Guidelines for Natural Hazard Risk Analysis on Public Conservation Lands and Waters

Part 3: Analysing landslide risk to point and linear sites

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EXECUTIVE SUMMARY

This report presents a guideline for a methodology for quantitative risk analysis (QRA) from landslide hazards at point sites (such as at huts and car parks) and linear sites (such as track and roads) within public conservation lands and waters (Department of Conservation [DOC]-managed land). There is increasing need to undertake risk analysis on public conservation lands and waters, due to increasing visitor numbers, and to understand natural hazard risks to visitor sites. This requires a consistent and standardised risk methodology across the various visitor sites on public conservation lands and waters. The risk analysis is required to be undertaken in order to: (1) identify and define ‘high risk’ areas, (2) help DOC manage the risk to visitors at ‘high risk’ locations and (3) inform visitors of the levels of risk from natural hazards they may be exposing themselves to when accessing these sites.

The methodology quantitatively assesses life-safety risk to visitors and workers on public conservation lands and waters by calculating, where requested by DOC, four risk metrics that include:

1. **Local personal risk (LPR)**, which represents the annual probability of death for a theoretical imaginary person present at a particular location for 100% of the time (24 hours a day and 365 days of the year).
2. **Risk per trip per day** for visitors, which is expressed in terms of the fatality risk experienced by an individual (probability of death) per day or per experience, if the walk takes several days, along a track and/or road within the given study area.
3. **Annual individual fatality risk (AIFR)**, which is expressed in terms of the fatality risk experienced by an individual (probability of death) over one full year of working in a given study area. The risk is calculated for: the worker(s) most exposed on public conservation lands and waters, which may include DOC staff, contractors, volunteers and concessionaires.
4. **Multiple fatality risk**, which is the relationship between the frequency of occurrence of a specified hazard and one or more people being killed if the hazard were to occur.

Additionally, the methodology assesses whether a hut or other similar significant infrastructure or asset can be impacted by a landslide hazard and, if so, what the potential mitigation options may be.

The methodology is based on the AGS (2007a–d) and JTC-1 guidelines (Fell et al. 2008b). It has been modified where appropriate to provide guidance specific to a New Zealand context and for analysing the risk from landslide hazards to point sites (e.g. huts and viewing areas) and linear sites (e.g. tracks and roads) present within the public conservation lands and waters.

The guideline outlines two levels of analysis: basic and advanced. The basic level of analysis represents an initial estimation of the landslide risk that workers or visitors are exposed to using simple and limited input datasets and data analysis. The advanced level of analysis involves greater time and resources dedicated toward data collection, input datasets, data analysis and peer review of the risk calculation process. Advanced-level analysis can be directed toward specific point sites, as well as sections along linear site studies where the additional cost is warranted to refine boundaries of risk zones and the estimates of risks and assist in the design of risk-reduction measures for those locations and high-risk point sites. The uncertainty associated with these estimated risk values may be reduced at an advanced level. The spatial scale at which the basic- or advanced-level risk analyses methods are undertaken will vary for the type of site, linear or point, and, in particular, the length of a linear

site. For example, risk analysis of a multi-day tramp along a linear route may require a more regional-scale analysis than that of a single-day tramp along a linear route. The guideline outlines for the various spatial scales, resolution and type of data inputs and subsequent data analysis required.

This guideline report provides an overview and technical guidance on how to carry out a QRA for landslide hazards within a given DOC study area. Practically, the QRA workflow involves:

1. Determining the different types of landslides that could occur within the study area; i.e. landslide susceptibility analysis.
2. Considering the full possible range of triggering events (e.g. earthquakes, rain) in terms of a set of earthquake, rainfall or background (i.e. no discernible trigger) events.
3. For basic analysis, choosing the maximum credible and most likely volumes for each type of trigger. For advanced analysis, choosing a small set of representative events for each type of trigger, spanning the range of severity of events from smallest to largest.
4. For each of the representative events and landslide types, estimating the:
    a. Annual probability of the landslide occurring ($P_{(L)}$).
    b. Probability of the landslide (e.g. debris from a landslide of a given type) reaching the element at risk (e.g. the person, track, road, hut) ($P_{(T:L)}$).
    c. Spatio-temporal probability that the person is in the path of the landslide when it reaches or passes the elements at risk ($P_{(S:T)}$).
    d. Vulnerability of the element at risk ($V_{(D:T)}$).
    e. Exposure of assets to landslide damage (1 = exposed, 0 = no exposure).
5. Combining 4(a)–(d) for all landslide types to estimate the risk per trip or AIFR for individuals at linear or point sites within public conservation lands and waters.
6. Summing the risk from all events to estimate the overall risk.

Various data inputs and analyses are required for the calculation of each of the steps. The guideline report therefore outlines the minimum data inputs, data analyses, reporting and peer-review requirements for both basic and advanced levels of QRA. This guideline report is accompanied by the Part 4 commentary report, which provides more detail and examples on the various data sources, analysis and reporting requirements, with appropriate references for further information. The intended users of the report are suitably qualified scientists, engineering geologists and geotechnical engineers with experience in carrying out landslide risk analyses.

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1.0 INTRODUCTION

1.1 Report Background

The number of people visiting public conservation lands and waters in New Zealand is increasing overall, with some locations being more in demand than others. Many of these visitors and visitor sites are exposed to natural hazards. For these reasons, there is an increasing need to carry out risk analyses to: (1) identify and define ‘high risk’ areas, (2) help the Department of Conservation (DOC) manage the risk to visitors at ‘high risk’ locations and (3) inform visitors of the levels of risk from natural hazards they may be exposing themselves to when accessing these sites.

Previously, there has been no standard risk analyses methodology or metrics implemented by DOC to allow them to consistently assess the risk from natural hazards across the different sites within public conservation lands and waters. Alongside this, no standard risk-tolerance criteria have been established. This has led to a wide variety of analyses methods, metrics and report styles used, thus making it difficult for DOC to consistently assess and use the results nationwide.

