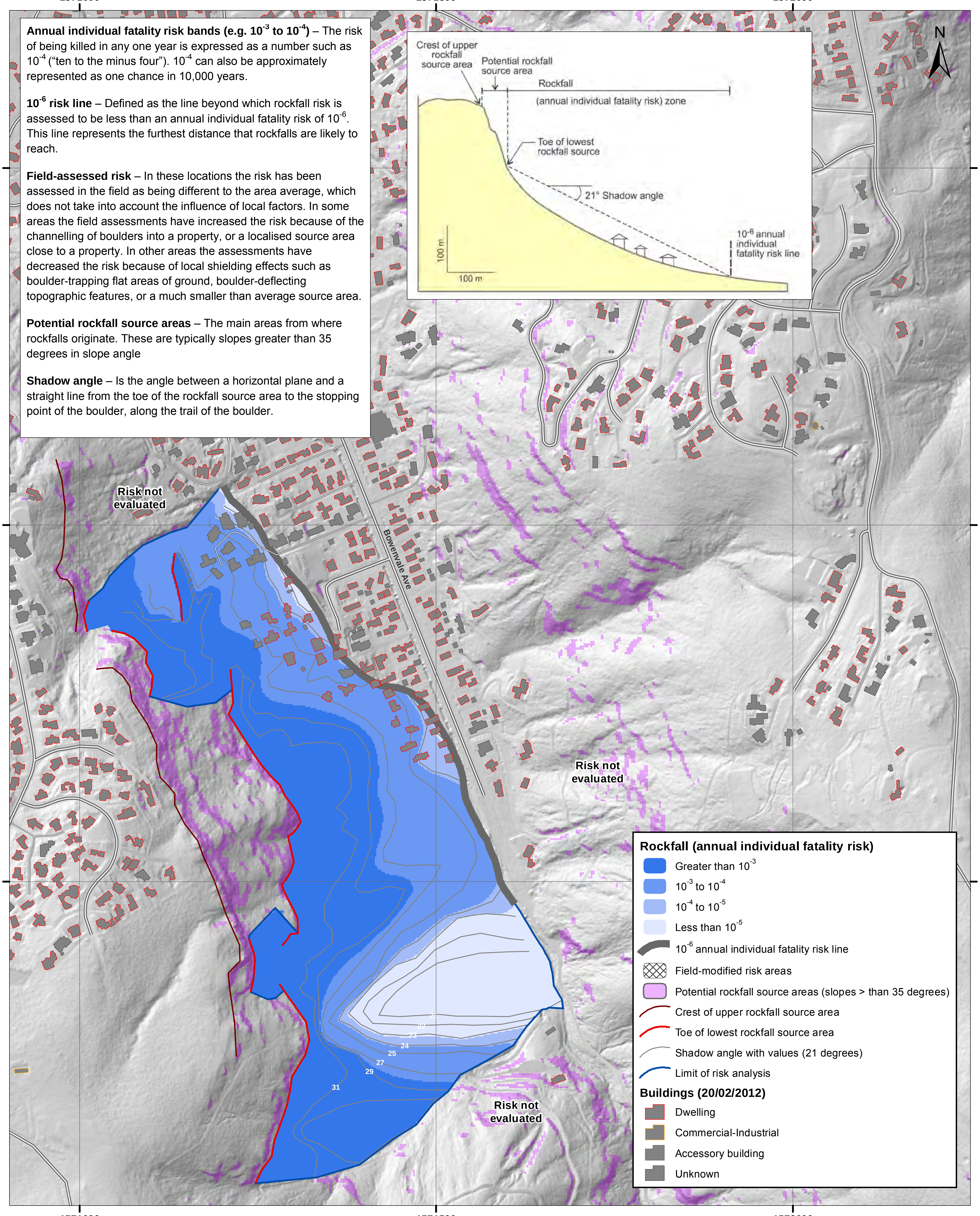
1. Figures
   a. The results from each modelled section line should be made into a figure to be included in the factual reports being compiled for each area. The figure should contain all of the information that would allow a third party to rerun the analysis, without having to access the Rocscience® rockfall program files (refer to attached example). These figures should contain the name of the relevant program files, and the Section numbers should be clearly annotated.

2. Summary table
    a. Tabulate the FINAL results in the agreed standardised spread sheet format (see attached), for each modelled section.
    b. Summarise the range of parameters for each area (suburb) (see attached table).

APPENDIX G   ROCKFALL RISK MAPS



SCALE BAR: 0 100 200 m			ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK	APPENDIX G FINAL ISSUE 2
EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).	DRW: DWH, BL CHK: CM	GNS SCIENCE TE PŪ AO	Avoca Valley Christchurch	PROJECTION: New Zealand Transverse Mercator 2000 REPORT: CR2011/311 DATE: July 2013



SCALE BAR: 0 100 200 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1m ground resolution.

Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

DRW: DWH, BL

CHK: CM

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ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Bowenvale Avenue Christchurch

APPENDIX G

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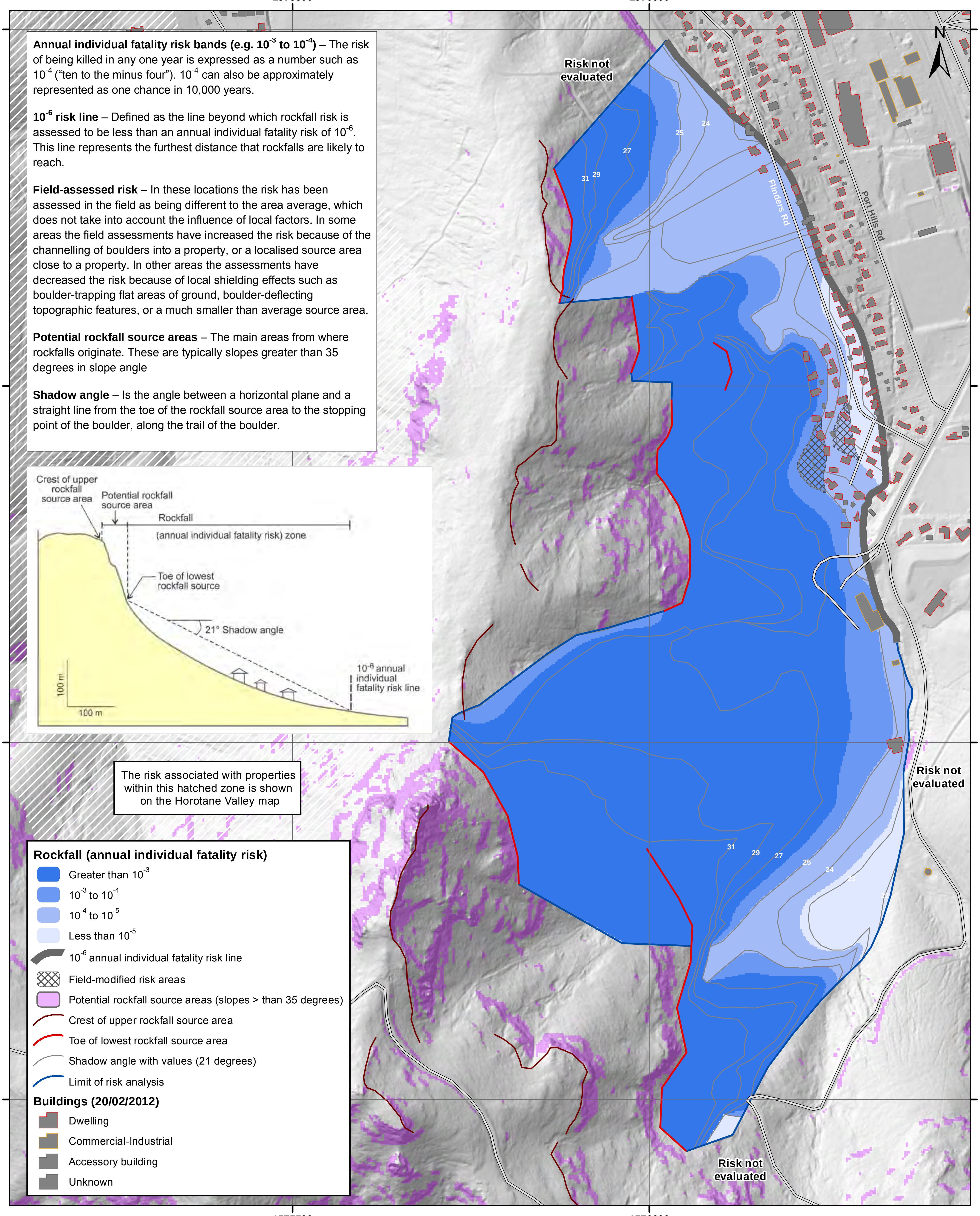
PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: July 2013



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EXPLANATION:

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DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Castle Rock Christchurch

