Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Principles and Criteria for the Assessment of Risk from Slope Instability in the Port Hills, Christchurch

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EXECUTIVE SUMMARY

This report provides an overview of the issues that need to be considered in establishing a risk-based approach to the management of slope instability hazards affecting people in their properties[1] in the Port Hills area of Christchurch following the 2010/11 Canterbury earthquakes. It has been prepared by GNS Science for Christchurch City Council with particular input from Tony Taig, a UK risk expert with considerable New Zealand experience, working under sub-contract to GNS Science.

The report describes the framework and process for managing risk laid out in the relevant Australia/New Zealand Standard (ISO 31000:2009) and then reviews risk policies and criteria that have been adopted outside New Zealand and the status of such policies within New Zealand. The report then considers the current levels of risk faced by New Zealanders in respect both of natural hazards and other hazards. The criteria to be adopted by Christchurch City Council in light of these precedents and of the levels of natural hazard and other risks faced by New Zealanders are then discussed. Options for risk treatment are discussed, with particular discussion of options involving removing people from the hazards via permanent evacuation of properties.

GNS Science conclude that risk criteria used in other contexts and information on New Zealand natural hazard and other risks can be used to inform the nature of the risk metrics and criteria that Christchurch City Council should adopt in relation to slope instability risk in the Port Hills, and to define the quantitative ranges within such criteria should be set in order to be consistent with practice elsewhere and with New Zealanders' apparent tolerance (or otherwise) for risk associated with other hazards.

GNS Science' recommendations are:

1. Christchurch City Council should establish risk criteria for determining the tolerability or otherwise of slope instability-related risk at properties in the Port Hills, based on societal acceptance of comparable levels of risk arising from other sources. Such criteria should be based around a defined sustainable upper limit of tolerability of annual individual fatality risk, representing the risk level above which Christchurch City Council does not consider it tolerable for there to be people at risk in their properties in the longer term.
2. The sustainable threshold of annual individual fatality risk should be set within a range from 3×10^{-5} to 1×10^{-3} per year, consistent with risk levels currently tolerated in New Zealand and with regulatory practice elsewhere. A suitable starting point for Christchurch City Council's deliberation as to where within this range to set their threshold would be a level of 1×10^{-4} (1/10,000 per year) annual individual fatality risk.
3. Christchurch City Council should consider ways to accommodate the preferences of current Port Hills householders who wish to remain in their properties despite assessed risk in excess of Christchurch City Council's sustainable upper threshold of tolerability, via options such as:

   a) definition of a higher absolute limit (e.g. 10^{-3} annual individual fatality risk) up to which relocation would be at the discretion of householders but above which it would be compulsory; and/or

[1] Risk to people at or in their homes is taken to include risk whilst present in the home or garden, but not to include other risks associated with living at the premises such as travelling to and from the home.

b) permitting householders to remain in their properties but preventing them from selling on to any party other than Christchurch City Council or another appropriate government agency when they moved or died.

4. Christchurch City Council should be appreciative of the sensitivity of the assessed risk levels to key uncertainties, and how much time has elapsed since the initiation of the Canterbury earthquake sequence. Christchurch City Council should require risk to be assessed based on a “best estimate” basis for the prevailing elevated seismic hazard conditions as the basis for evaluation against such risk criteria.
5. Christchurch City Council should adopt a lower threshold of annual individual fatality risk above which development is controlled to prevent accumulation of people in areas of substantial risk below the sustainable threshold of tolerability. Such a threshold could be set 10x below the tolerability threshold for general property uses involving significant occupancy by people, and 100x below the tolerability threshold for particularly sensitive property uses (e.g. schools, care homes, hospitals).

LIMITATION

This report does not analyse the statutory framework which determines the functions and role of Christchurch City Council in relation to management of hazards. That is outside the expertise of GNS Science and outside the scope of this report. Accordingly, all statements in this report regarding the role and responsibilities of ‘regulators” or of the Christchurch City Council are general opinions expressed by the authors, but must be subject to Christchurch City Council’s assessment of its statutory role under such legislation as the Resource Management Act 1991, Local Government Act 2002, and Building Act 2004.

1.0 INTRODUCTION

This report is about the slope instability hazards faced by people at their property. Throughout this report "at their property" is taken to mean "in their home or garden", but does not include when they are out walking or driving to or from home. These hazards include:

- Boulders rolling down slopes and into/through their property;
- Landslide or cliff collapse leading to rock and other materials impacting on their property; and
- Properties collapsing and/or falling from height as a result of landslide or cliff collapse.

The earthquakes of 22nd February and 13th June 2011 damaged many properties in the Port Hills suburbs of Christchurch via these hazards. Five people in the Port Hills area were killed, one in their home, one in their garden, two on park tracks and one on a construction site. Over 500 properties have been subject to dangerous building notices issued by the Christchurch City Council under the Building Act (access to the dwelling is not permitted until the dwelling is no longer dangerous), while about 2,100 properties overall remain "white zoned" by the Minister of Earthquake Recovery (i.e. their future status has yet to be decided by the Minister of Earthquake Recovery) at the time of writing. Some 1,400 of these white zoned properties are being assessed for the risk presented to their occupants by slope instability-related hazards.

Christchurch City Council has been working since February with the Port Hills Geotechnical Group and GNS Science to understand slope instability-related life risk in the Port Hills. The ultimate aim of this work is to establish a robust, risk-based framework for deciding which properties can continue to be occupied with sufficient safety, which cannot, and any other precautions that ought to be taken to safeguard properties in the area against slope instability-related risk.

A key part of any such framework is the basis on which decisions about land use will be made, and the criteria that will be used to judge what, if any, precautions are appropriate for a given property, up to and including permanent retirement of the land in question if the risk is considered too high to be tolerable.

The Christchurch City Council has various statutory functions in relation to natural hazards. Description and analysis of those is beyond the scope of this report. However, one function is under section 31 of the Resource Management Act 1991, which provides that the Council has the function of controlling actual or potential effects of the use, development or protection of land for the purpose avoidance or mitigation of natural hazards.

It is the responsibility of the Christchurch City Council to establish how it will make decisions about appropriate land use in light of slope instability-related hazards, including how the risks should be assessed and what risk criteria should apply.

This report has been prepared by GNS Science under contract to Christchurch City Council, with particular input from Tony Taig, a United Kingdom risk expert with considerable New Zealand experience, working under sub-contract to GNS Science. The aims, objectives and basis of the report are explained below.

1.1 Report Aims and Objectives

The aim of this report is to help Christchurch City Council decide what to do about slope instability-related risk in the Port Hills of Christchurch. The objectives of the report are to provide:

- An explanation of risk assessment in relation to the relevant Australia/New Zealand Standard ISO 31000:2009, hereafter referred to as ISO31000:2009 and of the authors' approach to developing specific guidance for Christchurch City Council on its own risk tolerability principles and criteria (Section 2);
- A brief review of existing approaches and criteria for making decisions about risk tolerability, both internationally and in the context of natural hazards in New Zealand (Section 3);
- Information on risks from some natural and other hazards faced by New Zealanders, with which slope instability-related risk might usefully be compared (Section 4);
- Discussion of the relevance of Sections 2-4 to the context of slope instability hazards to people at their properties (Section 5); and
- The authors' conclusions and recommendations for risk criteria for consideration by Christchurch City Council (Section 6).

The report is based on consideration of established risk management principles and processes including risk criteria used in relation to risk arising from natural hazards and other walks of life both in New Zealand and internationally.

Appendix A provides a brief overview of how rockfall-related risk to people at their properties is assessed in the relevant GNS Science companion reports (Massey et al. 2012a,b) in order to help Christchurch City Council appreciate the provenance of the risk information being provided for evaluation against the criteria discussed here.

2.0 APPROACH

This section explains first (Section 2.1) what is meant by "risk" and how this report and companion GNS Science reports (Massey et al. 2012a,b) relate to the principles and processes described in ISO 31000:2009. It then explains (Section 2.2) the approach adopted here to developing advice for Christchurch City Council on its own policies in relation to life risk tolerability for slope instability-related hazards to people at their properties.

2.1 Risk and the AS/NZS Risk Management Standard

The Australian/New Zealand Standard on Risk management – Principles and guidelines (AS/NZS ISO 31000:2009) defines risk as

"effect of uncertainty on objectives".

In this report the risk referred to is

“the likelihood of fatality to a specified individual or group of people as a result of slope instability.

ISO 31000:2009 lays out principles and processes for managing risk. The principles are that risk management:

a) Creates and protects value;

b) Is an integral part of all organizational processes;

c) Is part of decision making;

d) Explicitly addresses uncertainty;

e) Is systematic, structured and timely;

f) Is based on the best available information;

g) Is tailored;

h) Takes human and cultural factors into account;

i) Is transparent and inclusive;

j) Is dynamic, iterative and responsive to change; and

k) Facilitates continual improvement of the organisation.

In this case the primary value protected (a) is life, but other important values such as people’s wish to enjoy the amenities of their property have also to be considered. (b) and (c) are part of normal Council business, and this report pays particular attention to (d) to (h) so as to help Christchurch City Council with (i) and (j). A particular issue here is the dynamic nature of the risk, which is currently elevated because of the temporarily increased likelihood of seismic events in the wake of significant earthquakes, but is expected to decline over the coming years/decades. Continual improvement in this context is the arrival at the right balance between reducing risk to people in the Port Hills and allowing them to continue to enjoy living in their properties.

The process envisaged for managing risk in ISO 31000:2009 is illustrated in Figure 1.

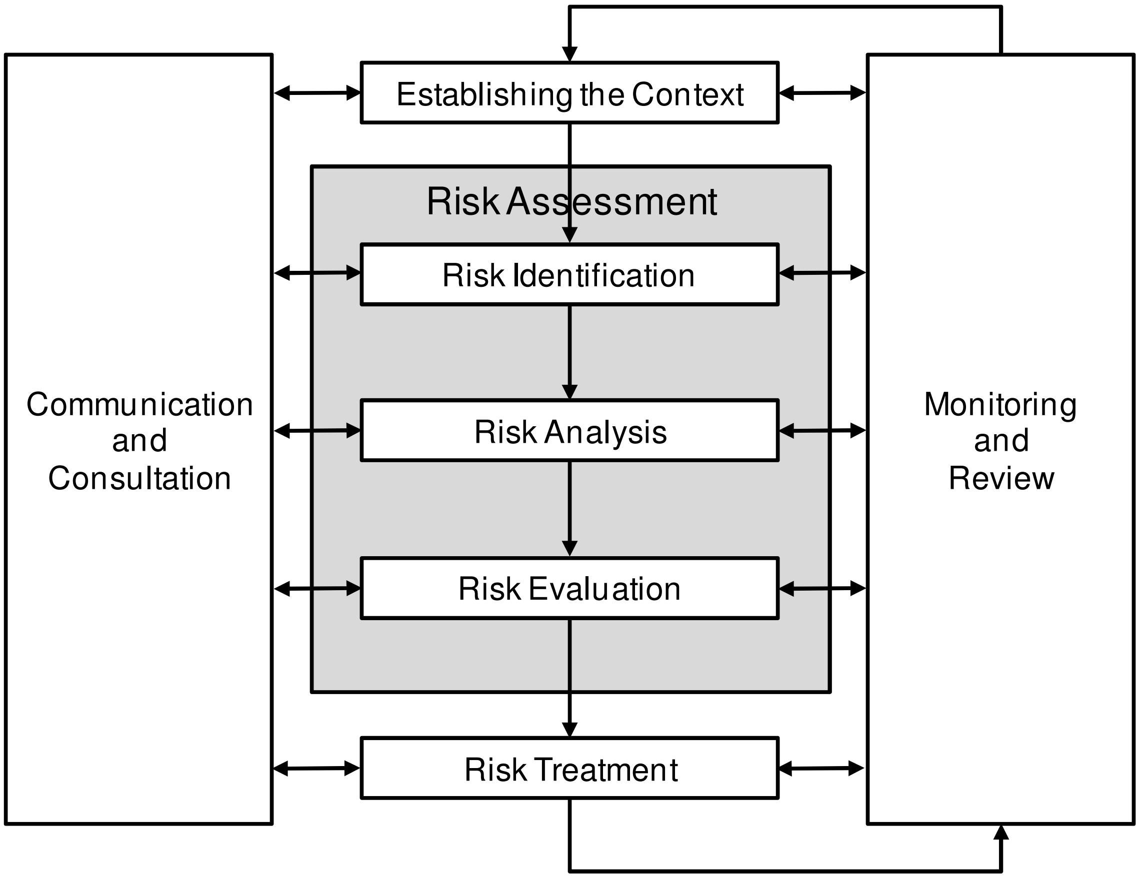


Figure 1 Risk Management Process – from AS/NZS ISO 31000:2009.

The purpose of this report is to help Christchurch City Council establish criteria to be used in evaluating risks and deciding what to do about them. This involves elements of all four of the process elements around the outside of Figure 1 – establishing the context, communication and consultation, monitoring and review, and making decisions about risk treatment.

Companion GNS Science reports (Massey et al., 2012a,b) provide assessments of slope instability-related risk. These reports cover the central "Risk Assessment" area shown in Figure 1 – they provide quantitative estimates of the risks involved, allowing those risks to be evaluated against the suggested risk criteria in this report.

The report does not address the governance of the process or strategies for risk treatment in any detail, but notes that stakeholder engagement in establishing risk criteria, and systematic consideration of options for treatment, are a vital part of the process for managing risk.

2.2 Approach to Developing Risk Criteria

In the absence of life risk criteria for natural hazards in New Zealand, this report's starting point is to review risk policies and criteria that have been developed in other contexts. Much of the relevant work originates from the UK and from Australia, but this report also considers the current policy situation in New Zealand in relation to natural and other hazards. This review forms the subject of Section 3 of the report.

A central conclusion emerging from this work is that, in order to be tolerable, accident risks from specific hazards need to be small or modest in comparison with other risks that people face. Section 4 reviews the risks faced by New Zealanders, both:

a) in relation to natural hazards, using both long-term statistics and a number of recent risk assessments to illustrate the scale and extent of such risks; and
b) in relation to other more everyday hazards such as cancer, heart disease, road and other accidents.