In 2008, GNS Science produced for DOC a geological site assessment process for huts and campgrounds (Hancox 2008). This used qualitative assessment and risk ratings for assessing the risk from landslides at points (individual hut sites). However, while this 2008 procedure is adequate for assessing hazards and risk in a qualitative way, it does not provide a consistent methodology for quantifying visitor risks at all sites. As such, DOC wish to ensure that the most suitable analyses methodology is applied to each situation, which in turn ensures that decision makers are given the right characterisation of risk to aid in making informed and consistent risk-management decisions across public conservation lands and waters.

The risk-analysis methodology used to quantify the life-safety risk to visitors and workers, as well as the risk of impacts to assets, on public conservation lands and waters from landslide hazards is based on the Australian Geomechanics Society (AGS) landslide risk-management guidelines developed in the 1990s and formalised in 2000 (AGS 2000). The inquiry into the fatal (18 fatalities) Thredbo (New South Wales, Australia) landslide in 1997 recommended the adoption of the AGS guidelines (2000) for regulators. These guidelines were subsequently updated in 2007 (AGS 2007–d). At the same time, and in conjunction with AGS, the Joint Technical Committee-1 (JTC-1) – comprising members from the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Society for Rock Mechanics (ISRM) and the International Association of Engineering Geologists (IAEG) – developed guidelines on landslide susceptibility, hazard and risk zoning for land-use planning (Fell et al. 2008a) to help establish ‘best practise’ landslide risk analysis and assessment methods. Subsequently, there have been numerous reviews of quantitative risk analysis and assessment (QRA) practises and associated methods for landslide hazards (Guzzetti et al. 2012; Kalsnes and Nadim 2013; Corominas et al. 2014, 2015), which includes reports and publications of the SafeLand[1] project.

This report is based on the AGS (2007a–d) and the JTC-1 guidelines (Fell et al. 2008b). It has been modified where appropriate to provide guidance specific to a New Zealand context and for analysing the risk from landslide hazards to point sites (e.g. huts and viewing areas) and linear sites (e.g. tracks and roads) present within the public conservation lands and waters.

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[1] https://www.ngi.no/eng/Projects/SafeLand/#Reports-and-publications

1.2 Purpose of the Report

The purpose of this report is to:

1. Provide technical guidance on how to carry out a QRA for landslide hazards within a given DOC study area, adopting basic- and advanced-level methodologies.
2. Outline the minimum data inputs, data analysis, reporting and peer-review requirements for both levels of QRA.
3. Provide technical guidance on the appropriate data sources and integration of these data sources within the QRA.

The intended users of the report are suitably qualified scientists, engineering geologists and geotechnical engineers with experience in carrying out landslide risk analyses.

1.3 Scope of Report

The report presents a guideline for a best-practise method for quantitively determining the risk from landslide hazards to individuals and groups of people (including people within vehicles) along linear sites and at point sites in public conservation lands and waters.

This method is primarily concerned with estimating risk to life. However, the methodology does examine whether a hut or other similar significant infrastructure or asset can be impacted by a landslide hazard.

The guideline firstly provides an overview of the landslide QRA process (Section 1.2) and then provides instructions on how to undertake the various steps of the landslide QRA process (Sections 3–10). This guideline report is accompanied by the Part 4 commentary report, which provides more detail and examples on the various data sources, analysis and reporting requirements, with appropriate references for further information.

The natural hazard risk-analysis framework is outlined in Part 1 (de Vilder et al. 2024) of this report series. The risk-analysis framework consists of a preliminary hazard and exposure screening tool (outlined in the Part 2 report [de Vilder and Massey 2024a]), the guideline (this report) and commentary (the Part 4 report [de Vilder and Massey 2024b]) to provide guidance on undertaking basic- and advanced-level risk analysis. The different levels of risk analysis are described below:

1.3.1 Preliminary Screening Tool

The purpose of the screening tool is to identify whether more analysis is needed at a site and, if needed, what the level (basic or advanced) of additional analysis should be. The Part 2 report sets out a flowchart that guides the user through the process, which ultimately ends with assigning the site a hazard and exposure class. The hazard and exposure class is a guide to what level of future analysis is required. It is intended that the hazards at each site are initially analysed using the screening tool. The results would then go to DOC to be reviewed by their panel of experts to confirm what the level of any future risk analysis might be.

The screening tool allows the user to identify: (1) the different types of landslide hazards that could affect the site; (2) the potential magnitude (how big they could be) and hazard footprint (area affected by the landslide) if it were to occur; and (3) the frequency of occurrence, which is how often it could occur. This includes identifying whether a site could be affected by slippage or falling debris hazards, which are terms mentioned in the Building Act (2004) and used in this report as follows:

1. **‘Slippage’** includes the movement or loss (including partial loss) of land from a slope when it occurs beneath, for example, a structure, path, road, car park, etc.
2. **‘Falling debris’** includes soil, rock, vegetation and snow or ice that may fall and ‘runout’ onto a site from upslope (the landslide source area), inundating the site.

The areas of slippage and failing debris are defined in order to determine the hazard footprint and therefore the number of people that may be exposed within the footprint(s) for the different hazard types. The hazard temporal probability (also known as the probability of occurrence) and exposure are then used to define the hazard class (Class 1–4) for a site, based on the hazard and exposure matrix. The purpose of the relative hazard and exposure matrix is to help DOC prioritise the sites in terms of future investigations and analysis and whether these should be (1) basic or (2) advanced, and what requirements/measures may be needed to manage the risk (see Table 1.1). The hazard and exposure matrix is broadly based on the risk-management framework contained in the original Risk Management Guidelines Companion to AS/NZS 4360:2004, now superseded by AS/NZS 31000:2009 (AS/NZS 2009).