APPENDIX G

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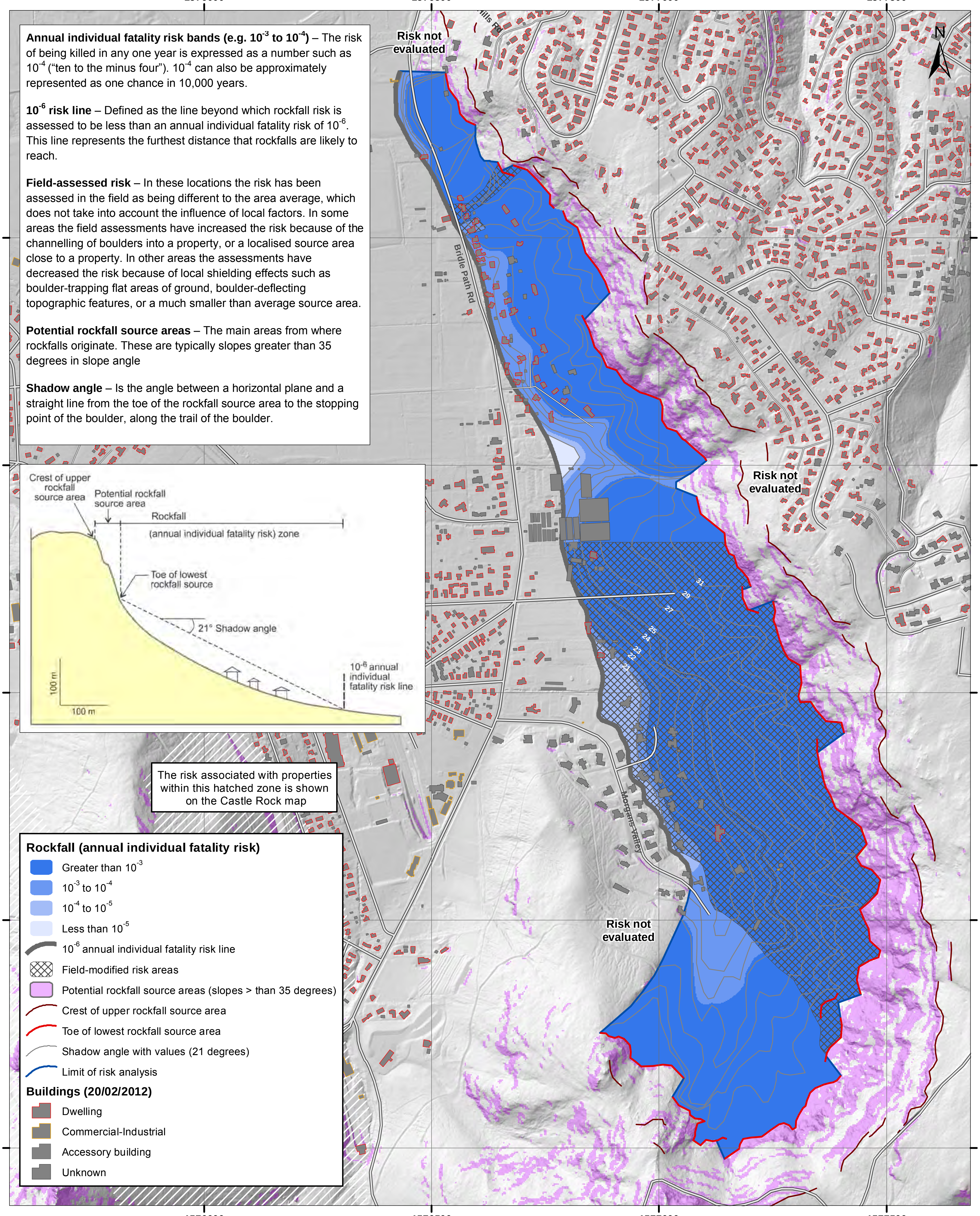
PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: July 2013



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EXPLANATION:

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DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Heathcote Valley Christchurch

APPENDIX G

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PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