The comparisons in (b) are based on the latest published statistics on mortality and population provided by the New Zealand Ministry of Health and Statistics.

The risks discussed in this report are generally relatively small in terms of the likelihood of a particular individual being killed per year. Thus the report makes extensive use of terminology expressing risk in terms of logarithmic numbers such as 10^{-4} ("10 to the power minus 4") per year. Table 1 shows how some of these numbers translate into more familiar terms and may be useful to keep to hand for readers who are not familiar with this "10 to the power minus ...." terminology.

Table 1 Translation of the "10 to the power minus … per year" terminology into other terms.

"10 to the minus ... per year"	Is the same as (per year)	Is approximately the same as	Is the same as
10^{-3}	0.001 or 0.1%	1,000 years	8% per lifetime[2]
10^{-4}	0.0001 or 0.01%	10,000 years	0.8% per lifetime
10^{-5}	0.00001 or 0.001%	100,000 years	0.08% per lifetime
10^{-6}	0.000001 or 0.0001%	1,000,000 years	0.008% per lifetime

To put these numbers in perspective, the odds of a Lotto Division 1 win (correctly picking 6 numbers out of 40) are, according to the New Zealand lotteries web site (www.nzlotteries.co.nz):

1 in 3,838,380 or about 2.6×10^{-7} per ticket.

If someone bought one ticket every week for 75 years, their lifetime odds of such a win would be:

1 in 984 or about 1.0×10^{-3} per lifetime.

[2] Based on average New Zealand life expectancy of about 80 years, from 2008 mortality and population data.

3.0 EXISTING LIFE RISK CRITERIA

The essence of all life risk criteria is to strike an appropriate balance between prohibition of one person imposing a risk on another and the freedom of the individual to do as they wish so long as it does not impose risk or burdens on others.

Acceptability of risk depends heavily on context and not just on how large or small the level of risk is. It can never be right to put others at risk gratuitously, for no good purpose, simply because the level of risk involved is very low. At the other extreme, there may be situations (such as a terminally ill patient considering a hazardous procedure to improve their quality/duration of life, or a dangerous military rescue to save people who will otherwise certainly die), where an odds-on risk of dying for a good cause might be perfectly acceptable. In the context of slope instability-related risk there is a balance to be struck between protecting people from the hazard, enabling them to life as/where they wish, and protecting people from the actions of others (e.g. the head of a household imposing risk on dependents, or a householder selling to someone ignorant of the risk).

Quantitative risk assessment is increasingly being used to inform government and private sector policy decisions of many kinds in New Zealand, but regulatory use of quantitative risk criteria is as yet little developed in New Zealand. Such criteria have, though, been in use overseas (for example in the UK, the USA, the Netherlands and Australia) for some years. Much of the early thinking on acceptable risk derives from the UK, in particular the UK Health and Safety Executive, while some of the most relevant and recent thinking in relation natural hazard risks (and landslides in particular) has been developed in Australia. These particular overseas examples are considered first (Section 3.1), before reviewing some current approaches that are used in other contexts in New Zealand (Section 3.2).

3.1 Some UK and Australian Precedents

3.1.1 UK Health & Safety Executive

The UK Health and Safety Executive (HSE) is the UK regulator of workplace health and safety, both for people at work and for members of the public who might be exposed to risk in or in the neighbourhood of workplaces. The UK Health and Safety Executive pioneered the use of quantitative risk as an aid to regulatory decision making, publishing a statement of principles for nuclear power stations in 1988 (HSE, 1988) which they updated and generalised in “Reducing Risks, Protecting People” in 2001 (HSE, 2001). Among the key principles established or affirmed in these documents were:

a) the importance for a regulator to consider who (e.g. the regulator, the person at risk?) should properly determine decisions about risks;

b) the general principle of reducing risks As Low As Reasonably Practicable (ALARP);

c) the distinction between risks which are **acceptable** (of little concern) and those which are **tolerable** (i.e. can be put up with in recognition of the wider benefits of the activity creating them);

d) the use of annual individual fatality risk as a primary risk metric;

e) the inadvisability of using quantitative risk estimates as the sole determinant of decisions, in light of the many other contextual factors that are important in deciding tolerability and of the uncertainties in many estimates of risk; and

f) a distinction in terms of what is tolerable between people who involuntarily have risks imposed upon them (e.g. members of the public living near a factory) and those who have some degree of choice and control over risk (e.g. the factory workforce).

The UK Health and Safety Executive suggested upper limits of tolerability of 10^{-4} per year annual individual fatality risk for members of the public, and 10^{-3} per year for employees. These upper limits were derived from consideration of other risks which appeared to be tolerated (or not) in other walks of life.

The UK Health and Safety Executive is a statutory consultee on all planning applications within zones (which the UK Health and Safety Executive defines) around hazardous installations, and has developed substantial guidance and support for Planning Authorities in determining the UK Health and Safety Executive's advice on related planning applications (HSE, 2011). The UK Health and Safety Executive provides guidance on whether a planning application should be refused on risk grounds based on: a) the annual individual risk of receiving a "dangerous dose"; and b) the sensitivity of the application concerned (e.g. a school or hospital is more sensitive than a low-occupancy store or warehouse). Because the purpose of this process is to prevent accumulation of people in higher risk locations (albeit beneath the upper threshold of intolerability) around the installations, the quantitative risk levels involved are considerably more precautionary (roughly a factor of 100 more so) than the upper thresholds of tolerability laid out in "Reducing Risks, Protecting People" (HSE, 2001).

3.1.2 Societal Risk

Another issue of much debate in the UK and internationally has been whether there are particular societal concerns associated with some types of risk which mean they should be treated in a more precautionary way than other risks. Greater sensitivity to a school or hospital than to a warehouse is one example where such concerns have been adopted in policy, based on a combination of the vulnerability and number of individuals at risk. A controversial example relates to whether people have a "scale aversion" to risk – that is, whether they regard 10 deaths occurring one at a time as more or less significant than the same 10 deaths all occurring at once as the result of a major accident.

The UK Health and Safety Executive and others have developed a variety of alternative risk metrics for the expression of "societal risk" (a measure of the aggregate risk associated with all individuals who may be exposed to it, and reflecting the number of people exposed as well as the scale of individual risk). These metrics include F/N curves, expected Person Lives Lost per year and various other forms of weighted/aggregated expressions of annual risk. The F/N curve, relating the tolerable frequency F of events killing N or more people, has been widely used internationally. In "Reducing Risks, Protecting People" (HSE, 2001) the UK Health and Safety Executive suggest that an event killing 50 people or more should be treated as intolerable if it could occur more than once in 5,000 years, regardless of the tolerability or otherwise of the associated individual risks. This has prompted much debate as to the hazard(s) and population(s) to which such a criterion should apply, as well as to what would be the corresponding intolerable frequencies of events killing more or fewer people.

The debate over societal concerns (of which the scale of accidents is just one subset) and the significance of "societal risk" and its suitability for use as a regulatory criterion continues to be the subject of much research and debate in the UK and elsewhere (e.g. HSE, 2009;

Evans, 2003; ERM, 2009). Individual risk is currently used by the UK Health and Safety Executive as its primary risk yardstick for the vast majority of hazardous installations, but it has been agreed by the UK Health and Safety Executive that societal risk will also be brought into the process, and means of achieving this are under development (HSE, 2008).

3.1.3 UK Airport Public Safety Zones (DfT, 2010)

An El Al cargo aircraft crashed into a block of flats on take-off from Schiphol in The Netherlands in 1992, killing the crew and 39 people on the ground. Since that time, the UK, USA and many other countries have introduced Public Safety Zones around the end of airport runways to safeguard people on the ground from the risk of aircraft crashing. In the UK these are based on contours of annual individual fatality risk for people assumed present on the ground for 100% of the time as follows:

- annual individual fatality risk greater than 10^{-4} per year: regarded as intolerable. The airport operator is required to make and hold open an offer to purchase all residential properties (and any commercial or industrial properties occupied as normal all-day workplaces). The property owner can if they wish continue to occupy and use their property but can sell only to the airport operator who, on purchase, must demolish the property.
- annual individual fatality risk greater than 10^{-5} per year but less than 10^{-4} per year: existing properties can continue in use, but Planning Authorities are required to refuse any application that would increase the occupancy of buildings by people (so for example a homeowner might be able to build a garage but not an extension with a new bedroom).

These zones are set based on a risk assessment looking 15 years ahead to allow for projected increases in air traffic volumes. While this example may seem remote from the context of slope instability (not least in that the risk can also be managed by reducing the likelihood of aircraft crashing in the first place), there are some distinct similarities. Both contexts involve objects external to a property household descending onto it, and both involve hazards of which people had been aware for some time without necessarily recognising the level of risk involved (the risk might have been “accepted”, without being deemed “acceptable” with reference to a relevant risk criterion). In both cases it is thus necessary to deal with properties in places where, with the knowledge now available, regulatory authorities may not wish them to be located.

The principles espoused by UK Health and Safety Executive have been developed and applied elsewhere in Europe and in English-speaking countries. Two Australian sets of guidelines have been widely used in relation to natural hazards in New Zealand and thus deserve particular consideration here:

- the Australian National Committee on Large Dams (ANCOLD) Guidelines on Risk Assessment (ANCOLD, 2003); and
- the Australian Geomechanics Society (AGS) Practice Note Guidelines for Landslide Risk Management 2007 (AGS, 2007).

3.1.4 Australian National Committee on Large Dams

While developed for dams, the Australian National Committee on Large Dams risk guidelines have been referenced in several natural hazard contexts in New Zealand. The Australian National Committee on Large Dams guidelines (ANCOLD, 2003) recommends both individual risk and societal risk (in the form of an F/N curve) risk criteria as follows:

a) annual individual fatality risk is intolerable above 10^{-4} per year (existing) or 10^{-5} per year (new) dams; and

b) F/N criteria for the maximum tolerable frequency F of killing N or more people where:
   N = 1: F ≤ 10^{-3}/year (existing dams) or ≤ 10^{-4}/year (new dams)
   N = 10 F ≤ 10^{-4}/year (existing dams) or ≤ 10^{-5}/year (new dams)
   N = 100 F ≤ 10^{-5}/year (existing dams) or ≤ 10^{-6}/year (new dams), with a horizontal "cut off" above this value (i.e. this value of F applies to all N of 100 or more)

The threshold of individual risk tolerability for existing dams was derived by comparison with existing risks faced by Australians (McDonald, 2008) – a graph of mortality rate versus age shows that the lowest risk people in Australia (as in most countries) are young children, with mortality rates a little higher than 10^{-4} per year from all causes.

The Australian National Committee on Large Dams guidelines adopt the UK Health & Safety Executive distinction between acceptable and tolerable risk, with risks having to be a factor of 100 or more lower than the upper limit of tolerability to be considered "acceptable". The principle underpinning the numerical levels adopted (McDonald, 2008) is explained as

"A dam or other facility should not impose on any individual an increment of risk that is more than a small fraction of their background risk."

The criteria for societal risk were derived from publications by other regulators, in particular the UK Health and Safety Executive who have not to date applied such criteria in everyday regulatory contexts. One reason for this is the difficulty in deciding to what population or group the criteria should apply. Aspiring to a less than 0.001 annual frequency of a fatal accident affecting the specific population in the catchment below a dam may be entirely reasonable. But applying such a frequency as a limit of tolerability for the whole of New Zealand, or Canterbury, or Christchurch, or even the Port Hills, starts to appear extremely restrictive in comparison with the accident risks already tolerated by society in relation to (for example) road accidents, falls in the home or drowning (see also Section 4 below).

An important principle adopted in the Australian National Committee on Large Dams criteria, and a natural extension of the "As Low as Reasonably Practicable" principle, is that when designing a new dam (when the opportunity to build in risk controls at marginal cost is available), the upper threshold of tolerability should be significantly lower than that for an existing dam (for which that opportunity is no longer available).

3.1.5 Australian Geomechanics Society

The Australian Geomechanics Society Guideline (AGS, 2007) makes an important statement at the beginning of its consideration of risk criteria, which is that it is up to the regulator (rather than, for example, technical experts) to establish its policy in relation to risk. GNS Science supports this position.

The Australian Geomechanics Society guidelines go on to suggest as starting points for discussion individual risk levels the same as those used in the Australian National Committee on Large Dams criteria (10^{-4} per year for existing slopes/developments, 10^{-5} per year for new ones). The Australian Geomechanics Society also advises that *"Societal risk should be evaluated for buildings having high numbers of occupants, such as schools, hospitals, hotels or motels where many lives are at risk. This then addresses society's aversion to loss of many lives from single landslide events"*, but does not suggest specific societal risk criteria.

The Australian Geomechanics Society guidelines make a similar distinction between "acceptable" and "tolerable" risk as do the Australian National Committee on Large Dams and the UK Health and Safety Executive.

Finally, in the context of overseas risk guidance relevant to landslide and rockfall, Hong Kong has particular pressure on space for building close to rockfall-hazardous sites, and commissioned guidance on tolerable risks in the 1990's (ERM, 1998). This report recommended individual risk tolerability limits similar to those of the Australian National Committee on Large Dams and the Australian Geomechanics Society, and a societal risk (F/N) criterion similar to that of the Australian National Committee on Large Dams but with a vertical cut-off for very large events (events killing over 1000 people to be considered intolerable, regardless of frequency).

These Australian and Hong Kong sources all propose individual annual individual fatality risk tolerability criteria of 10^{-4} per year for existing facilities and 10^{-5} per year for new ones. Different views are taken on societal risk and are discussed in Section 5.

3.2 Risk Criteria in New Zealand Regulation

Quantified risk assessment is increasingly being used in New Zealand to inform regulatory and other public policy decisions; GNS Science is not aware at this time of any quantitative risk criteria having been formally adopted by a government department or regulatory agency in New Zealand as a basis for granting consents or in other decision making contexts.