Table 1.1 Risk-management actions and associated hazard and exposure class. DOC risk significance level and DOC evaluation category is based on a-risk appetite group.[2]

Class	DOC Evaluation Category	Risk-Management Actions
Class 1	Tolerable	No further risk analysis required. DOC should develop appropriate risk-management plans and re-evaluate these if there is a change in hazard activity or the number of people exposed.
Class 2	Tolerable if reduced as low as reasonably practicable (ALARP)	Basic level of risk analysis required. The analysis should highlight and identify the potential impacts to persons on the public conservation lands and waters. Identified high-risk sites may require further advanced-level risk analysis and consideration of mitigation options.
Class 3	Tolerable if reduced ALARP and Intolerable	Urgent action is required. This may involve interim risk-management solutions (e.g. closures) while solutions are developed. Basic-level risk analysis must be undertaken, and an advanced-level risk analysis may be required.
Class 4	Intolerable	Urgent action is required. This may involve interim risk-management solutions (e.g. closures) while solutions are developed. Basic-level risk analysis must be undertaken, and an advanced-level risk analysis may be required. Class 4 represents the highest priority for further risk analysis and risk-management actions.

1.3.2 Basic-Level Analysis

A basic level of analysis represents an initial quantitative estimation of the landslide risk that workers and visitors are exposed to using simple and limited input datasets and data analysis.

The steps in a basic risk analysis are:

1. Identify hazard types.
2. Estimate likelihood of hazards.
3. Estimate consequences if the hazard were to occur.
4. Derive appropriate risk metrics.

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[2] Risk-tolerance levels for Department of Conservation visitor sites. DOC-6399012.

The basic-level analysis is similar to the preliminary hazard and exposure analysis, as it assesses the risk posed by the maximum credible volume and most likely landslide volume. However, more time and resources should be dedicated to the hazard and risk analysis. For instance, this may involve more time spent in the field or more time spent collating a landslide inventory.

Due to the simplified level of analysis, the estimated risk from the basic analysis is inherently more uncertain, so the risk estimates may span several orders of magnitude. For example, the estimated annual individual fatality risk (AIFR) may be 10^{-4} (1 chance in 10,000 of being killed per year), but the uncertainty on the estimate may range between 10^{-3} and 10^{-5} (1 chance in 1000 to 1 in 100,000).

Such analysis may be site-specific, for example, at the location of a hut or bridge, but they could also be at the local and regional scale, for example, along an entire walking track, and could be used to determine areas along the track that may need a more advanced level of analysis.

1.3.3 Advanced-Level Analysis

An advanced level of analysis involves greater time and resources dedicated toward data collection, input datasets, data analysis and peer review of the risk calculation process. Advanced-level analysis can be directed toward specific locations and sections along linear site studies where the additional cost is warranted to refine boundaries of risk zones and the estimates of risks and assist in the design of risk-reduction measures for those locations and high-risk point sites. The uncertainty associated with these estimated risk values may be reduced. The DOC expert panel will determine which study areas with basic-level analysis require further advanced-level analysis.

Such analysis may be site-specific, for example, at the location of a hut or bridge, but they could also be at the local scale, for example, an advanced level of analysis may be carried out for a section of a walk that could be several kilometres in length, for example, Cape Kidnappers (Massey et al. 2020).

1.4 Department of Conservation Expert Panel

The purpose of this panel, as outlined in the Part 1 report, is to assess the risk-analysis reports, risk-evaluation and risk-mitigation activities occurring across the different sites of the public conservation lands and waters. Panel activities may include:

- Review of the results from the screening tool and corroboration or not of the level of analysis required at a site.
- Review of the results from the different levels of the natural hazard risk-analysis framework and provision of advice on any more analysis that might be needed.
- Provision of guidance on what risk-management procedures may be adopted at each site and of oversight to ensure such procedures are applied consistently across all of DOC.
- Provision of input for other considerations that need to be taken into account, such as management plans, heritage values, biodiversity values, natural features and other visitor values.

The expert panel may comprise:

- Relevant DOC staff (covering a wide range of the appropriate issues).
- DOC staff with knowledge of the site.
- An experienced engineering geologist or geotechnical engineer expert in quantitative risk analyses who has strong connections to other relevant experts and therefore can request their advice when needed.
- Specific technical expertise (for example, a geotechnical engineer, tsunami scientist, volcanic hazard specialist, etc.)

It is anticipated that the makeup of the panel may change with time / the nature of the analysis and hazards being analysed.

The panel may also consider further risk analysis and risk-management decisions from natural hazards not included within the initial preliminary or basic levels of the natural hazard risk-analysis framework. For example, tsunami generated by causes other than earthquake, such as volcanic eruptions or landslides, are not covered by the basic tsunami risk analysis. In this example, it may be particularly important to identify this hazard and potential risk if the landslide basic or advanced analysis identifies that a substantial volume of landslide debris could enter a ‘large’ body of water.

The panel should meet as and when needed. In some cases, DOC should have an established alternative process whereby, after the preliminary or basic level, the advanced level can be fast-tracked without waiting for the panel to convene.

1.5 Terminology

The terminology for describing risk used in this report is attached as Appendix 1. This is based on the terminology outlined in Corominas et al. (2015) and Fell et al. (2008b). The terminology for describing landslides is attached as Appendix 2. This is based on Cruden and Varnes (1996).

The terminology must be used by all consultants carrying out risk analyses for DOC.

2.0 METHOD OUTLINE OF LANDSLIDE QUANTITATIVE RISK ANALYSIS

2.1 Landslide Risk and Risk Management

Landslide hazard is defined as the probability of a landslide occurring within a defined time period and area. Landslide risk is defined as a measure of the probability of a landslide hazard occurring and severity of a consequence to life, health, property or the environment. Risk management is the systematic application of policies, procedures and practises to the tasks of identifying, analysing, assessing and mitigating risk. (Corominas et al. 2015). This guideline report is primarily concerned with estimating risk to life. However, the methodology does examine whether a hut or other similar significant infrastructure or asset can be impacted by a landslide hazard.