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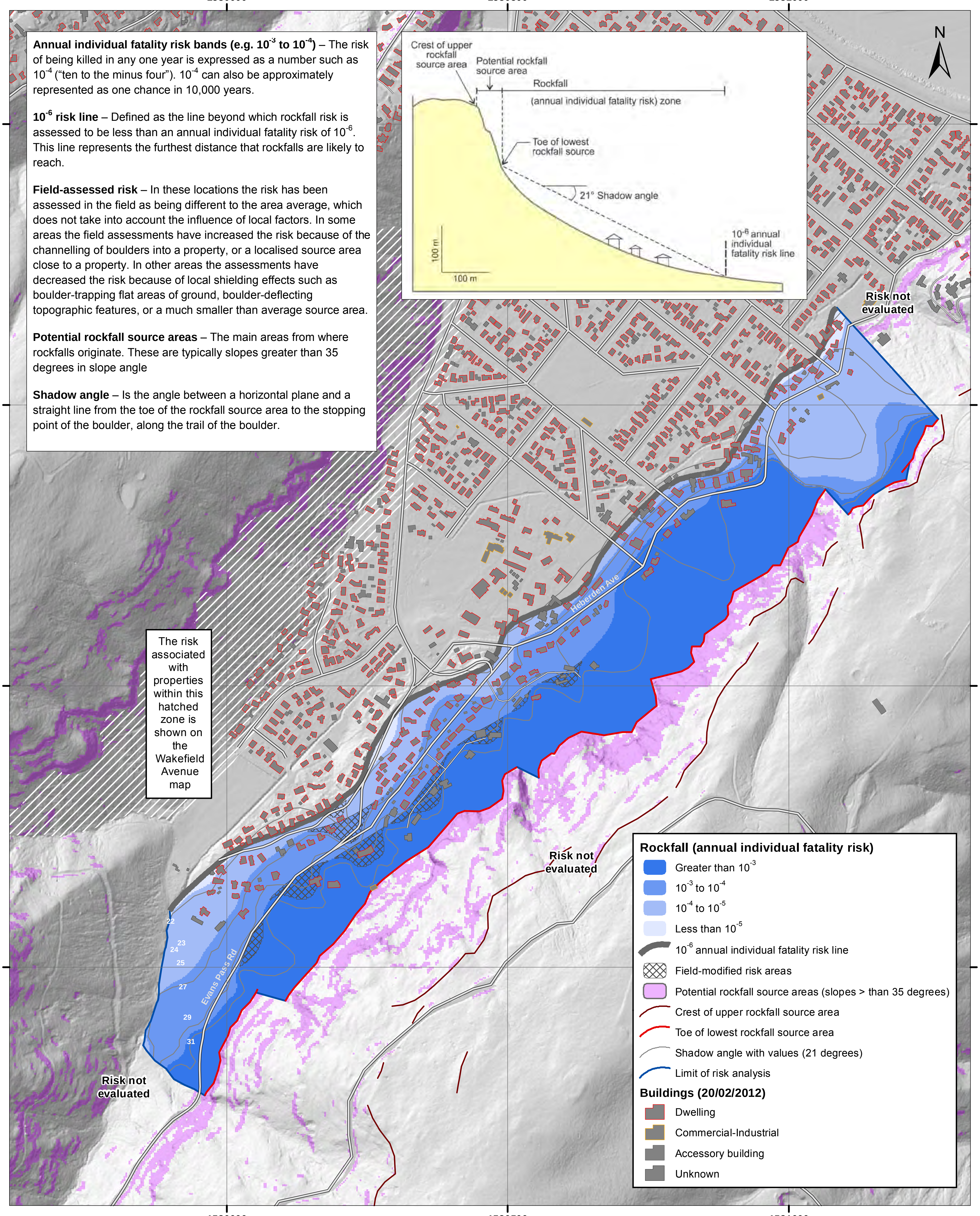
Annual individual fatality risk bands (e.g. 10^{-3} to 10^{-4}) – The risk of being killed in any one year is expressed as a number such as 10^{-4} ("ten to the minus four"). 10^{-4} can also be approximately represented as one chance in 10,000 years.

10^{-6} risk line – Defined as the line beyond which rockfall risk is assessed to be less than an annual individual fatality risk of 10^{-6}. This line represents the furthest distance that rockfalls are likely to reach.

Field-assessed risk – In these locations the risk has been assessed in the field as being different to the area average, which does not take into account the influence of local factors. In some areas the field assessments have increased the risk because of the channelling of boulders into a property, or a localised source area close to a property. In other areas the assessments have decreased the risk because of local shielding effects such as boulder-trapping flat areas of ground, boulder-deflecting topographic features, or a much smaller than average source area.

Potential rockfall source areas – The main areas from where rockfalls originate. These are typically slopes greater than 35 degrees in slope angle

Shadow angle – Is the angle between a horizontal plane and a straight line from the toe of the rockfall source area to the stopping point of the boulder, along the trail of the boulder.



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ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Heberden Avenue Christchurch