The New Zealand Civil Aviation Authority (CAA, 2008) provides guidance to planning authorities on land use at or near airports. This encourages local authorities to protect aerodromes to ensure the safety of people and property on the ground (among other reasons), and advises that *"Zoning solely to obstacle limitation surface*[3] *is insufficient to prevent the construction of incompatible uses such as housing or uses that attract congregations of people in the approach areas*" (CAA, 2008). The use of Runway Protection Zones in the USA (very similar to the UK Public Safety Zones described above) is described, but no criteria are suggested for how to define such zones.

As regards hazardous substances, the New Zealand Ministry for the Environment (MfE) provides an Assessment Guide for Hazardous Facilities (MfE, 2002) which promotes the practice of risk assessment and includes a discussion of risk evaluation and risk criteria. No standard criteria are presented for New Zealand, but the individual risk criteria adopted for New South Wales, Australia (including an upper individual fatality risk level for residential land use of 10^{-6} per year) are presented as an example.

[3] Note – the obstacle limitation surface is to protect aircraft and associated navigational and communication functions, not to protect people on the ground, hence the need for the additional guidance on land use provided in (CAA 2008).

In relation to natural hazards and transport, the New Zealand Transport Agency (NZTA) makes regular use of risk assessment to inform decisions on roads vulnerable to slope instability-related hazards and has published research into the development of related performance criteria (NZTA, 2006). These have not yet, to the authors' knowledge, been formalised into generally adopted risk criteria.

In relation to natural hazards and people at their properties, the Australian Geomechanics Society 2007 guidelines are widely used in the context of landslide risk but are not formally adopted by any particular agency. The New Zealand guidelines for assessing planning policy and consent requirements for landslide prone land (Saunders and Glassey, 2006) aim to assist planners and other interested parties in determining whether planning documents and resource consent applications at regional and district levels incorporate appropriate information on landslide and slope instability hazards. They provide information on the criteria used to assess landslide hazards at the consent stage, and examples of issues, objectives, policies, rules and assessment criteria. Basic landslide concepts are outlined to assist planners in understanding landslide processes, triggers, hazards and risk assessment. However this document does not recommend levels of tolerable or intolerable individual or societal risk.

Risk assessments have been developed for tsunami risk to New Zealanders living near the coast (Berryman, 2005; Webb, 2005) which enable individual risk to be evaluated against criteria similar to those described above (ANCOLD, 2003; AGS, 2007) – these assessments are described further in Section 4.1 below.

In relation to seismic hazards, various forms of criteria have been developed typically relating the return period of earthquake for which a building or structure should be designed to the nature of its use. For example:

a) In judging the risk of building across active faults (Kerr et al., 2003), where life risk was considered to be high because of likely collapse due to fault displacements, a 3,500 year return period[4] was set for developed sites (5,000 years for green field sites) for residential buildings;

b) For medium hazard dams where failure could result in "a few deaths" the maximum design earthquake in a period of 2,500 years was recommended as the basis for life risk assessment (Mejia et al., 2001).

Both of these approaches evolved in light of the seismic provisions of the New Zealand building code. The commentary section of NZS1170.5 states*: "Internationally, an accepted basis for building code requirements is a target annual earthquake fatality risk in the order of* 10^{-6} *(ISO 2394:1998). In design terms it is generally accepted that fatality risk will only be present if a building fails, i.e. collapses. The maximum allowable probability of collapse of the structure is then dependent on the probability of a person being killed, given that the building has collapsed. This conditional probability will be dependent on structural type and other factors and is likely to be in the range* 10^{-1} *to* 10^{-2} *.... Acceptable annual probabilities of collapse might therefore be in the range* 10^{-4} *to* 10^{-5}*."*

In practice, it is not practicable to design for a collapse limit state, as building performance is

[4] Note – there is no simple correspondence between the design return period event and individual risk, which is the product over all possible events (from very short to very long return periods) of event frequency x probability of death for an individual, given the event occurs.

too uncertain at such levels. Instead, design is for a lower level of earthquake motion, for a level of structural performance that can be more reliably predicted. This limit state is referred to as the Ultimate Limit State. For normal buildings, the Ultimate Limit State is usually associated with 500-year return period motions, while it is suggested (NZ Loadings Standard, NZS1170.5, 2004) that buildings should be assessed conservatively against a 2500-year return period motion. A possible logic linking this approach through to an annual individual fatality risk for building occupants (note – the Building Code does not attempt to translate return period events into risk or vice versa) of order 10^{-6} per year is thus:

a) Events up to a 500-year return period (2×10^{-3} exceedence frequency per year) will result in no worse than the Ultimate Limit State;
b) Events necessary to cause collapse will be substantially rarer (10^{-4} to 10^{-5} per year, with some confidence provided by assessment against a 2500-year return period or 4×10^{-4} per year exceedence frequency event); and
c) The probability of a building occupant being killed in the event of collapse is modest (of order 10^{-2} to 10^{-1}).

Whilst there can be high confidence in step (a) of this logic, steps (b) and (c) are clearly subject to considerable uncertainty; as mentioned above the Building Code and related documents do not at present link requirements expressed in terms of particular return period events to risk. It seems clear, though, that the intent of the building code requirements is to deliver a risk level nearer to that aimed for in the context of imposed risks from hazardous installations rather than the levels associated with existing buildings and structures that are the subject of the AGS (2007) and ANCOLD (2003) guidelines.

In addition to these instances of policy being explicitly formulated, there are a number of implicit risk policies emerging as a result of action taken in the light of information from risk assessments carried out for natural hazards in New Zealand. These are discussed in Section 4.1 below.

4.0 FATALITY RISKS NEW ZEALANDERS FACE

Whenever and wherever risk criteria have been developed, risk comparisons have played an important part. In this section relevant individual fatality risk information for New Zealanders is collated.

Section 4.1 provides an overview of natural hazard life risk faced by New Zealanders, based first on direct historical experience, and second on selected findings of recent risk assessment studies.

Section 4.2 then provides estimates of New Zealand individual fatality risk for some more common causes of death, identifying the overall contribution accidents make to fatality risk and the major contributors to accident risk.

4.1 Natural Hazard Risks in New Zealand

4.1.1 Direct Historical Fatal Event Experience

Figure 2 shows major fatal natural hazard events since 1858 (the earliest year covered by historical population statistics available from Statistics New Zealand) in New Zealand.

Numerous smaller (mostly single fatality) events are not shown in the figure, and the colour coding is approximate (for example some of the “earthquake” fatalities were killed in rockfalls or landslides triggered by earthquakes).

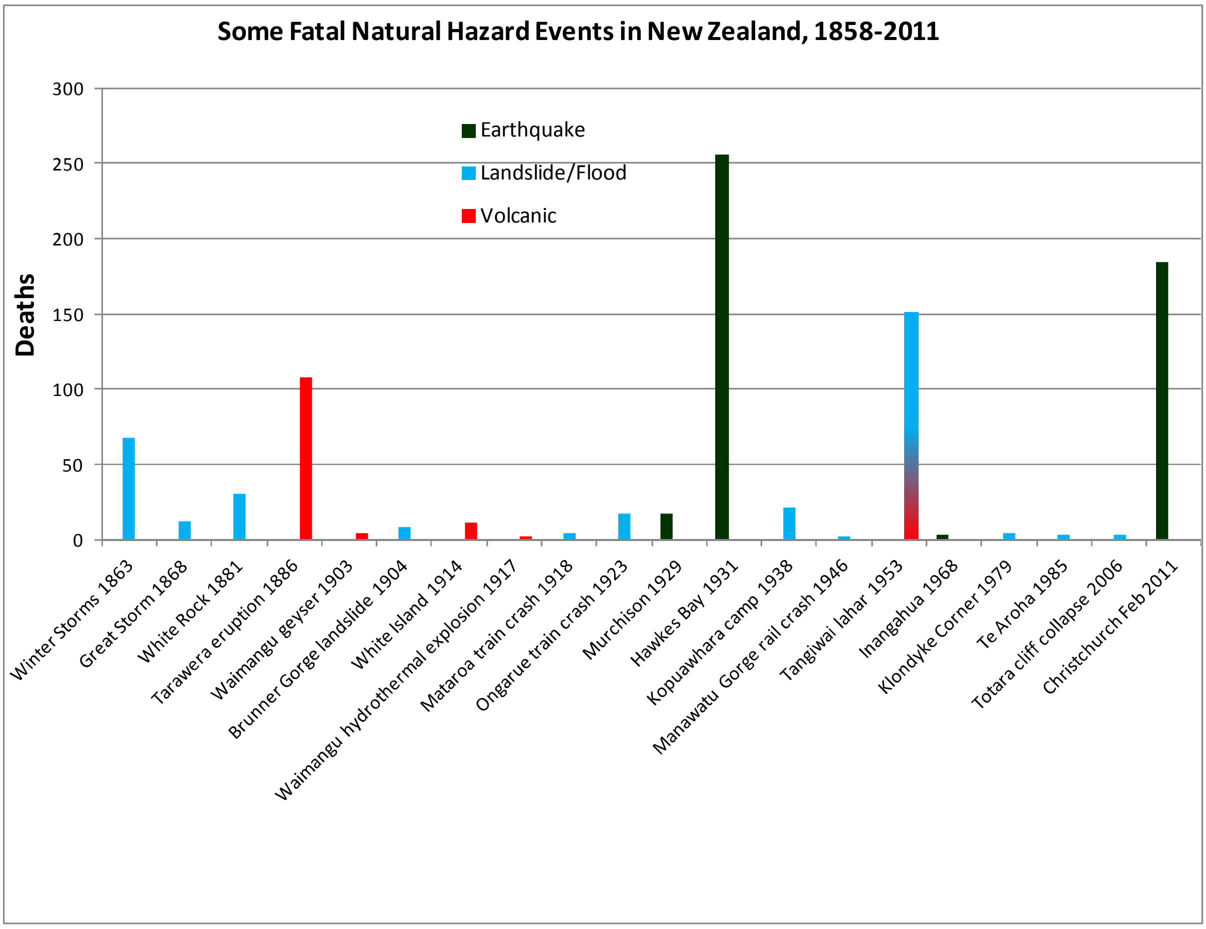


Figure 2 Selected Fatal Natural Hazard Events in New Zealand, 1858-2011.

The primary sources for the figure are the New Zealand Ministry for Culture and Heritage (MCH) “New Zealand History Online” New Zealand Disasters Timeline (MCH, 2012) and the GNS Science landslide catalogue. There can be a high degree of confidence that the major earthquake, volcanic and major landslide events are complete, but there are almost certainly many other smaller incidents, for example due to flooding (rivers were responsible for the deaths of over 1000 European settlers by 1870).

The average population of New Zealand over this period was 1.774 million[5]. The total fatalities shown in the figure over the period for each hazard type, and the corresponding average historic annual individual fatality risk (averaged over the whole New Zealand population) is shown in Table 2. Note that because of the incompleteness of the source information as mentioned above the total fatalities estimates err on the low side. On the other hand improvements in building standards and hazard awareness have reduced the relatively high rate of fatal incidents in New Zealand’s early years.

[5] Source – Statistics New Zealand resident NZ population estimates 1926 to present day, and historic estimates 1858-1925 interpolated from census data points from Statistics NZ for 1858, 1874, 1878, 1881 and every 5 years subsequently to 1926.

Table 2 Historical New Zealand Population Average Natural Hazard Individual Risk.

Hazard	Total Fatalities 1858-2011	Average annual individual fatality risk ('10 to the minus..')	Average annual individual fatality risk (1 in ... years)
Earthquake	474	1.7×10^{-6}	0.6 million
Volcanic activity	126	4.6×10^{-7}	2 million
Landslide/flood	340	1.2×10^{-6}	0.8 million

The total average natural hazard fatality risk faced by New Zealanders over this period was thus, on average, a little under 3×10^{-6}, or 3 in a million, per year.

These hazards are unevenly distributed across the population; in practice the majority of the population are likely to experience significantly lower levels of natural hazard risk while a minority experience significantly higher levels of risk in areas where hazards are concentrated. This is apparent from the results of risk assessments, examples of which are provided in Section 4.1.2.

4.1.2 Risk Assessment Insights

Earthquake: Casualties have been predicted both for major earthquakes generated by rupture of selected major active faults affecting the Wellington region and for the whole of New Zealand, based on the New Zealand National Seismic Hazard Model (Cousins, 2010). The "all New Zealand" estimates range from a single fatality (estimated to occur every 10 years) up to 700 fatalities (estimated to occur every 5,000 years). These estimates are broadly consistent with the historical individual risk estimate shown in Table 2.

Table 3 shows the estimated casualties from major earthquakes on selected Wellington region active faults. The two right-hand columns have been added by the authors to provide an approximate estimate of the average deaths per year expected from each fault in the region[6]. These figures assume a 40% chance of events occurring in daytime and reflect the range of event frequencies corresponding to the range of return periods shown.

Table 3 Wellington Region Earthquake Consequences (Cousins, 2010).

Scenario	Return Period (years)	Deaths (shaking)		Deaths (tsunami)		Average expected deaths per year	
		workday	night	workday	night	from	to
Wellington fault rupture	840-1000	740	200	260	79	0.6	0.7
Wairarapa-Nicholson fault	1200-4800	250	82	96	200	0.1	0.3
Subduction Zone alone	800-1200	42	14	33	1000	0.5	0.8
Subduction Zone to Cook Strait	>1500*	96	32	3000	2900	0.6	2.0
** assumed here to be in range 1500-5000*							
		TOTAL average expected deaths/yr				1.8	3.7

Based on these figures the average individual fatality risk to people in the Wellington region

[6] Note that this is certainly an underestimate, as the frequencies assumed for the faults include larger faults than those whose fatalities are assessed in this table, and no contribution is included from faults less serious/more frequent than those shown.