Figure 2.1 shows the framework for landslide risk management.

Risk management addresses the following questions (adapted from Ho et al. [2000]; Lee and Jones [2014]):

Assessment:

1. What can cause harm (Landslide Susceptibility and Characterisation)? (Section 2)
2. How often might this occur (Landslide Temporal Probability)? (Section 3)
3. What can go wrong, and how bad could it be (Consequence Analysis)? (Section 6)
4. What is the probability of loss (Risk Estimation)? (Section 7)
5. What does the risk value mean and are the risks tolerable (Risk Evaluation)?

Management:

6. What can be done, at what cost, to manage and reduce unacceptable levels of risk (Risk Mitigation)?
7. Was the mitigation successful; has the risk changed and/or does it need re-analysis and re-assessment?

This guideline report and the Part 4 commentary report only addresses items 1 to 4 above (landslide risk analysis). The consultant is expected to undertake the landslide risk analysis section of the method, with the risk estimation results from this feeding into the subsequent risk-evaluation and risk-mitigation stage. Risk evaluation and risk mitigation will be undertaken by the DOC staff, with input from the consultant.

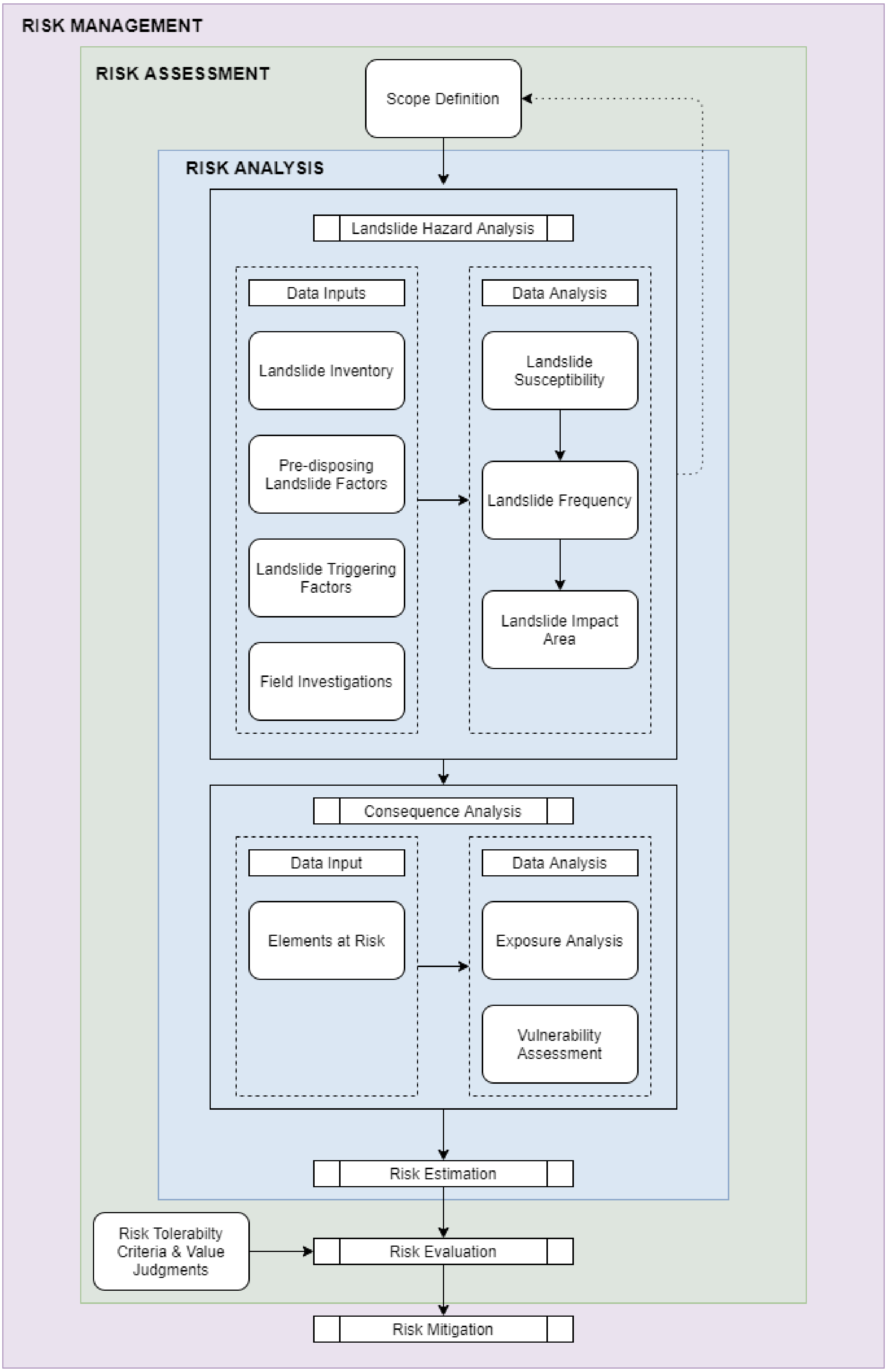

Figure 2.1 Landslide risk-management framework (adapted from AGS [2007c]; AS/NZS [2009]).

2.1.1 Landslide Quantitative Risk Analysis

Landslide hazard is defined as a landslide that has the potential for causing an undesirable outcome, with landslide hazard probability defined as the probability of a landslide occurring within a defined time period and area (Corominas et al. 2015). Landslide hazard analysis therefore involves:

1. Determining the various types of landslides that can occur (landslide hazard identification).
2. Where they might occur (i.e. source area).
3. How big they will be (i.e. magnitude).
4. How often they occur (i.e. frequency).
5. If they do occur, what the hazard footprint is (i.e. landslide runout assessment).

Steps 1 to 4 above determine frequency, or annual temporal probability, of the landslide event occurring. Steps 1 to 3 and Step 5 determine the probability that the landslide reaches the element at risk, for example, the track, road or hut. The type of landslide, its magnitude and source area and the terrain below will influence the travel distance of the landslide.