APPENDIX G

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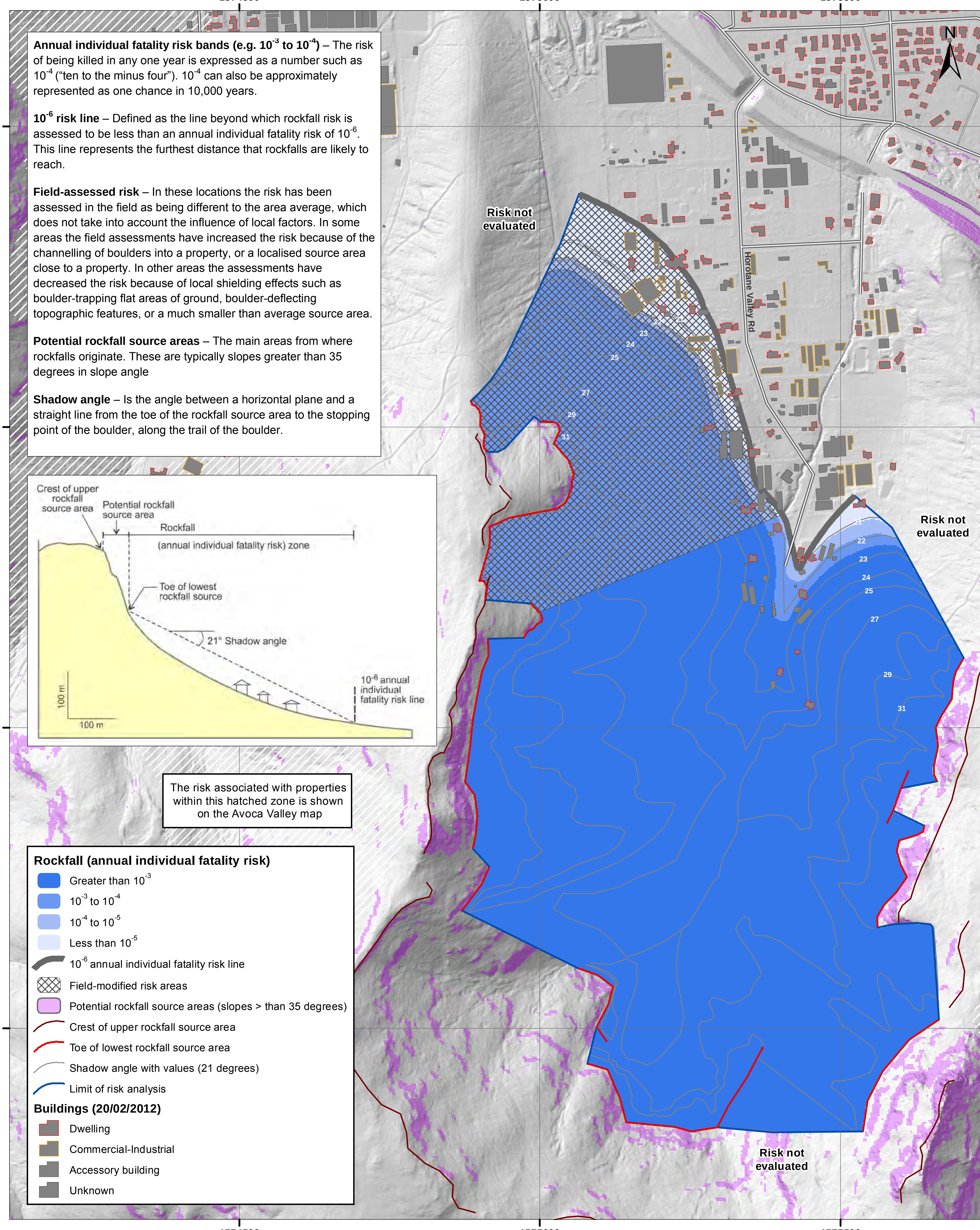

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EXPLANATION:

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CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Horotane Valley Christchurch