(of whom there were 483,300 in June 2010 – Statistics New Zealand) from these faults alone was in the range of 4 x 10^{-6} to 8 x 10^{-6} per year. This is an underestimate as explained in footnote 3 above. Moreover, there are large differences in earthquake risk across the region (see for example Wellington Regional Council http://www.gw.govt.nz/Earthquake-hazard-maps/) because of different degrees of ground shaking, different stocks of buildings and different exposure to hazards such as landslide or rockfall triggered by earthquakes. It therefore appears inevitable that while a majority of Wellingtonians may be subject to below-average levels of seismic risk at their properties, some thousands or tens of thousands of others are subject to seismic annual individual fatality risk at their properties in excess of 10^{-5} per year.

Tsunami: Tsunami risk for major cities in New Zealand has only been quantified for the first time in recent years (Berryman, 2005; Webb, 2005). Table 4, compiled from these two sources, shows the median estimated fatalities for a 500-year tsunami event for some major East Coast cities, and translates them into a rough estimate of average annual individual fatality risk for everyone in those cities. The right hand column shows the estimated range of individual risk experienced by people living between 2 and 4 m above sea level in each city.

These figures are before any new mitigation measures are put in place. The figures assume no warning so in this respect overstate the risk – but it is noted that a significant proportion of the risk is associated with near-field events for which warning time would be very limited, so the overstatement in this respect is not by a large factor. On the other hand, for the same reasons as are explained above for earthquakes, these figures underestimate annual individual fatality risk (i.e. they do not include any contribution from more frequent events, and the consequences of larger events in the "less often than once every 500 years" category would be more severe than those shown here). On balance it is considered that the annual individual fatality risk figures in the table provide a reasonable, if approximate and perhaps slightly overstated estimate of the true levels of individual risk involved.

Table 4 Tsunami risk estimates for some East Coast cities.

	Berryman (2005)			***Webb (2005)***
City	**Estimated Fatalities in a 500-year event**	**Population**	**Average Annual Individual Fatality Risk, whole city**	**Annual Individual Fatality Risk range at 2-4 m above sea level**
Gisborne	440	31000	2.8 x 10^{-5}	> 10^{-4}
Napier/Hastings	320	100000	6.4 x 10^{-6}	10^{-4} to 10^{-5}
Christchurch	280	334000	1.7 x 10^{-6}	10^{-4} to 10^{-5}
Wellington	188	179000	2.1 x 10^{-6}	> 10^{-4}
Dunedin	160	107000	3.0 x 10^{-6}	10^{-4} to 10^{-5}
Whakatane	74	34000	4.4 x 10^{-6}	10^{-4} to 10^{-5}
Timaru	24	24000	2.0 x 10^{-6}	> 10^{-4}

The conclusion is that tens of thousands of people in these cities are likely to be living with tsunami annual individual fatality risk in excess of 10^{-5} per year, while hundreds, if not thousands, are likely to be living with tsunami annual individual fatality risk in excess of 10^{-4} per year. Such risk levels are the reason for substantial initiatives having been taken in the relevant communities to mitigate tsunami risks.

Volcanic Events: No specific individual risk estimates have been made for volcanic eruption events, but it is noted (GNS Science Volcano Hazard Fact Sheets *http://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/New-Zealand-Volcanoes/Fact-Sheets*) that return periods for significant events at several North Island volcanic centres are of the order of a thousand to a few thousand years, for example:

- The time between eruptions at the Okataina Volcanic Centre (e.g. Tarawera) is between 700 and 3,000 years;
- The Taupo Volcanic Centre has experienced 3 major eruptions and at least 25 smaller eruptions in the past 27,000 years; and
- The Auckland Volcanic field has experienced 20 eruptions in the past 20,000 years.

Whilst it is hoped and expected that warning systems would enable fatalities to be minimised in a large majority of volcanic events, it is also to be anticipated that a subset of events will occur with limited warning, putting large numbers of people at annual individual fatality risk likely to be in the region of 10^{-6} to 10^{-5} per year (> 10^{-4} per year event frequency x 1-10% probability of fatality if event occurs).

Landslide/Flood: These risks are very localised and are typically managed by Regional Councils through the Resource Management Act. Regional Councils are increasingly using risk assessment to assess flood risk to specific communities (e.g. Saunders and Berryman, 2006).

One example for the Thames Coast (Environment Waikato, 2003; URS, 2003) provides estimates of both individual risk and of the likelihood of a fatal accident occurring in specific communities. A number of areas were identified where average annual individual fatality risk was estimated to be around 5 x 10^{-5} per year. It is to be anticipated that several other locations on other river flood plains around New Zealand might involve annual individual fatality risk levels at or around this level.

A risk assessment was carried out for a motel and campsite located in Franz Josef, next to the Waiho River (Optimx, 2002). This identified a high likelihood of flooding via the river overtopping its stop banks, with a 10-20% chance per year of occurring, but with a substantial degree of warning. Of more concern were sudden floods triggered by earthquake or landslide, estimated to have a 2-4% chance per year of occurring, with little warning, and with a high likelihood of fatality for people present. The annual individual fatality risk for a person present 100% of the time at the camp site from these “little warning” scenarios would have been of order 0.01 to 0.02 per year – potentially significantly greater than 10^{-4} for a visitor staying a week at the campground. Unsurprisingly, these risks were considered intolerable by the Ministry of Civil Defence Emergency Management and others (MCDEM, 2002) and a concerted effort was made by central and local governments and the campsite owner to relocate to a safer location.

Another interesting situation in which one of the authors has been involved is that of Little

Waihi village, on the shore of Lake Taupo (Massey et al., 2009). Several large landslides have occurred on the Waihi Fault scarp above the Hipaua thermal field at the southern end of Lake Taupo in the last ~230 years including at least three fatal events:

- A well-documented event in May 1846 killed 64 people in the village;
- A 1910 landslide led to one fatality; and
- An earlier event in about 1780 apparently buried a pa at the mouth of nearby Omoho Stream with the loss of possibly 150 lives.

Large failures of this type could occur again via rainfall, seismic or other triggers. They could affect State Highway 41 over a length of about 300 m, and possibly overwhelm a fishing lodge on the edge of Lake Taupo and some houses within the village, despite most of the village having been relocated north of the major landslide hazard zone following the 1910 event. The likelihood of a large, rapid debris flow in the future has been estimated at about 1 event every 80 years or so (Hegan et al., 2001), which might translate into an annual individual fatality risk of about 10^{-3} to 10^{-2} per year in the high hazard area.

The villagers self-evacuated following earth tremors in 2009, so are clearly acutely sensitive to the hazard. The primary risk control adopted here was to relocate the village rather than to try to protect existing properties from future landslides, and to live with the residual risk and take good heed of any warning signs of impending problems.

On 18 May 2005 a band of intense rain passed over the catchments behind Matata, a small township situated on the eastern coast in the Whakatane District, triggering many landslides and causing major property damage. There is evidence that equally large or larger debris flows have occurred many times in the past 7,000 years, and the annual frequency of debris flows affecting the township is likely to be about 1 in 500 years (McSaveney et al., 2005). The risk of an individual resident being killed in such an event is estimated by the authors to be in the range of a few % to a few 10's of %, leading to a crude estimate of annual individual fatality risk in the landslide runout zone in an approximate range from 10^{-4} to 10^{-3} per year.

One further interesting example is provided by Aoraki (Mount Cook) Village, where floods and debris flows are a well-recognised hazard and it is recognised that a number of dwellings are at unacceptably high levels of risk (DOC, 2004). The strategy adopted here (DOC, 2004) is as follows: *"Existing facilities subject to natural hazards at unacceptable levels will be relocated to safer ground, as resources permit. Where no safer alternative is available the facility may be closed as a temporary measure during times when the risk is considered by the Area Manager to be unacceptably high."* As in the Waihi Village case, the preferred longer term strategy is for relocation, with careful monitoring and temporary measures being taken at times of high hazard in the interim.

4.1.3 Conclusion – Natural Hazard Risks faced by New Zealanders

It is concluded that New Zealanders are living with natural hazard annual individual fatality risk of order:

- 10^{-6} or more per year averaged over the whole population;
- 10^{-5} or more per year for large numbers (tens or 100's of 1000's) of people; and

- 10^{-4} or more for significant numbers (100's or 1000's+) of people in high risk areas.

4.2 Other Risks New Zealanders Face

Statistics breaking down fatalities in New Zealand (by cause of death, age, sex, and other factors) are maintained and published by the Ministry of Health. The most recently available data set, used here, is for 2008 (Ministry of Health, 2008).

4.2.1 Annual Fatality Risks – an Overview

Figure 3 shows the average mortality from selected causes. The equivalent curves for males would be a little higher and for females a little lower across the whole of the age ranges, with young men and boys particularly more accident-prone than young women and girls. Note that the vertical axis is logarithmic – each division corresponds to a factor of ten higher than the previous one (1E-03 is the same as 1 x 10^{-3}, or 0.001, or 0.1%). Such a scale enables all the points to be seen on one chart but means there can be very wide factors of difference corresponding to relatively small vertical separations.

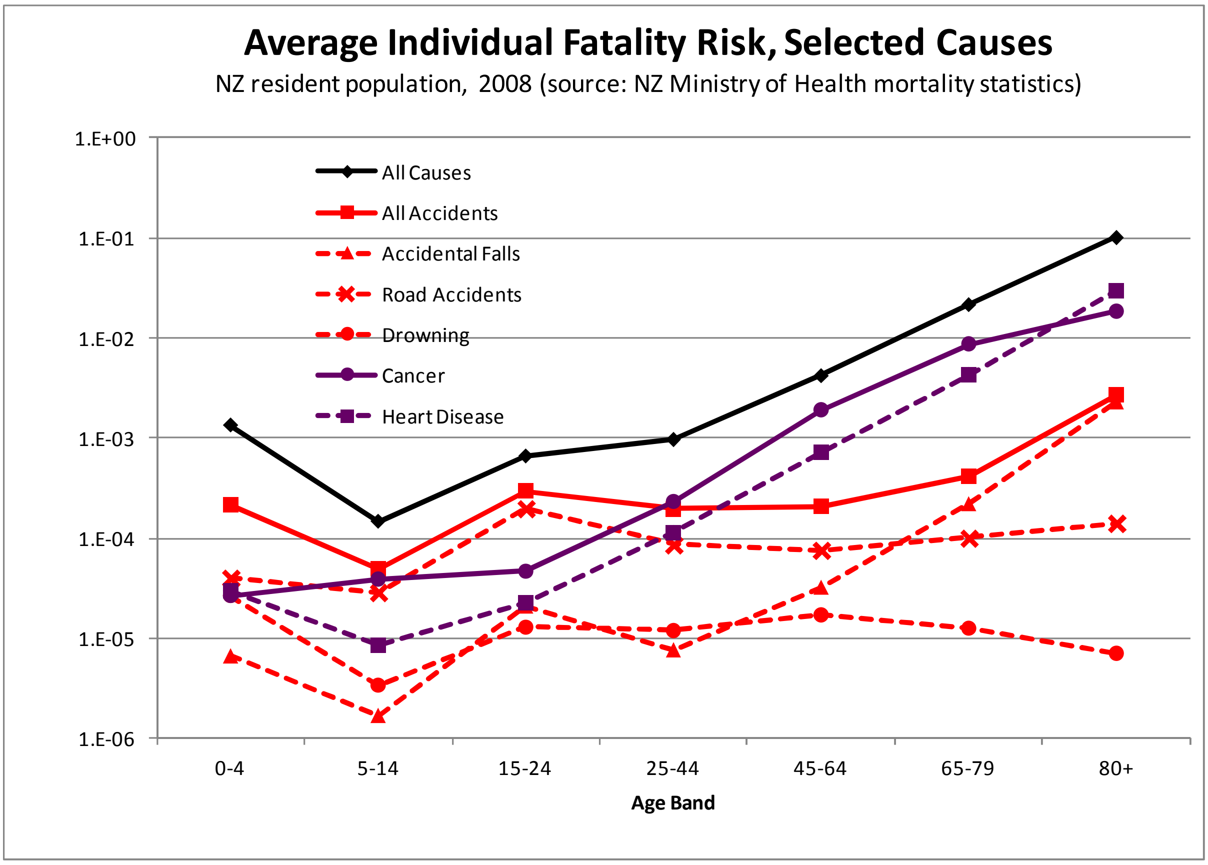


Figure 3 New Zealand Average Individual Fatality Risks 2008, Selected Causes (Ministry of Health, 2008).

Significant observations on this chart include:

a) after the first year or so of life, most risks increase with age;

b) accidents are the largest source of risk facing young people, while cancer and heart disease are the largest source of risk facing older people;

c) accident-related risk is dominated by road accidents for younger people and by falls for older people; and

d) accident-related risk has a "hump" for the 15-24 age group (this is associated largely with risk-taking behaviours by young men in particular).

Figure 4 shows the ranges of annual individual fatality risk, for both men and women, represented by the variations with age shown in Figure 3.