Landslide hazard analysis is undertaken through engineering geological and geomorphological field mapping; consideration of the topography of landslide source areas and the slopes below on which the elements at risk are sited; records of past landslides in the study area; and consideration of the potential rainfall, snowmelt, volcanic activity and seismic loading conditions. This is often assisted by using base datasets of landslide susceptibility, magnitude-frequency, source areas and runout analysis. These base datasets typically include:

- **engineering geological and geomorphological mapping**, which informs
- **landslide inventories**, which detail past landslide occurrence;
- **pre-disposing factors**, which may predispose a slope to landsliding; and
- **triggering factors**, which result in landslide occurrence.

Base datasets that are commonly or readily available are discussed in the Part 4 commentary.

The use of these base datasets assumes that landsliding will likely occur where it has occurred in the past, and landslides are likely to occur in similar geological, geomorphological and hydrological conditions as they have in the past (Varnes 1984).

2.1.1.1 Landslide Risk Analysis

The annual probability that a person may lose their life should be calculated from:

$$P_{(LOL)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(D:T)} \quad \text{Equation 2.1}$$

where:

$P_{(LOL)}$ is the annual probability that the person will be killed.

$P_{(L)}$ is the annual probability of the landslide occurring.

$P_{(T:L)}$ is the probability of the landslide (e.g. the debris from a landslide of a given type) reaching the element at risk (e.g. the track, road, hut).

$P_{(S:T)}$ is the spatio-temporal probability of the person at risk (the proportion of a year that the person is in the path of the landslide when it reaches or passes the element at risk).

$V_{(D:T)}$ is the vulnerability of the person to the landslide event (the probability that the person will be killed if impacted by the landslide). Here, it is recommended that the vulnerability should also include the potential for a person to be aware of the hazard and take evasive action.

There are several situations where the risks from a number of landslide hazards have to be summed to give the total risk. These include:

- Where the element at risk and persons are exposed to a number of types of landsliding, for example, boulder fall, debris flows and translational sliding.
- Where the landsliding may be triggered by more than one phenomenon, for example, rainfall, earthquake, human activity.
- Where the element at risk and persons are exposed to a number of different sizes of landslide of the same classification, for example, debris flows of 50 m^3, 5000 m^3 and 100,000 m^3 volume.
- Where the person is exposed to a number of slopes on which landsliding can occur, e.g. when in a vehicle driving along a road in which there are 20 cut slopes, each of which is a potential source of rockfalls.

In these cases, Equation 2.1 should be written as:

$$P_{(LOL)} = \sum_{i=1}^{n}(P_{i(L)} x Pi_{(T:L)}\, x Pi_{(S:T)} x Vi_{D:T}$$ Equation 2.2

where n is the number of landslide hazards.

This assumes that the hazards are independent of each other, which often may not be correct. If one or more of the hazards may result from the same causative event, for example, a single rain event or earthquake, then the probabilities should be estimated using the theory of uni-modal bounds as follows:

(i) The upper bound

From de Morgan's rule, the estimated upper bound conditional probability is

$$P_{UB} = 1 - (1 - P_1)(1 - P_2) \ldots\ldots(1 - P_n)$$ Equation 2.3

where:

P_{UB} is the estimated upper bound conditional probability, and

P_1 to P_n is the estimate of several individual hazard conditional probabilities.

This calculation should be done before applying the annual probability of the common causative event. If all the conditional probabilities P_1 to P_n are small (<0.01), Equation 2.3 yields the same value, within acceptable accuracy, as obtained by adding all the estimated conditional probabilities.

(ii) The lower bound

The lower bound estimate is the maximum individual conditional probability.

Hazard and Risk-Analysis Workflow

Practically, the hazard and risk-analysis workflow involves the following steps:

1. Determining the different types of landslides that could occur within the study area; i.e. landslide susceptibility analysis.
2. Considering the full possible range of triggering events (e.g. earthquakes, rain) in terms of a set of earthquake, rainfall or background (i.e. no discernible trigger) events.
3. For basic analysis, choosing the maximum credible and most likely volumes for each type of trigger. For advanced analysis, choosing a small set of representative events for each type of trigger spanning the range of severity of events from smallest to largest.
4. For each of the representative events and landslide types, estimating the:
    a. Annual probability of the landslide occurring ($P_{(L)}$).
    b. Probability of the landslide (e.g. debris from a landslide of a given type) reaching the element at risk (e.g. the person, track, road, hut) ($P_{(T:L)}$).
    c. Spatio-temporal probability that the person is in the path of the landslide when it reaches or passes the elements at risk ($P_{(S:T)}$).
    d. Vulnerability of the element at risk ($V_{(D:T)}$).
    e. Exposure of assets to landslide damage (1 = exposed, 0 = no exposure).
5. Combining 4(a)–(d) for all landslide types to estimate the risk per trip or annual individual fatality risk for individuals at linear or point sites within public conservation lands and waters.
6. Summing the risk from all events to estimate the overall risk.

Various data inputs and analyses are required for the calculation of each of the elements of the risk equation (Equation 2.1). These are discussed in the report.

2.1.2 Risk Analysis and Uncertainty

Uncertainty is an inherent component of risk analysis. Throughout the risk-analysis process for both basic and advanced levels of analysis, the consultant should assess which sources of input data are the least certain, or have gaps, for which there is lowest qualitative confidence in the quality and/or accuracy of the input data and data analysis. An advanced-level analysis may require further risk sensitivity analysis, which is covered in Section 8.6.

2.1.3 Risk Metrics

The natural hazard risk-analysis framework requires that the following risk metrics should be used for basic and advanced risk analysis of landslide hazards, plus advanced risk analysis for tsunami and volcanic hazards. The metrics should be used **where requested by DOC** for the appropriate analysis. These metrics are as follows:

1. **The local personal risk (LPR)**. This represents the annual probability of death for a theoretical imaginary person present at a particular location for 100% of the time (24 hours a day and 365 days of the year). It is a useful metric to visualise the spatial distribution of risk within a given study area and can be used to help plan or re-align tracks and roads.