APPENDIX G

FINAL ISSUE 2

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

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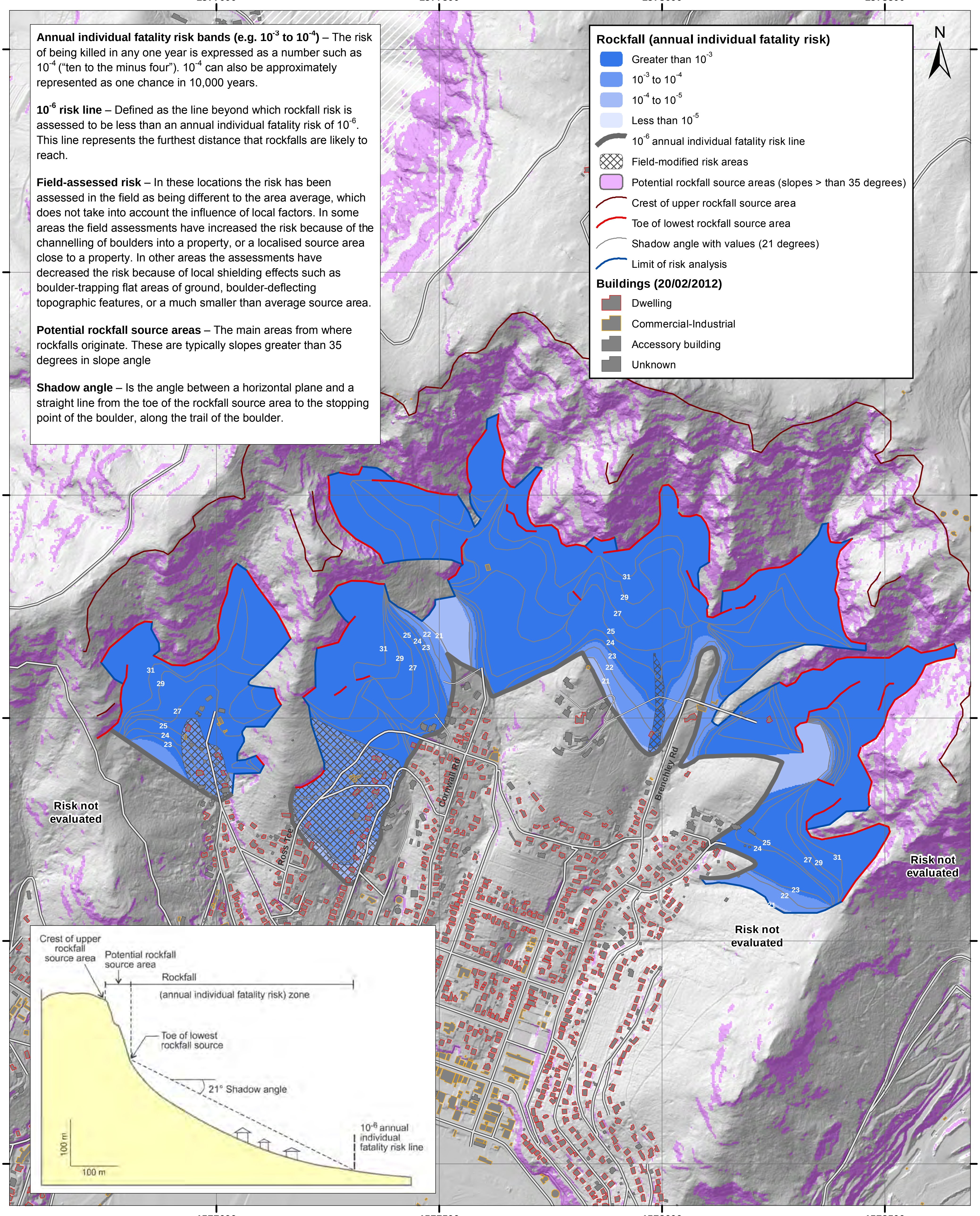

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DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Lyttelton Christchurch