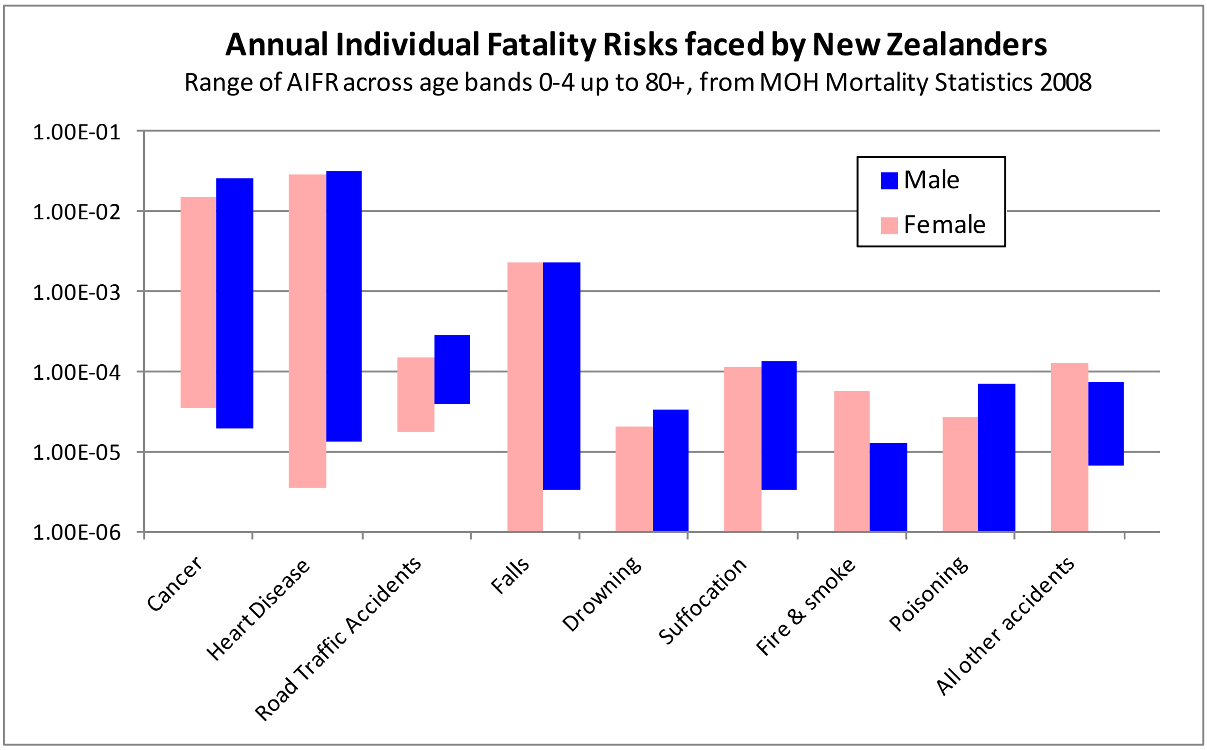


Figure 4 Range of Annual Individual Fatality Risk Across Age Bands, New Zealand (Ministry of Health, 2008).

This reinforces the point about risks changing with age – road traffic accidents can be seen as having an unusually narrow variability in risk with age. The figure also brings out the generally higher risk faced by men rather than by women. When describing a level of risk as "low" (e.g. in relation to the other risks people face) care is clearly necessary in terms of "to whom, and compared with what?"

4.2.2 Lifetime Risk Comparisons

Small numbers, particularly when expressed in terms of "ten to the power of minus 4" and similar, can be difficult to understand. It may be helpful to re-express some of these risks in terms of their overall contribution, over a lifetime, to chance of death. Figure 5 shows (note this is now on a linear scale) the overall chance over a lifetime[7] of dying from various causes. This shows clearly:

a) the substantial lifetime difference between accidents and disease (the latter are more

[7] These chances are calculated assuming a person faced the fatality risk from each cause at each age that was faced by a person of that age from that cause in 2008.

than 10x likely to be the ultimate cause of death of New Zealanders); and

b) the dominance over a lifetime of the risks that increase rapidly with age.

The latter point complicates using lifetime-average risks as a comparison for natural hazard accident risks. The lifetime averages for many causes of death are dominated by the high risks in later years of life. The corollary is that most people (those who are not elderly) face risks which are considerably smaller than the lifetime average.

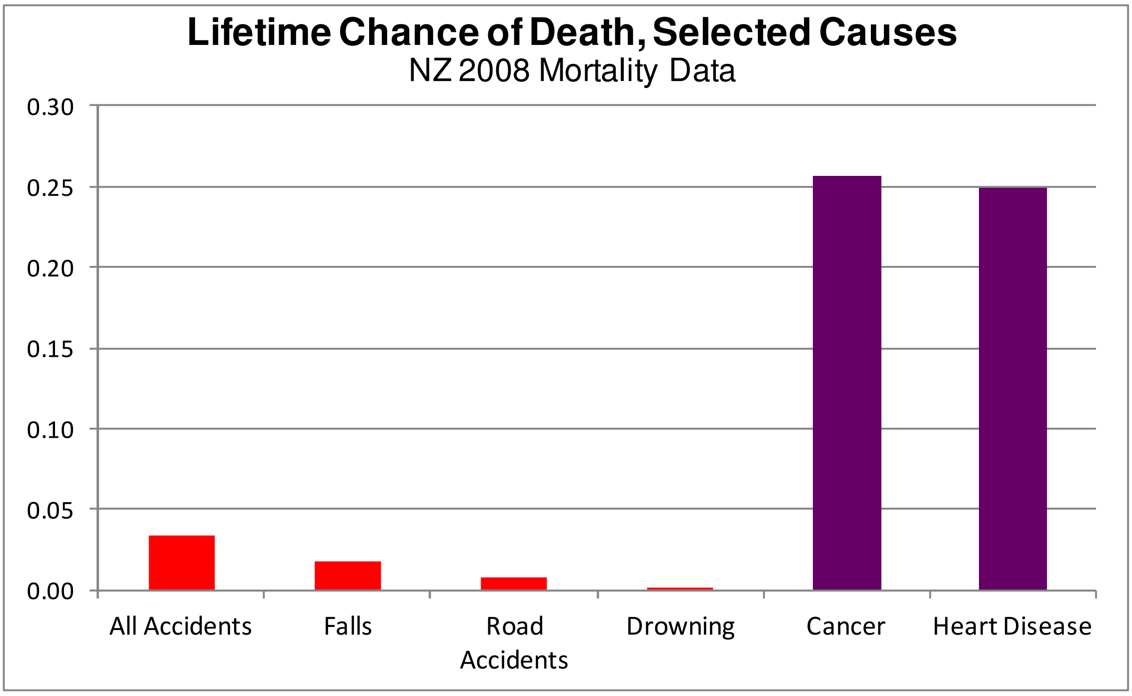


Figure 5 Lifetime Chance of Death, Selected Causes. Based on New Zealand Ministry of Health (2008) mortality data.

Having discussed existing risk policies and criteria, and the levels of risk faced by New Zealanders in Section 4, the report moves on in Section 5 to discuss what policies and criteria would be most relevant in the context of slope instability-related risk for people in their Port Hills properties.

5.0 DISCUSSION

This section discusses what risk criteria and associated policies would be appropriate for Christchurch City Council in light of the particular features of slope instability risk, and of the previous sections of the report. It addresses in turn:

a) the particular features of slope instability-related risk as assessed in the GNS Science companion reports (Massey et al. 2012a,b) (5.1);
b) how best to define and measure "risk" for this purpose (5.2);
c) establishing a Christchurch City Council risk tolerability criterion (5.3); and
d) how to treat risks that are intolerable, or that are not generally acceptable (5.4).

5.1 Features of Port Hills Slope Instability-Related Risk

In considering how to evaluate the risk results from a complex and technical risk analysis, it is important that Christchurch City Council has an appreciation of the provenance of the risk information provided to it. To assist in developing this understanding, Appendix A provides an overview of the approach adopted for the assessment of rockfall-related risk in the companion reports (Massey et al. 2012a,b), and of the key uncertainties involved.

The purpose of Appendix A is to help the reader understand broadly how the risk assessment process works, and to give an appreciation of the very different provenance of risk information that results from it in comparison with, for example, identification of flood risk areas. Contour maps of risk show calculations in which each property has a value of risk associated with it. However, this does not mean that the information is as crisp and definite as that on a traditional contour map. Risk information, in this case as in many others, is subject to uncertainty.

Despite those uncertainties, the risk information is useful and suitable for use in decision making. It does mean that risk regulators need to take into account the provenance of the information when using it. There should not be too much significance attached to marginal differences in risk when/if there are other important statutory, social, economic, cultural or environmental factors that Christchurch City Council might also wish to take into account. If the risk is uncertain by a factor of 10 either way, then stretching the interpretation of risk tolerability criteria by a factor of 1.5 or 2 looks modest in comparison.

The importance of these uncertainties, and the social, environmental, economic and statutory nature of the decisions as to which assumptions should be used in the assessment, mean that the user of the information (the regulator) needs to have an appreciation of what goes into the assessment. The regulator and other stakeholders also need to have an appropriate say in the judgments made when estimating risk. The way in which risk assessment results are evaluated in relation to risk criteria is as important for the decisions that will flow from such evaluation as are the risk criteria themselves. In considering how to decide which risks are tolerable and which are not, Christchurch City Council therefore needs to consider both:

a) where to set its threshold(s) of intolerable or other actionable risk; and

b) how it wishes risk to be evaluated against those criteria.

In such areas GNS Science may be able to propose a reasonable starting point for Christchurch City Council's consideration, but it is up to Christchurch City Council to decide their policy.

Some of the key features of relevance in establishing risk management policy and risk criteria in this context are:

a) the hazard has natural causes while the risk results from the combination of the hazard with the location of people's properties;
b) the risk is experienced by people in their properties;
c) the risk is currently elevated but will diminish with time as the elevated likelihood of seismic events in the wake of the 2011 earthquakes falls; and
d) the risk estimates are uncertain within about a factor of 10 either way – that is, an assessed risk of 3×10^{-4} per year might be as high as 3×10^{-3} per year or as low as 3×10^{-5} per year.

As regards (a) and (b), the risk is not one which is being imposed on people by others for a wider social good. Thus those at risk are not in the same category as (for example) residents near a hazardous substances facility or a major dam. Some would argue that people should be free to decide where to live, and that it should be left to the individual to decide what is an acceptable (or tolerable) risk on their own property. Were they fully informed about the risk and the only person exposed to it this might indeed be the case, but Christchurch City Council needs also to consider complicating factors such as:

i. dependents living with the homeowner who do not have a choice where to live;
ii. the distinction between informed acceptance of risk and failure properly to appreciate its nature and level;
iii. people previously unaware of this hazard who may not have the means to relocate of their own accord;
iv. whether it is acceptable to sell on an "at risk" property and if so with what constraints; and
v. people who might visit the property for social and leisure purposes, or in the course of their work (which might take them to multiple at-risk properties, for example a postman's round might cover a whole area of at-risk properties).

The first question the UK Health and Safety Executive asks itself in any regulatory decision process is whether the issue is one on which it should be the decision maker, or whether the decision should be left to others (HSE, 2001). Christchurch City Council should consider this in the context of slope instability-related risk to people at their properties in the Port Hills. Options for making decisions about the risk might include:

1. providing well-explained information about risk and leaving decisions about it entirely to the househoulder; or

2. imposing an upper threshold of risk tolerability above which occupation of properties will not be tolerated; or

3. some form of hybrid arrangement, perhaps:

   a) defining two levels of risk with an absolute upper limit above which occupation of properties is not tolerated, and a somewhat lower threshold above which occupation is discouraged (and/or retirement of the property from use as a dwelling is enabled or incentivised) but where the ultimate decision is left to the homeowner unless the risk exceeds the absolute upper limit; or

   b) adopting a "you don't have to move but you can only sell to us" approach as happens in airport public safety zones in the UK.

While much of the discussion in Christchurch has been around option 2 above, there are precedents for the other options. Government in New Zealand leaves decisions about the tolerability or otherwise of fire-related risk in single dwellings to the householder (effectively option 1 above), while option 3 is used in the UK in relation to airport public safety zones.

The authors suggest that, in light of the complicating factors (i) to (v) above, Christchurch City Council should not leave decisions about risk entirely to householders (i.e. should NOT adopt the first of the options above). Slope instability-related risk is less amenable to simple low-cost measures to prevent and mitigate the relevant hazards than is fire risk, and in GNS Science' view Christchurch City Council might attract considerable criticism for failure to act to prevent occupancy of dwellings at some of the high levels of risk assessed in our companion reports (Massey et al. 2012a,b).

As regards the current elevated level of risk in the wake of recent earthquakes, that level is expected to fall by a factor of about 5 over the next 5–10 years (i.e. a risk which measures 5 units now will measure only 1 unit in 5–10 years time). This gives Christchurch City Council a number of options to consider, in particular the Council could:

i. Base decisions on current risk levels, knowing that in some years' time those decisions will look more precautionary than they do now because the risk has fallen;
ii. Base decisions on the longer-term risk levels likely to prevail after the current elevated risk period has passed, and find a way to live with the current relatively short-term elevated levels of risk; or
iii. Make decisions now based on the current level of risk, with a view to revisiting those decisions in 5-10 years time when the risk, hopefully, will have reduced.

The authors views on this issue are informed also by consideration of the uncertainty in the risk. Were the risk to remain steady as time progressed, it would be appropriate, as is standard practice in, for example, the setting of building design standards, to take a fairly precautionary view. That is, to base decisions on a risk value towards the upper, rather than the central, end of the range emerging from the risk assessment. The Building Code, for example, defines earthquakes as the basis for building design based on the 84^{th} percentile (84% confidence limit) of the assessed range of possible earthquake severities with a given return period, rather than the 50^{th} percentile or other form of "central" or "best" estimate.

In the particular case of slope instability-related risk in the Port Hills, the risk is currently elevated because of the heightened seismic hazard in the wake of recent major earthquakes. There is a high degree of confidence that this risk will reduce over the coming years and decades. What is currently a central estimate of risk will become a more conservative or pessimistic estimate in the longer term, as illustrated in Figure 6 below.