2. **The annual individual fatality risk (AIFR)**. This is expressed in terms of the fatality risk experienced by an individual (probability of death) over one full year of working or visiting in a given study area. The risk is calculated for: (1) the worker(s) most exposed; and (2) the visitor most exposed, for example, a person who may do a walk several times a year. A worker is an inclusive term for any person undertaking work-related activity on public conservation lands and waters, which can include DOC staff, DOC volunteers, DOC contractors and concessionaires.
3. **Individual risk per day or per experience of up to one day for visitors**. This is expressed in terms of the fatality risk experienced by an individual (probability of death) per day or per experience, if the walk takes several days, along a track and/or road within the given study area.
4. **Multiple fatality risk**. This is the relationship between the frequency of occurrence of a specified hazard and one or more people being killed if that hazard were to occur (Lee and Jones 2014). At some sites, a large landslide, or several smaller landslides triggered by a single event such as an earthquake, could cause multiple fatalities. Multiple fatality risk is scenario-based. Two broad risk metrics are considered for multiple fatality risk, which include:
    a. **fN:** fN pairs or curves are calculated by linking some specific scenarios that relate the number of people who might be in a group with the likelihood of them being killed if a hazard of a given magnitude were to occur (N) and the frequency of the hazard occurring (f). For basic analysis, this is presented as a series of fN pairs. For advanced analysis, multiple fN pairs can be calculated and combined to create an FN curve that is then plotted on a diagram, where ‘F’ is the frequency of any/all scenarios with greater than or equal to N fatalities occurring.
    b. **Annual Probable Lives Lost (PLL):** The product of probability (f) and number of fatalities (N) yield probable life loss (PLL). PLL describes the expected number of deaths over a period of time. PPL from various independent risk scenarios (e.g. fN pairs) can be summed to yield the total PLL for an assessed landslide or study area. If probability is presented as an annual probability, then it is the annual probable life loss. The annual probability of life loss should be calculated for 1 fatality, 5 fatalities and the worst-case scenario.

The risk metrics used are generally relatively small in terms of the likelihood of a particular individual being killed per year. Thus, the risk-analysis reports will present the risk in terms of numbers such as 10^{-4} (‘10 to the power of minus 4’) per annum. Table 2.1 shows how some of these numbers translate into more familiar terms and may be useful to keep on hand for readers who are not familiar with ‘10 to the power of minus ...’ terminology.

Table 2.1 Translation of the ‘10 to the power of minus … per year’ terminology into other terms.

‘10 to the minus ... per year’	Is the same as … (per year)	Is approximately the same as once in …	Is the same as …
10^{-3}	0.001 or 0.1%	1000 years	8% per lifetime[3]
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

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

2.1.4 Risk Tolerability and Associated Risk-Management Actions

The natural hazard risk-analysis method provides risk estimates from the different geological hazards experienced across the public conservation lands and waters, from which DOC can assess and evaluate the tolerability of the risk and the potential risk-mitigation options (Figure 2.1). Risk evaluation and risk mitigation will be undertaken by the DOC staff, with input from the consultant.

In the context of risk evaluation, the estimated risk metrics from the landslide risk analysis, in particular, the advanced analysis, can be compared against other risks workers and visitors may experience, such as:

1. Fatalities on the public conservation lands and waters themselves.
2. Risks from natural hazards (in New Zealand in particular)
3. Workplace risk (in New Zealand)
4. General mortality and morbidity statistics (specific to New Zealand)
5. Popular tourist activities in New Zealand
6. Other sport and leisure activities (in New Zealand)
7. Travel to and from DOC sites
8. Fatalities in National Parks and the ‘great outdoors’, generally in other countries.

Taig (2022a, 2022b) outlines and establishes relevant risk comparators for DOC and provides advice on setting risk-tolerability criteria. The risk comparators are used to inform DOC’s decision-making around risk-tolerability. DOC has largely accepted the advice from Taig (2022a, 2022b) on risk-tolerability criteria on public conservation lands and waters and developed its risk-tolerability guidance (see Figure 2.2).

A consistent risk-tolerability criteria across public conservation lands and waters will improve the consistency and transparency of decisions both for DOC (on issues such as whether risk-mitigation measures are needed at a site and, if so, what would be the best approach) and for visitors to and users of the public conservation lands and waters (to help inform their own decisions about where they feel is safe for them to go and what they should do to keep themselves safe).