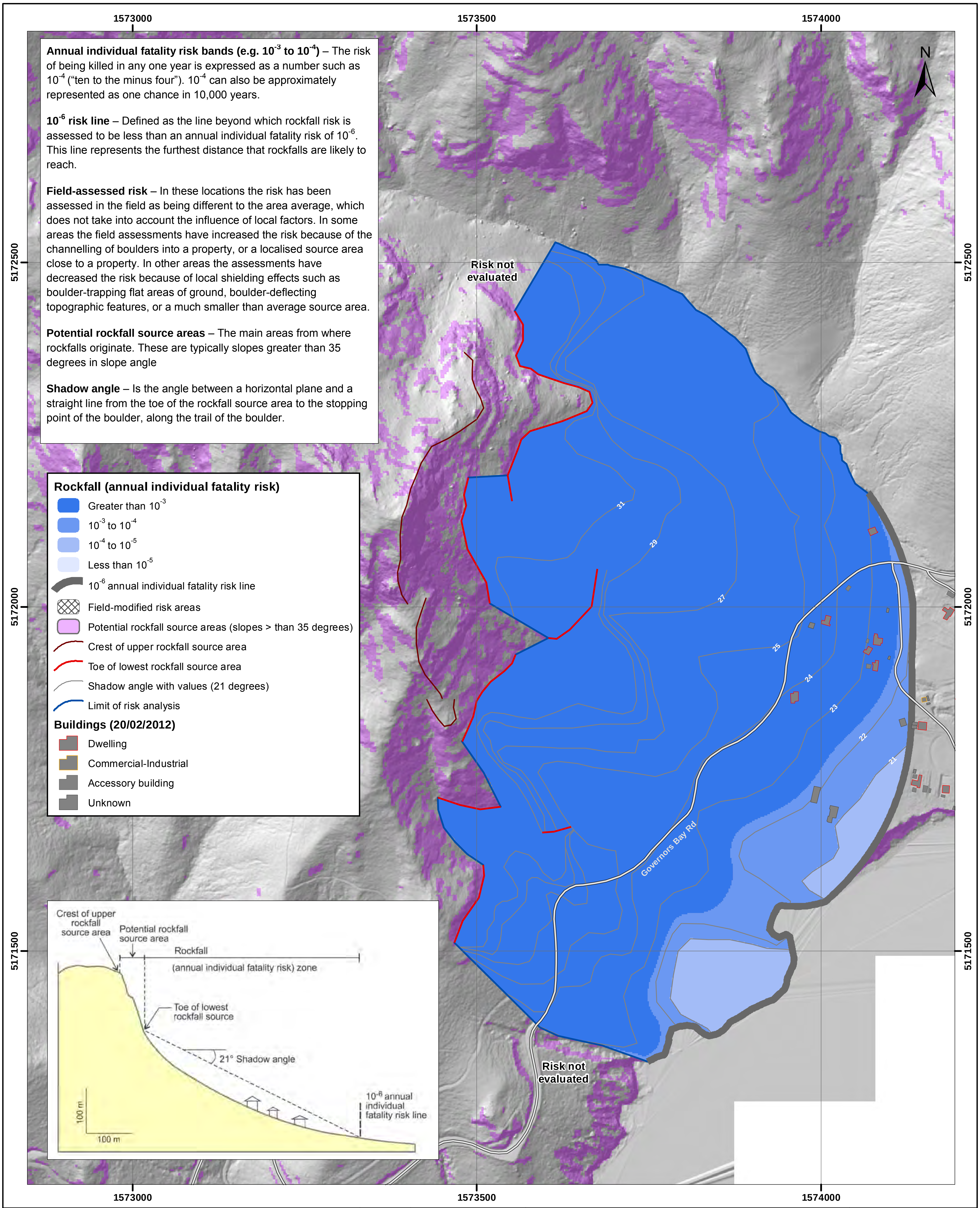
APPENDIX G

FINAL ISSUE 2

PROJECTION: New Zealand Transverse Mercator 2000

REPORT: CR2011/311

DATE: July 2013



SCALE BAR: 0 100 200 m

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CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Rapaki Bay Christchurch

APPENDIX G

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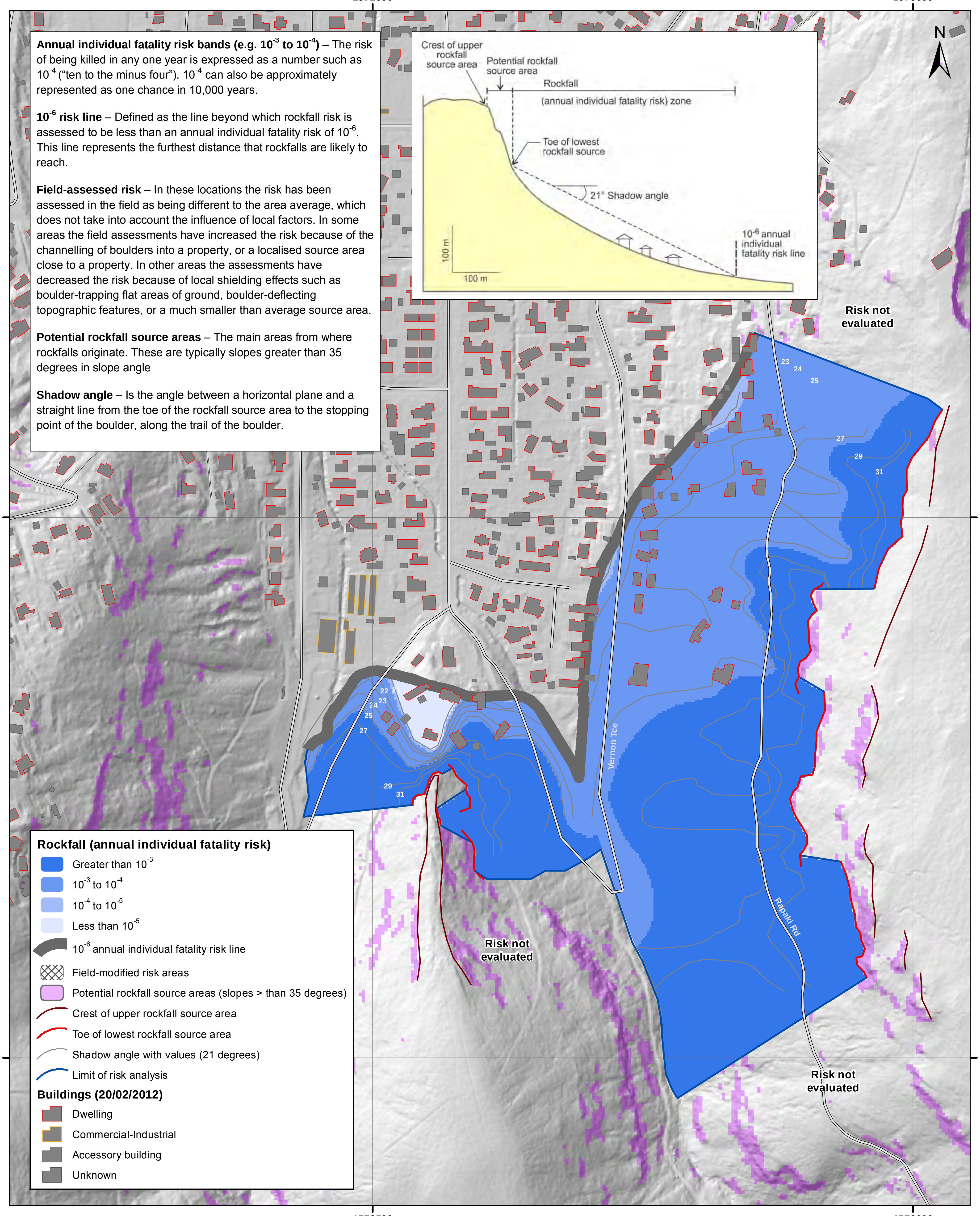