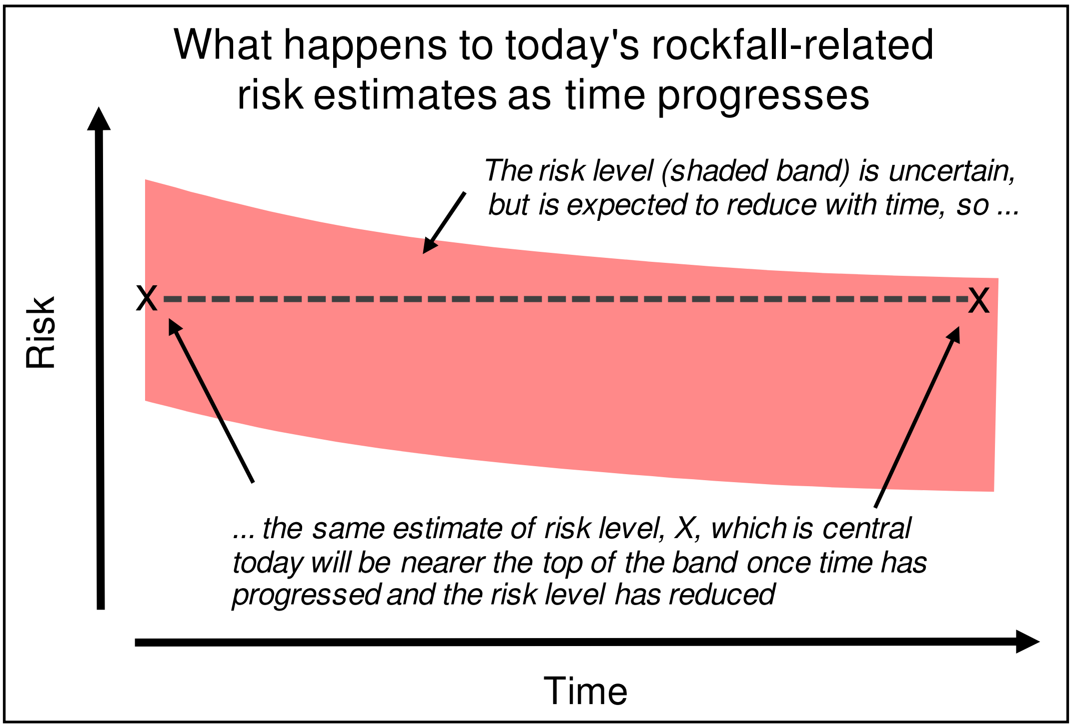


Figure 6 Today's Central Risk Estimate is Tomorrow's Precautionary Estimate.

In the face of uncertainty in the assessed risk levels, Christchurch City Council needs to consider its policy on how "risk" is to be estimated and evaluated against a tolerability criterion. For example, is a risk of 9×10^{-5} per year with an uncertainty of a factor of 10 either way to be treated as above or below a 10^{-4} tolerability threshold? If Christchurch City Council leaves such issues open to interpretation by risk analysts or other technical experts it risks having the intent of its policy distorted by the interpretations of others.

In this particular case, the authors suggest that Christchurch City Council adopt option (i) above. That is, that the estimated risks to be compared with the criteria developed here should be based on a central/best estimate of the current risk, rather than at a more precautionary level. A risk assessed as in the above example at 9×10^{-5} per year (uncertain x10 in either direction) would thus be treated as "less than 10^{-4} per year", although it is possible, in view of the uncertainty, that it is considerably larger than 10^{-4} per year. As time goes on the best estimate of the risk will decrease, though it will still be uncertain; the possibility that it is higher than 10^{-4} per year will shrink as time progresses, i.e. it will become more precautionary. This option is suggested:

- in preference to option (ii) because it avoids a considerable period (many years) within which either people are kept out of their properties or allowed to occupy properties at uncomfortably high levels of risk; it is also robust to the possibility of further earthquakes in the next few years which would restart the clock for the decrease in seismic hazard (as happened in December 2011); and

- in preference to option (iii) because it provides a pragmatic way in which to provide certainty quickly (which the authors understand from discussions with Christchurch City Council and other stakeholders is a desirable attribute of any decision process), without the need to revisit decisions in the short to medium term (5-15 years).

5.2 Defining and Measuring Risk

All the precedents in New Zealand and overseas for making decisions about risks to people in their properties rely heavily on the annual individual fatality risk measure which has been the primary focus of this report.

The one other measure that has been widely used, perhaps because of its place in the Australian National Committee on Large Dams guidance (ANCOLD, 2003) is a societal "F/N" risk measure based on the frequency F of events that cause N or more fatalities (regardless of who is at what level of individual risk, e.g. URS, 2003; Optimx, 2002). A particular sub-set of this is the frequency with which any fatal accident occurs (i.e. N greater than or equal to 1), which was used as the risk metric in a study of the impending lahar risk on Mt Ruapehu by one of the authors (Taig, 2002).

In the context of a dam, where the owner has particular responsibility for the integrity of the structure and the population at risk is a very well-defined group of people in the catchment below it, this concept has value – the owner wants to know and cares very much how often a fatal accident might occur involving their dam, and cares very much how many people might be involved. The Australian National Committee on Large Dams guidance point for frequency of a fatal accident (i.e. fatal accidents should not occur more than once per 1000 years) appears a reasonable goal.

In the context of the Ruapehu lahar, where a very specific decision was made by government to allow an event to proceed that could readily (albeit at some expense) have been prevented, the key issue of concern was not individual risk at all (no homes were at particular risk in the path of the lahar). The greater concern here was that someone (perhaps a road or rail user, a camper at the Tangiwai memorial or a tramper on the mountain) might be killed – the likelihood of a fatal accident, rather than the risk to any specific individual, was the matter of particular concern.

In the context of slope instability-related risk to residents in the Port Hills, the key issue is the difficult decision at the level of individual households as to whether the risk to occupants of a property is tolerable, and if not what to do about it. Christchurch City Council and the community are well aware of the potential for multiple fatality events associated with this hazard, but this has not at any stage been a significant factor in the debate over what is right for individual properties. All other specific land use planning guidance based on risk of which we are aware (e.g. HSE, 2011; CAA 2008) uses annual individual fatality risk as the basis for definition of risk-based zones because it provides clear and equitable treatment of individuals, and because aggregate metrics of risk (such as F/N curves or frequency of a fatal accident) do not assist in defining zones where individuals face different risk levels. In this context it is suggested that Council policy should be based firmly on annual individual fatality risk.

It may be useful for Christchurch City Council to be aware of the associated frequency of events involving different numbers of fatalities, (the risk estimated in the companion reports is dominated by larger events that might involve multiple fatalities, particularly at night when more people are at home). The authors suggest, though, that this be treated as a secondary issue in risk decision making because it is the level of risk faced by individuals rather than the (well recognised) potential for multiple fatalities, that has consistently been the issue of particular concern in this context.

5.3 Risk Tolerability

The key issue for Christchurch City Council to decide (subject to its statutory responsibilities, which may require other measures or different criteria) is a criterion or criteria as to what level of slope instability-related risk is or is not tolerable for people in their properties in the Port Hills. Figure 7 provides a summary of some of the more important risk comparators and existing criteria discussed earlier in this report. Some key considerations for Christchurch City Council in deciding what level of risk should be deemed tolerable and what level intolerable are:

a) With reference to the left-hand area of Figure 7 ("Existing criteria"), the fact that the risk is pre-existing and is associated with where people choose to live rather than being imposed by other people suggests that a tolerability threshold should be selected from the upper, rather than the lower, half of the chart.

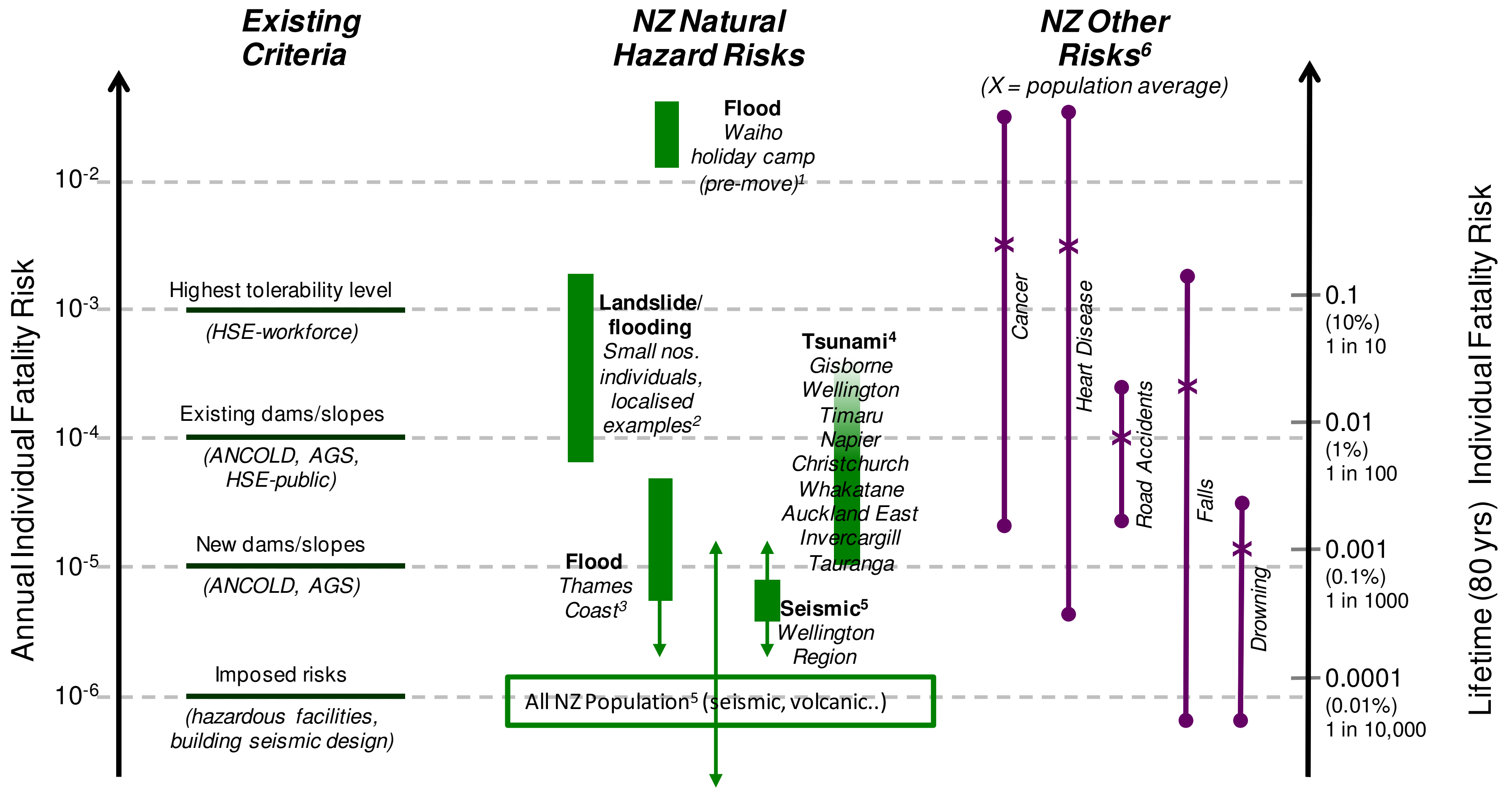
b) The central area of Figure 7 ("NZ Natural Hazard Risks") suggests that 10^{-5} annual individual fatality risk would be too low a threshold of tolerability; tens if not hundreds of thousands of New Zealanders probably experience natural hazard risk at or above this level already.

c) As regards the right hand side of Figure 7 ("Other NZ risks"), the average lifetime risks associated with cancer and heart disease (each about 3×10^{-3} annual individual fatality risk) are too high to be considered as candidates for accidental death tolerability thresholds – these are the primary causes of death in New Zealand and other developed countries and it would be unprecedented to tolerate public exposure to a particular source of accident risk at such levels.

d) An obvious starting point for consideration by Christchurch City Council would be an annual individual fatality risk of 10^{-4} per year. This is consistent with the thresholds of tolerability
   - adopted by the Australian National Committee on Large Dams and suggested by the Australian Geomechanics Society for existing dams/properties
   - adopted by the UK Health and Safety Executive for members of the public, and
   - adopted in civil aviation for protecting people near airport runways in the UK.

   It would imply that many hundreds (or possibly thousands or more) households in New Zealand were already at intolerable risk from other hazards such as landslide and tsunami, but such cases are largely already subject to substantial initiatives to reduce risk[8].

[8] For example through the national tsunami warning system and public education to self-evacuate low-lying homes if a very strong earthquake is felt, and through policies of relocation and heightened hazard awareness and temporary measures to deal with localised high risks of landslide/flooding



Notes:

1. Derived by the authors from results of MCDEM risk assessment (Optimx, 2002)
2. Estimated by the authors based on reasonable event return periods and likely consequences - see Report Section 4.1.2
3. Upper estimate for High Risk zones; arrow denots wide range of risks downward (URS, 2003)
4. AIFR at 2-4m above sea level, no effectiveness assumed for warning (Webb, 2005)
5. Averages over large populations; arrows denote likelihood of substantial groups of people at higher/lower risk
6. Bars show range of values across age bands for men and women (Ministry of Health, 2008)

Figure 7 Comparison of New Zealand Risks and Existing Criteria.

There is no absolute scientific right or wrong about any particular risk tolerability threshold. If Christchurch City Council and the community have a strong wish to be precautionary about this hazard, the tolerability threshold might be reduced to perhaps 3×10^{-5} (a level as low as 10^{-5} is not recommended for the reasons given above). If on the other hand large numbers of fully informed householders wish to remain in properties at higher levels of risk and Christchurch City Council is prepared to let them do so (and if the regulatory framework permits), the tolerability threshold might be relaxed to 3×10^{-4} or even 10^{-3} annual individual fatality risk without major inconsistency with practices outside New Zealand and risks within it.

Policy options include adopting criteria relevant to:

a) Acceptable risk relating to future planning applications which might have the effect of increasing the population at risk (for which a risk level somewhat lower than the upper threshold of tolerability discussed above would be appropriate);

b) Intolerable long-term risk in the view of Christchurch City Council (based on the suggestions and considerations above), as a basis for provision of any incentives to relocate, but at a level where individual householder preferences to remain in their properties might still be accommodated at least on a temporary basis; and

c) An absolute upper limit of tolerability, above which near term evacuation/relocation would be compulsory regardless of householder preferences (set rather higher than the tolerability threshold discussed above – for example at annual individual fatality risk 10^{-3} per year if the long-term intolerability threshold were set at 10^{-4} per year).