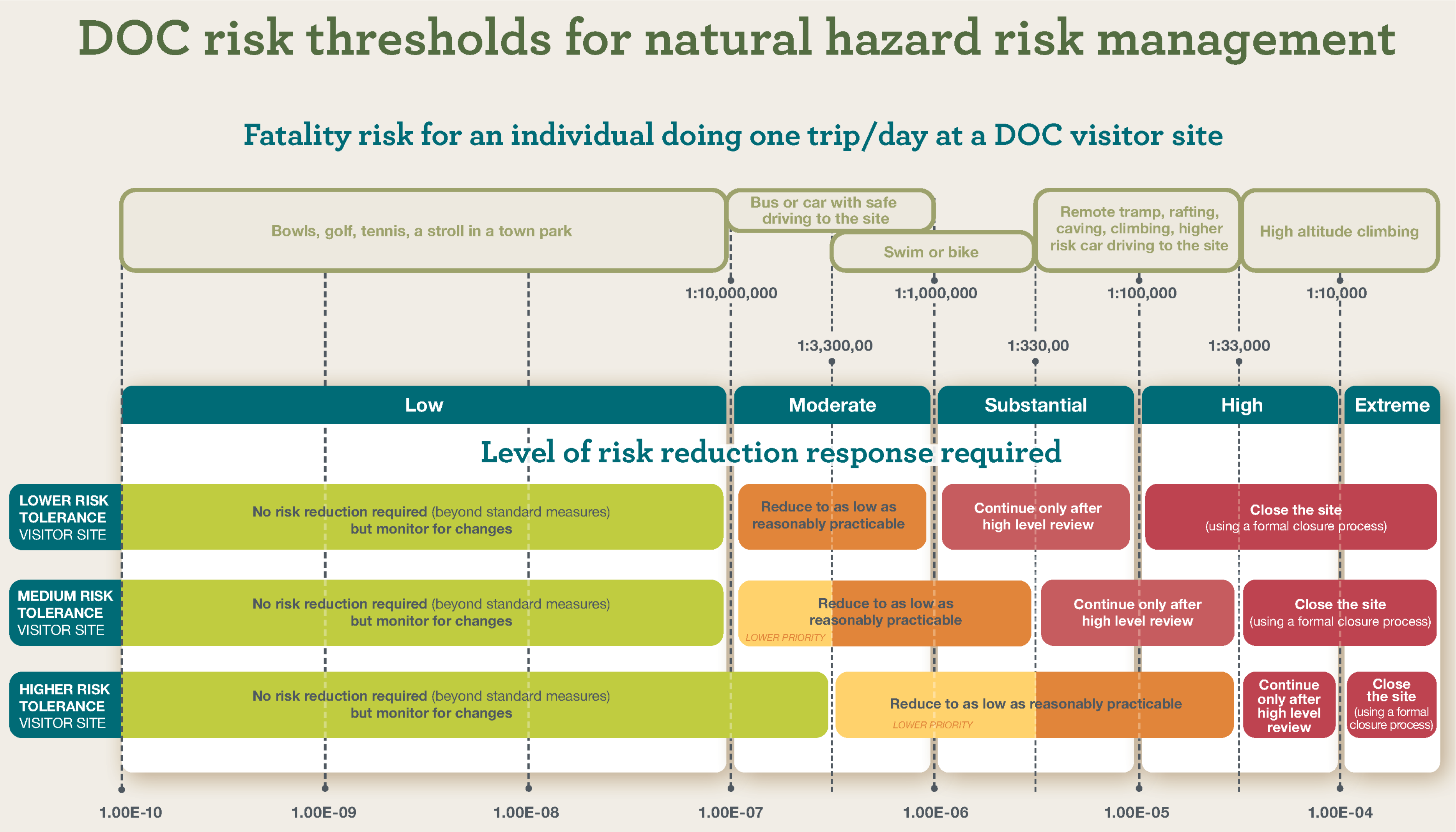

Figure 2.2 Risk thresholds for different user groups.

The guidance classifies visitor sites into three different risk-tolerance groups, as shown in Table 2.2.

Table 2.2 Natural hazard risk-tolerance levels for Department of Conservation (DOC) visitor sites.

Natural Hazard Risk-Tolerance Levels for DOC Visitor Sites There are three risk-tolerance levels for quantitative risk assessments.	
Risk Tolerance	**Type of DOC Visitor Site (Predominant Visitor Group)**
Lower Risk	• Short-stop traveller sites • Day-visitor sites that are promoted as short walks or day hikes • Overnighter sites
Medium Risk	• Day-visitor sites • Backcountry comfort-seeker sites, including great walks
Higher Risk	• Backcountry adventurer sites • Remoteness-seeker sites

For each visitor-site risk-tolerance group (Table 2.2), there are different risk thresholds for natural hazard risk management (Figure 2.2). Linked to these thresholds are DOC's risk-reduction response categories (see Figures 2.2 and 2.3) The DOC risk-reduction response categories are also associated with internal DOC risk-management actions (Figure 2.3). Appendix 3 outlines the respective roles of the consultant and DOC staff throughout the risk-analysis and risk-management process

Reduce to as low as reasonably practicable (ALARP) sits between risks that are 'de minimis', or insignificant (where no mitigating action would normally be taken), and an intolerable level above which the risk should be reduced or the activity giving rise to the risk stopped (see Figures 2.2 and 2.3). Risk in the 'reduce to ALARP' range is not an intolerable risk, but reasonably practicable risk-reduction methods can be considered within local resource constraints, stakeholder preferences and other factors to either lower the risk or stop it rising. Providing hazard and risk information to help visitors understand risk and manage it for themselves would, for example, be a reasonable risk-reduction method.

What do the risk reduction response categories from quantitative natural hazard risk assessments mean for DOC?

Descriptions of the four risk reduction response categories	
No risk reduction required (beyond standard measures) but monitor for changes	The level of risk from the assessed natural hazard is low. Apply DOC’s normal visitor asset management and visitor safety communication standards and practices to the site. Reassess the risk if the hazard changes. For hazards assessed to be at this risk level, monitoring can usually be simple and ad-hoc. In some cases, more formalised monitoring regimes will be required.
Reduce to as low as reasonably practicable	**Requires Operations Manager led social process to establish the mitigations needed.** The District’s Operations Manager runs a social process with key members of their local team (Senior Ranger, Supervisor, and experienced Rangers) to work through the mitigation requirements using DOC’s hazard management guideline for visitor sites on public conservation lands and waters (DOC-7462131). If you need support to run this session, email the Visitor Safety Team. Capital intensive and resource intensive mitigations are not recommended for hazards assessed to be at this risk level. Ensure that the mitigations employed are proportional to the risk, and the predominant visitor group **– avoid over-management**. Bespoke mitigations such as Trigger Action Response Plans (TARPs) are generally discouraged at this risk level. Reassess the risk if the hazard changes – a formalised monitoring regime may be required to identify changes.
Continue only after high level review	**Requires Director led social process required to establish risk acceptability and the mitigations needed.** The Region’s Operations Director runs a social process with key members of the district team (Operations Manager, Senior Ranger, Supervisor), Heritage and Visitors Unit staff (Senior Visitor Advisor and Senior Visitor Safety Advisor), and any other relevant subject matter experts, to work through whether the risk can be reduced to an acceptable level for the predominant visitor group and the mitigations required to do so. If mitigations cannot reduce the risk to an acceptable level for the predominant visitor group, closure may be required using the Closures SOP (DOC-7362830). Capital intensive mitigations such as moving a hut or rerouting a track may be appropriate. Eliminating the risk through site redesign is desirable. Investment to reduce risk is well justified at this risk level. Bespoke mitigations such as Trigger Action Response Plans (TARPs) may be required and can be justified. Reassess the risk if the hazard changes – a formalised monitoring regime may be required to identify changes.
Close the site (using a formal closure process)	Close the site using the **Closures SOP** (DOC-7362830). The Region’s Director runs a social process with representatives and subject matter experts from the across the business to decide the future of the site. The Senior Leadership Team will need to be briefed on these discussions and any decisions made. Unless the site can be redesigned to eliminate the risk (such as moving a hut or rerouting a track), divestment and permanent closure is very likely at this risk level.