SCALE BAR: 0 100 200 m

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ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Vernon Terrace Christchurch

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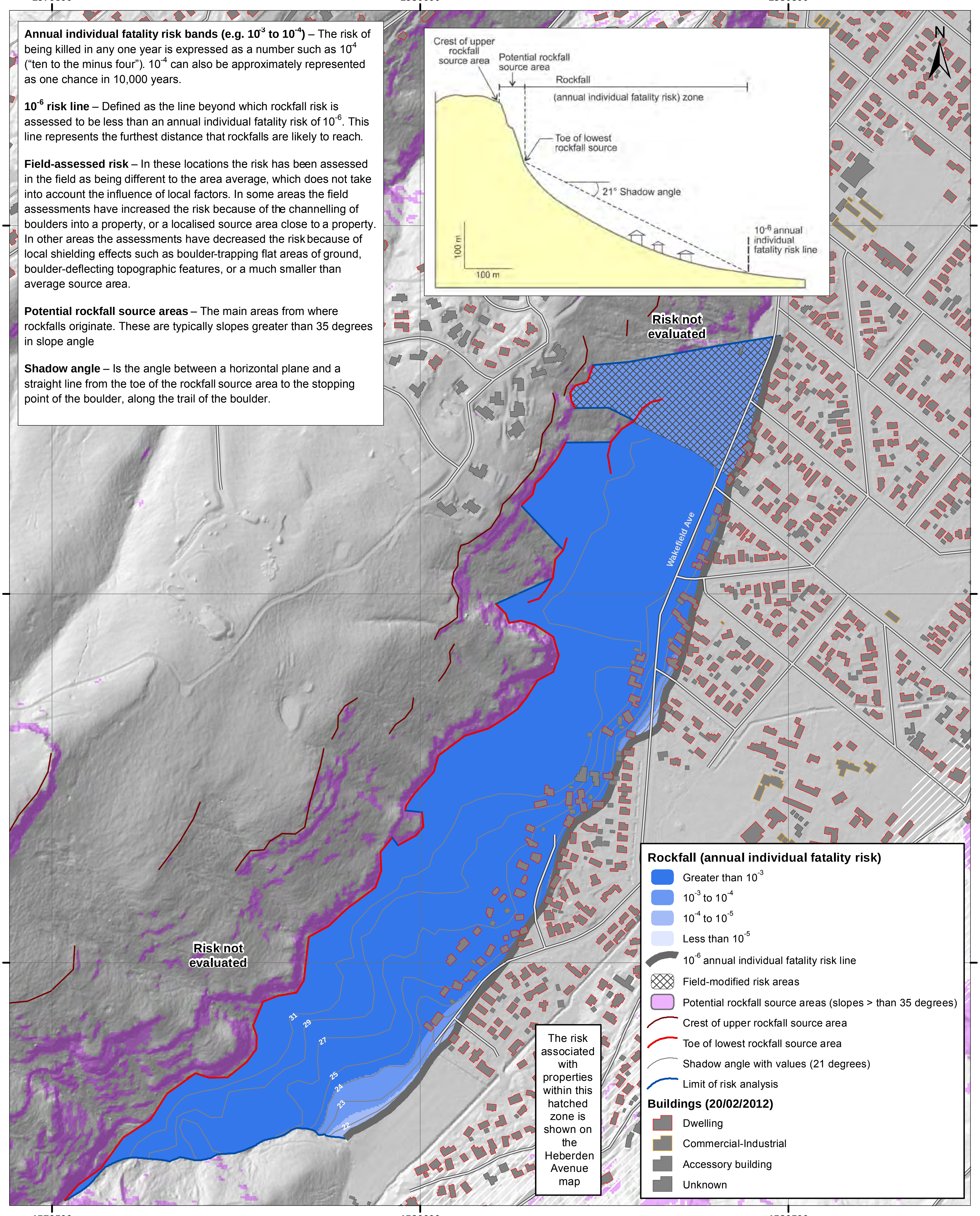

SCALE BAR: 0 100 200 m

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DRW: DWH, BL

CHK: CM

ROCKFALL ANNUAL INDIVIDUAL FATALITY RISK

Wakefield Avenue Christchurch

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