It is noted that the level of risk adopted as a threshold of tolerability is not the only way in which Christchurch City Council might express a preference for risks to be evaluated in a more or less precautionary way. For example if the risk were uncertain by a factor of 10 in either direction and Christchurch City Council wished risk to be evaluated such that there was a very high degree of confidence of avoiding properties being left occupied at risk levels greater than X, then to secure that high confidence any assessed risk Y should be treated as though it could be 10x times higher than Y – that is, the criterion becomes $10Y < X$ rather than simply $Y < X$. If on the other hand Christchurch City Council wished there to be a very high degree of confidence that people were not being forced out of their properties without a very good reason, they might wish there to be a very high degree of confidence that risk indeed was greater than X. The criterion might then become $Y < 10X$.

Christchurch City Council thus needs to consider not only its criteria for tolerability of risk, but also how it wishes risk to be evaluated against those criteria. The approach to evaluating risk in the face of uncertainty in the assessed risk level should be decided based on Christchurch City Council’s view as to the balance of benefits for the community in acting with a greater or a lesser degree of precaution in the face of uncertainty.

5.4 Treating High Risk Levels

In this section, the case of risks deemed intolerable is considered first, followed by discussion of risks below the intolerability threshold but too high to be generally acceptable.

If a risk is intolerable then the normal solution would be either to reduce it, or to abandon the activity giving rise to it (in this case this would mean abandoning properties), or to negotiate some intermediate solution. The established and well accepted "four R's" approach to risk reduction in emergency management involves:

a) Reduction (prevention or mitigation of the events creating the risk);
b) Readiness;
c) Response; and
d) Recovery.

In the context of life risk, Recovery is not an option; once life is lost it is not recoverable. Readiness (in terms of reducing household members' vulnerability to slope instability-related hazards once they have struck the property) has limited potential in contrast with ground shaking hazards where simple precautions such as preventing heavy objects falling over or sheltering under a doorframe can have substantial benefits. Readiness in terms of preventing slope instability hazards reaching the property is considered below as part of "Reduction". Response likewise has limited scope post-event. So far as the authors are aware all those killed by slope instability-related events in the 2011 Canterbury earthquakes died quickly. The pattern of slope instability-related fatalities generally in New Zealand and overseas is that the scope for saving lives post-event is limited.

This leaves Reduction as the most viable general strategy. Three principal risk reduction strategies are possible:

a) Prevent the rockfall/debris from leaving the source; and/or
b) Reduce the likelihood that the rockfall/debris will lead to the fatality of a person at their property; and/or
c) Remove people from the risk.

Any such strategies will require their effectiveness and benefits to be evaluated in relation to their cost. Some time will be required to devise, evaluate and then implement relevant risk reduction strategies and it may be worthwhile applying some initial filtering process to ensure that properties for which risk reduction is unlikely to be feasible or cost-effective are not subject to the inevitable delays associated with these steps which apply to properties with greater potential for risk reduction. There are precedents in New Zealand for continuing to accept risks over a limited period of time in order to allow further treatment to be designed, funded and implemented, for example as was done by Wellington City Council during the 1970's (WCC, 2009).

As regards (a), the risk of both boulder fall and cliff collapse as assessed in our companion reports (Massey et al. 2012a,b) is dominated by relatively large seismic events involving peak ground accelerations in the range of 1-2 g. It is possible that actions to secure a slope against more minor and frequent rockfalls would simply lead to a greater accumulation of material being available for the more severe and rare events which dominate the risk assessment. Thus the benefits in risk reduction terms of securing material on the slope may be limited.

As regards (b), there has been much attention given to the possibility of installing rockfall fences or earth mounds or bunds to prevent rockfalls reaching properties. In the case of houses subject to the hazard of inundation below cliffs such solutions have little potential to be effective. In the case of boulders rolling down hillsides such solutions may be valuable, but will need to take into account possibilities such as boulders bouncing, or of multiple boulders following similar paths in a large event, which were revealed at some locations in the 2011 earthquakes.

With regard to both (a) and (b), prevention at source and barriers above properties require ongoing monitoring and maintenance, which may involve significant cost.

With regard to (c), the risk to life disappears if a property is permanently evacuated. "Keeping people away from the hazard" as opposed to "keeping the hazard away from the people" thus provides a highly effective risk reduction, and one which does not require ongoing monitoring and maintenance once the property has been removed. The obvious downsides are that people may need to be compensated to avoid facing heavy financial loss, and that some people may not wish to move.

If risk reduction by physical work does not prove feasible, the sole remaining option is removing people from the risk. The options here include:

a) immediate compulsory evacuation for all properties above a risk tolerability threshold; or

b) definition of multiple tolerability thresholds with different degrees of compulsion/persuasion for different levels of risk (e.g. a lower level of risk above which evacuation would be voluntary and a higher level of risk above which it would be compulsory); or

c) allowing flexibility as to when evacuation is to occur (e.g. allowing people to remain at their property if they wish to do so, in full knowledge of the risk, until a certain date or until they choose to sell the property).

Arrangement of type (b) or (c) have the advantage of allowing some degree of individual choice for householders, whilst ensuring that very high risk properties are evacuated quickly (b) or that properties where risks are intolerable are not passed on through the sales chain (c). Option (c) has the additional effect of spreading out over time the period within which householders are compensated financially for their properties.

As an example of option (b), if Christchurch City Council's own view was that annual individual fatality risk greater than 10^{-4} per year was intolerable, but that householders should be allowed some freedom of choice within a limited range above that level, it might be decided to make evacuation of the property voluntary at risk levels higher than 10^{-4} per year, but compulsory at risk levels higher than 10^{-3} per year. An example of option (c) is provided by the UK airport Public Safety Zones policy[9].

Turning now to risks which, though not intolerable, are not so low as to be generally acceptable, the key principle which should guide Christchurch City Council in addressing these risks is that they should be reduced as low as is reasonably practicable. Compulsory abandonment is not something that could be forced on people unless a risk were deemed intolerable, but a strategy which is applied in several land use planning contexts outside New Zealand is:

[9] Under the UK airport Public Safety Zones policy discussed in Section 3.1.3 above, the householder in an "intolerable risk" zone may stay in their home if they wish, but may sell only to the airport, who must make and hold open a fair offer for the property and, on purchasing it, must demolish it.

a) to prevent the accumulation of more people in areas at high but not intolerable risk; and
b) to take opportunities, as they present themselves, to shift the use of land in high risk areas towards recreational or other uses involving lower occupancy by people.

Christchurch City Council's policy should in GNS Science' view include such measures in relation to slope instability-related risk in the Port Hills, where there appear to be sites for properties which are at significant, if not intolerable, levels of slope instability-related risk. The levels at which such preventive measures are built into land use policy may be tailored according to the sensitivity of the land use in question. Given the substantial uncertainties in assessed risk levels and the potential for risk to reduce rapidly with distance from the hazard source, the risk levels used for such purposes should not be too closely spaced – separation by a factor of about 10 in risk would be consistent with practice elsewhere (e.g. HSE, 2011). Thus risk-based planning zones might be defined as

- intolerable (risk greater than X, say 10^{-4} annual individual fatality risk);
- not suitable for any development involving a high level of occupancy by people (risk greater than 10% of X, say 10^{-5} annual individual fatality risk); and
- not suitable for particularly sensitive developments such as schools, hospitals or care homes[10] (risk greater than 1% of Z, say 10^{-6} annual individual fatality risk).

6.0 CONCLUSIONS AND RECOMMENDATIONS

GNS Science conclude that risk criteria used in other contexts and information on New Zealand natural hazard and other risks can be used to inform the nature of the risk metrics and criteria that Christchurch City Council should adopt in relation to slope instability risk in the Port Hills, and to define the quantitative ranges within such criteria should be set in order to be consistent with practice elsewhere and with New Zealanders' apparent tolerance (or otherwise) for risk associated with other hazards.

GNS Science' recommendations are:

1. Christchurch City Council should establish risk criteria for determining the tolerability or otherwise of slope instability-related risk at properties in the Port Hills, based on societal acceptance of comparable levels of risk arising from other sources. Such criteria should be based around a defined sustainable upper limit of tolerability of annual individual fatality risk, representing the risk level above which Christchurch City Council does not consider it tolerable for there to be people at risk in their properties in the longer term.
2. The sustainable threshold of annual individual fatality risk should be set within a range from 3×10^{-5} to 10^{-3} per year to remain consistent with risk levels currently tolerated in New Zealand and with regulatory practice elsewhere. A suitable starting point for Christchurch City Council's deliberation as to where within this range to set their threshold would be a level of 10^{-4} (1/10,000 per year) annual individual fatality risk.
3. Christchurch City Council should consider ways to accommodate the preferences of current Port Hills householders who wish to remain in their properties despite assessed risk in excess of Christchurch City Council's sustainable upper threshold of tolerability, via options such as:

[10] The precise categories could be chosen to correspond to categories of building use already used in New Zealand planning

a) definition of a higher absolute limit (e.g. 10^{-3} annual individual fatality risk) up to which relocation would be at the discretion of householders but above which it would be compulsory; and/or

b) permitting householders to remain in their properties but preventing them from selling on to any party other than Christchurch City Council or another appropriate government agency when they moved or died.

4. Christchurch City Council should be appreciative of the sensitivity of the assessed risk levels to key uncertainties, and how much time has elapsed since the initiation of the Canterbury earthquake sequence. Christchurch City Council should require risk to be assessed based on a "best estimate" basis for the prevailing elevated seismic hazard conditions as the basis for evaluation against such risk criteria.
5. Christchurch City Council should adopt a lower threshold of annual individual fatality risk above which development is controlled to prevent accumulation of people in areas of substantial risk below the sustainable threshold of tolerability. Such a threshold could be set 10x below the tolerability threshold for general property uses involving significant occupancy by people, and 100x below the tolerability threshold for particularly sensitive property uses (e.g. schools, care homes, hospitals).

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APPENDIX A ESTIMATING RISK AT PORT HILLS PROPERTIES

The approach being used by GNS Science to estimate risk is explained below (A.1), followed by a parallel explanation of some of the key uncertainties involved in making such an estimation (A.2). Three distinct hazards are being evaluated by GNS Science:

a) Rockfall (boulder fall) down steep (but not vertical) slopes;

b) cliff collapse (affecting houses both at the top of and beneath the cliff); and

c) landslide (again affecting houses both on/above and those below the landslide).

Similar approaches are used in assessing the risk from each of the hazards. The approach and uncertainties are explained here for the rockfall hazard, for which the method is furthest developed and which is the dominant hazard for the majority of homes at significant risk levels.

A.1 Estimating Risk – The Approach

The risk assessment approach being used by GNS Science for people living in the Port Hills with respect to the hazard of boulders rolling down slopes and through their properties involves six important stages as follows:

1. Creating a set of hazard scenarios to represent the totality of all possible seismic and non-seismic scenarios that could generate significant rockfalls, and then estimating for each:
2. the appropriate frequency and number/nature of boulders produced,
3. the proportion of boulders that will travel a given distance downhill,
4. the probability that a person will be in the path of one or more boulders if present at their property ,
5. the probability that that person will be killed if in the path of one or more boulders, and
6. the probability that the person will be present at their property when the scenario occurs.

These are explained briefly in turn.

1. **Creating a Set of Hazard Scenarios**: A seismic hazard model is constructed using an earthquake source model and a mathematical relationship (called an attenuation relationship) that describes how earthquake shaking decreases with distance for a given magnitude of earthquake. The source model consists of a 10 km by 10 km background grid of earthquakes of a range of sizes. These earthquakes are given a certain likelihood of occurrence determined from historical rates of seismicity. The new GNS Science seismic hazard model for Christchurch also takes account of the current (decreasing) rate of aftershocks and the small chance that larger earthquakes may also be triggered. To complete the source model, future earthquakes on active faults in the region, including the Alpine Fault, are also added. Using the attenuation relationship, the likelihood of a given severity of earthquake shaking being exceeded (in terms of peak ground acceleration, Peak Ground Acceleration[11]) at the place of interest can be

[11] Peak Ground Acceleration is a measure of the "kick" the ground gives to anything in contact with it. It provides a better correlation with damage to buildings and structures than does the Richter scale or other earthquake magnitude scales which relate to the total energy released. It is usually expressed as a multiple of "g", the acceleration due to gravity.

calculated. For risk assessment purposes, the whole possible range of earthquake Peak Ground Acceleration in the Port Hills is divided into five bands of Peak Ground Acceleration as follows:

a) <0.1 g;

b) 0.1 to 0.4 g;

c) 0.4 to 1 g;

d) 1 to 2 g; and

e) More than 2 g.

Boulders are also produced by other natural phenomena – ageing and weathering by ice, rain, wind etc. So to represent the totality of risk of boulder falls onto properties or people we need also to consider the infinitely wide range of possible boulder generation scenarios involving other, non-seismic phenomena. A similar approach is used to divide up the infinite range of possibilities into a small set of broad bands of events (involving different numbers of boulders and different ranges of return periods).

2. **Estimating Scenario Frequency (F) and Number of Boulders Produced**: The next step is to estimate, for each representative boulder-generating scenario, a pair of values of the frequency with which that scenario will arise, and the number of boulders it will generate. The frequency is derived from seismic hazard models which tell us the frequency with which a given earthquake Peak Ground Acceleration will be exceeded – so the frequency of all events within a band of Peak Ground Acceleration from (say) 1 to 2 g is extracted from the model by taking the frequency of all events involving Peak Ground Acceleration greater than 1 g, and subtracting from this the frequency of all events with Peak Ground Acceleration greater than 2 g.

   The number of boulders generated is then estimated on a suburb-specific basis with reference to known events, usually towards the upper end of events spanned by the band within the scenario. Thus for earthquakes generating ground motions of 1-2 g and smaller there are good data for most Port Hills suburbs on numbers of boulders produced in the 22nd February and 13th June 2011 earthquakes (and the smaller aftershocks of the past year). A less precise estimate is made of the (larger) number of boulders that might be generated by an even larger earthquake through extrapolation. This does not unduly affect the overall uncertainties because once the numbers of boulders are so large that there is virtual certainty that a person or house will be in the path of one or more of them the risk cannot increase further as the number of boulders increases. The largest component of the risk in our current estimates is due to boulders triggered by accelerations in the range 1-2 g and this observation is robust to substantial changes in numbers of boulders generated by more severe events.

   For non-earthquake scenarios whatever evidence is available on old boulders present in individual suburbs and known not to have derived from earthquake events is pieced together with more recent information (typically this has only been collected for the past 10-15 years) on known boulder fall events. This provides reasonably reliable estimates for the past decade or two, but a good deal of estimation and extrapolation is involved in estimating how frequently we should expect non-seismic hazard scenarios producing larger numbers of boulders.

Another key issue here is the characteristics (shape and size) of boulders that are produced. The work of GNS Science and the Port Hills Geotechnical Group has focused on boulders of minimum longest dimension 0.5 m, and the risk assessment approach itself uses an average boulder diameter of 1 m as the basis for its calculations of both numbers of boulders generated, and of the effects of boulders falling down slopes.

3. **Estimating Boulder Travel Downhill**: Properties are not built on the cliffs and rock outcrops where boulders are generated, but are instead located further down the slopes typically on the sides or at the bottom of valleys. Larger boulders travel further than smaller ones, as is evident from the large size of many of the boulders which crashed through properties in the 22nd February and 13th June 2011 earthquakes in comparison with the very large numbers of smaller boulders deposited further up the slopes. For each suburb, the risk assessment examines the proportion of boulders that reach a given "shadow angle" (the angle down from the horizontal between the bottom of the source area and a given point on the hillside below it). Boulder travel is characterised on a suburb-specific basis in terms of the proportion of boulders generated that reach a given shadow angle. This information is derived from all the known rockfalls in the suburb, and is then assumed to apply to all boulder generation scenarios.

4. **Estimating the Likelihood a Person is in the Path of One or More Boulders (P1)**: At a given shadow angle, each scenario is characterised in terms of the number of boulders reaching up to or beyond that shadow angle. The chance that a person (if present at their property) will be in the path of any one boulder is then taken as the ratio of the width of the path swept out by a boulder (twice the boulder diameter plus the "diameter" of the person). The chance that a person will be in the path of one or more of the number of boulders reaching that shadow angle for each scenario is then worked out using simple statistics[12], assuming the boulders are all distributed randomly across the slope of the hillside.

5. **Estimating the Probability of Fatality if a Person is in the Path of One or More Boulders (P2)**: There are two aspects of this parameter: a) the possibility that a person will see or hear the boulder(s) coming and be able to get out of the way, so avoiding being struck; and b) the probability, if struck, that the person will be killed rather than being non-fatally injured. It is difficult in practice to see how people could be aware of and dodge boulders, and given the scale of the boulders involved the chance of death if struck is assumed to be quite high – so this probability is high with little possibility envisaged of it being reduced.

6. **Estimating the Probability that a Person is Present at Home (P3)**: This is simply assumed equal to the proportion of their time the person spends at their property. In practice this will vary widely, from almost 100% (e.g. for some very young and very elderly people) to a few % or less (e.g. holiday home owners). As is common practice in risk assessment for the purposes of planning advice and risk tolerability estimation, the GNS Science assumption (consistent with established practice in other regimes using individual fatality risk to define land use planning zones for dwellings – DfT, 2010; HSE, 2011) is that occupancy of the property is for 100% of the time, ensuring that the assessment is robust against any reasonable use that might be made of the property in future.

[12] i.e. if P_N is the probability of being in the path of one or more of N boulders, then $P_N = 1 - (1-P_1)^N$

The overall risk for each scenario is then taken as the product of F x P1 x P2 x P3, and the risk from all scenarios is added together to estimate the annual individual fatality risk due to boulder fall. The results (see the example in Figure A.1) are specific to each suburb (in some cases to particular hillsides within suburbs), but are generic in that they assume boulders are distributed randomly across the relevant hillsides, so do not take account of local features such as ridges and valleys that might tend to channel boulders in a particular direction, or of different boulder sources in different parts of the suburb.

Detailed local knowledge developed by the Port Hills Geotechnical Group consultants is being used to test the realism of the GNS Science risk estimates against the evidence available locally in order to decide whether there are strong grounds for treating individual properties differently from what would be implied by the assessed level of annual individual fatality risk there.

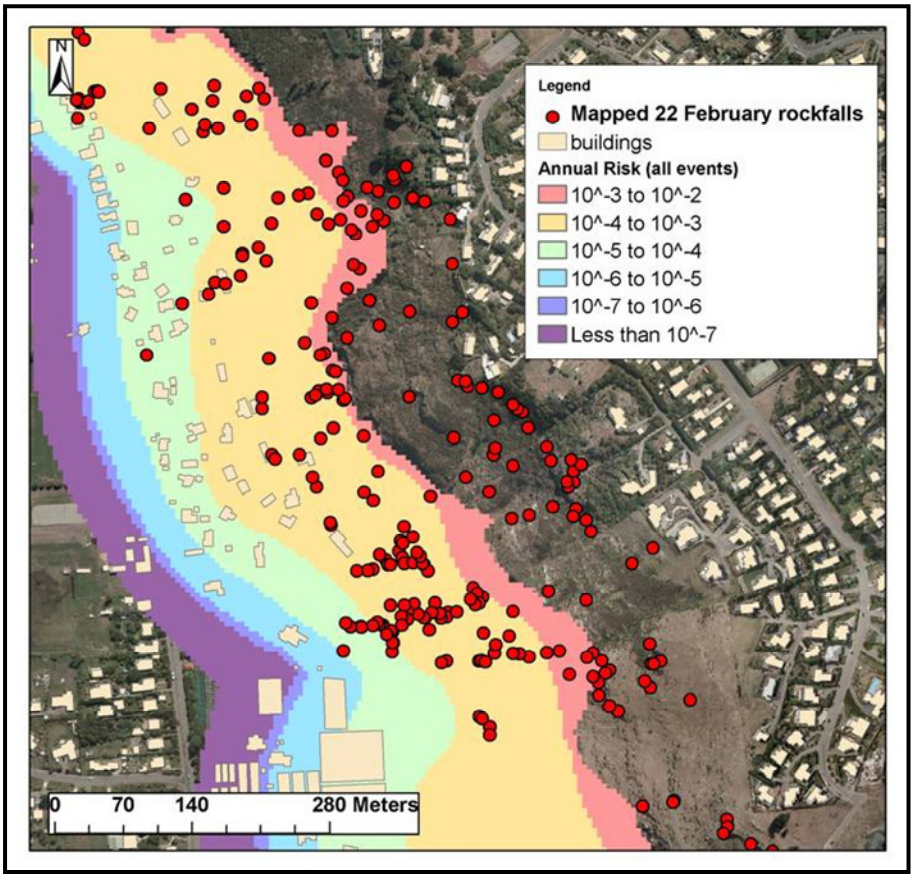

Figure A.1 Nature of GNS Science risk outputs – an illustrative example.

A.2 Important uncertainties

It will probably already be clear from reading Section A.1 that many assumptions need to be made in making the above estimates, and that there are significant uncertainties in the results so produced. This is the case with many risk assessments but need not compromise their value in supporting difficult decisions, so long as the provenance of the risk information resulting from the assessments is kept in mind when using that information. Some of the major uncertainties are identified below (using the same 6 headings as in section A.1 above).

1. **Scenarios**: There is a good deal of uncertainty inherent in calculating the likelihood of future ground shaking at a specific location. A large component of the uncertainty arises from the fact that the strength of ground shaking from earthquakes of a certain magnitude at a certain distance is highly variable (e.g. because of different local ground conditions). This variability is captured in the model so that both median and percentile estimates of ground shaking can be calculated. Other uncertainties are treated in a similar way. There is established precedent (e.g. in dam safety) for using a higher percentile (typically the 84th percentile) in the context of life safety issues than would be used for economic analysis (where the median would typically be used), in order to provide a greater degree of precaution when dealing with life as opposed to economic risk.

2. **Frequency/Number Of Boulders**: There are significant uncertainties in this area. In particular:

   a) As discussed above, the likelihood of an earthquake causing a given severity of ground shaking is increased substantially after a major earthquake, and it takes several years for the likelihood to fall away to the long-term average. The difference could be a factor of 7–8x for the most important earthquakes in the risk assessment, leading to a factor of 3–4x effect on the risk overall (including all earthquake and other rockfall triggers). So there is an important choice as to whether to use the estimated earthquake risk now, or that which will apply on average over a longer term (e.g. the 50-year design life often assumed for buildings).

   b) The likelihood of an earthquake of a given severity at a particular location is substantially uncertain, whichever time period is chosen for its prediction.

   c) There is much room for discussion as to the mechanism by which boulders are produced and whether "typical" events would generate more or fewer boulders than recent earthquakes. Does an earthquake shake out all the loose boulders and we then have to wait for years of weathering to get substantially more? Or does an earthquake itself generate an increased volume of shattered rock with a propensity to form boulders easily? The widely assumed view is that rock outcrops behave something like a conveyor belt so that an earthquake both shakes loose the boulders on the outside and generates the next "crop" of boulders by fragmenting the rock behind. But such assumptions (on which the risk assessment is based) could prove wrong either way. The GNS Science assessment incorporates a factor by which to scale up the boulder numbers estimated from recent events, to take into account (particularly in the near term) the highly fractured and broken state of many of the rock outcrops in the Port Hills as a result of recent seismic activity.

   d) The risk assessment makes some quite simple assumptions about the size distribution of boulders, which is in practice rather complex – though in the context of properties this may not be too important an issue as whatever smaller boulders are generated are substantially less likely to reach properties than are the larger boulders considered in the risk assessment.

3. **Estimating Boulder Travel Downhill**: Boulder travel is a highly random process. Fewer boulders reach the lower shadow angles where there are more houses, but the ones that do tend to be the larger boulders, and so are the most dangerous. While we can be confident these lower shadow angles are much lower risk than their higher shadow angle counterparts, the small numbers of boulders reaching them means that the low-shadow-angle "tail" of the distribution of boulders reaching far down the hill, and in particular the proportion that might travel further than those observed in 2011 earthquakes, is significantly uncertain.

4. **Estimating the Probability of Being in the Path of One or More Boulders**: The main uncertainty here is to do with the uneven distribution of boulders across the slope. For very large number of boulders events, the hillside can become "saturated" with boulders – that is, there are so many boulders reaching a given shadow angle that there is virtual certainty that anyone present would find themselves in the path of one or more boulders. This actually reduces the significance of one of the above components of uncertainty as to numbers of boulders produced in an exceptionally rare and severe earthquake. If there are so many that anyone present will be in the path of one, it does not make any difference to risk if there are 2 or 3 times as many again.

   There is a significant uncertainty as to what is the effective "path width" of a boulder in terms of its ability to harm people. Many of the properties that were struck by boulders reveal evidence of masonry, woodwork, furniture and other debris "missiles" having been scattered for some distance around a boulder. If a person is in their property when it is struck by a boulder it may be that it could seriously injure or kill them without having to come into contact with them – landing within a few metres might be sufficient.

5. **Estimating the Probability of being Killed if in the Path of Boulders**: The uncertainty here is perhaps less important than those in other parts of the assessment, as it is widely assumed that if someone finds themself in the path of a large boulder travelling at speed they are a) very unlikely to be able to get out of the way, and b) very likely to be killed if struck by it. The GNS Science assessment assumes a 70% probability of being killed if in the path of a boulder.

6. **Estimating the Probability a Person is Present**: The issue here is that this will vary widely from person to person. The question here is thus more "What should we choose to assume?" rather than "What is the uncertainty?" For example, if a property has an annual individual fatality risk predicted to be just above the intolerable threshold, would we be comfortable allowing the occupant to claim that, because they used it as a holiday property, their occupancy was only 10% of that assumed by GNS Science so the risk to them was actually tolerable? The answer in practice almost certainly has to be "no". In view of the longer term existence of houses and the difficulty of controlling their use any risk assessment relevant to the safety of properties should be predicated on people spending the majority, if not all, of their lives at home. In the GNS Science assessment, as in other regimes where risk assessment is used to guide planning and risk tolerability decisions around hazards, occupancy of 100% is assumed.

OVERALL UNCERTAINTY: To some extent, the uncertainties as to the consequences of postulated boulder generation scenarios can be bounded by comparing the predictions of the GNS Science risk assessment (e.g. as to number of properties that would be struck by boulders) with the actual observations from the 2011 earthquakes. But there will inevitably remain considerable uncertainties and choices to be made in the assessment, particularly for the issues in relation to frequency/ number of boulders under item 2 above.

The purpose of this Appendix has been to help the reader understand broadly how the risk assessment process works, and to give an appreciation of the very different provenance of risk information that results from it in comparison with, for example, identification of flood risk areas. Contour maps of risk show calculations in which each property has a value of risk associated with it. However, this does not mean that the information is as crisp and definite as that on a traditional contour map. Risk information, in this case as in many others, is subject to uncertainty.

Despite those uncertainties, the risk information is useful and suitable for use in decision making. It does mean that risk regulators need to take into account the provenance of the information when using it. There should not be too much significance attached to marginal differences in risk when/if there are other important statutory, social, economic, cultural or environmental factors that Christchurch City Council might also wish to take into account. If the risk is uncertain by a factor of 10 either way, then stretching the interpretation of risk tolerability criteria by a factor of 1.5 or 2 looks modest in comparison.

The importance of these uncertainties, and the social, environmental, economic and statutory nature of the decisions as to which assumptions should be used in the assessment, mean that the user of the information (the regulator) needs to have an appreciation of what goes into the assessment. The regulator and other stakeholders also need to have an appropriate say in the judgments made when estimating risk. The way in which risk assessment results are evaluated in relation to risk criteria is as important for the decisions that will flow from such evaluation as are the risk criteria themselves. In considering how to decide which risks are tolerable and which are not, Christchurch City Council will therefore need to consider both:

a) where to set its threshold(s) of intolerable or other actionable risk; and

b) how it wishes risk to be evaluated against such criteria.

In such areas GNS Science may be able to propose a reasonable starting point for Christchurch City Council's consideration, but it is up to Christchurch City Council to decide their policy.

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