Figure 2.3 The four Department of Conservation (DOC) risk-reduction response categories and associated internal DOC actions.

3.0 SPATIAL SCALE AND EXTENT OF ANALYSIS

The preliminary hazard and exposure analysis screening tool (see Part 2 report) should be used at all spatial scales in order to determine the level and scale of any future analysis. The spatial scale at which the basic- or advanced-level risk analyses methods are undertaken will vary for the type of site, linear or point, and, in particular, the length of a linear site. For example, risk analysis of a multi-day tramp along a linear route may require a more regional-scale analysis than that of a single-day tramp along a linear route. Table 3.1 outlines the different spatial scales for risk analysis. The resolution and type of data inputs, and subsequent data analysis, will also vary with spatial scale and the level of analysis required as determined by the screening tool process.

Table 3.1 Spatial scales of analysis for the linear and point sites (Corominas et al. 2014).

	Spatial Scale	Type of Site	Level of Analysis
National	>1:250,000	N/A for this work	N/A
Regional	1:25,000–1:250,000	Linear	Screening and Basic
Local	1:5000–1:25,000	Linear or Point	Screening, Basic or Advanced
Site-Specific	<1:5000	Point	

3.1 Setting the Study Area Boundary

The initial study area boundary will be set by DOC when they initially scope the work and will depend on whether the site is a point or linear site, or a series of points along a linear site. This boundary will be approximate and need to be refined. This should be done at several stages and refined as/when needed. The preliminary screening tool should identify the study area boundaries based on the extent of the identified hazard footprints and the site being assessed.

It should be noted that there may be multiple hazard zones within the study area boundary, within which there may be several hazard footprints. A **Hazard Zone** is defined as: an area of ground within which the topography/morphology, geology, geomorphology and landslide hazard types are similar. This differs from a **Hazard Footprint**, which is defined as: the area of ground that could be affected by a particular type of hazard that could occur within a hazard zone. Therefore, a study area may contain multiple hazard zones, within which there may be multiple hazard footprints. For example, where a site may be exposed to both rockfall and debris flow hazards, or even non-landslide hazards such as tsunami or volcano hazards, each with their own hazard zone and hazard footprint.

The screening tool can be used to identify hazard zones and footprints within a larger study area boundary, the level of analysis required for the site(s) within them and the scale of analysis, from regional to site-specific. The study area boundaries can be re-defined during the basic- and advanced-level analysis to ensure that all landslide hazards that can credibly impact the site (i.e. their hazard footprint) are included within the study area.

4.0 DATA COMPILATION / DESKTOP STUDY

Section 4 through to Section 7 present the tasks that should be considered for a basic-level analysis and indicates the additional requirements for an advanced-level analysis where appropriate.

The consultant should be made aware that not all of the tasks described will necessarily be required for a particular site analysis, due to the lack of input data and associated constraints on data analysis. The exact scope of the analysis should be agreed with DOC prior to commencing work, recognising that as the study progresses it may identify different needs. Any changes in scope must be agreed with DOC and confirmed in writing.

4.1 Data Sources

Relevant base data and their sources, as outlined in Table 4.1, should be compiled and recorded. All existing information within the study area boundaries and at the appropriate spatial scale for the site (Table 3.1), including geology, geomorphology, aerial photographs, topographic data, results from previous investigations, rainfall and earthquake records, etc., should be reviewed. This information is used to compile the base datasets of the landslide inventory, pre-disposing factors and triggering factors, which feed into the landslide susceptibility, frequency and impact area (runout) analysis. This should be done using the study area boundary.

Table 4.1 Sources of the different datasets and their use.

Source	**Dataset**	**Use**	**Access**
LINZ (Land and Information New Zealand)	Highest resolution Digital Elevation Model (DEM) for the area (in most cases, this will be the national 8 m DEM)	Landslide Inventory Pre-Disposing Factors	https://data.linz.govt.nz/ NZTA, Regional and District Councils, DOC
	Any available current and historic imagery, such as the Retrolens database		https://data.linz.govt.nz/ http://retrolens.nz/
GNS Science	*Geological Map of New Zealand* (QMAP)	Pre-Disposing Factors	http://data.gns.cri.nz/geology/
	Probabilistic estimates of the strength of earthquake shaking from the *National Seismic Hazard Model* (NSHM)	Triggering Factors	https://hazard.openquake.org/gem/models/NZL/
	Already mapped landslides, located in the *New Zealand Landslide Database*	Landslide Inventory	http://data.gns.cri.nz/landslides/wms.html
	Active Fault Database	Pre-Disposing Factors	http://data.gns.cri.nz/af/
NIWA (National Institute of Water & Atmospheric Research)	Weather records from the *National Climate Database* (CliFlo)	Triggering Factors	https://cliflo.niwa.co.nz/
	Probabilistic estimates of the magnitude and frequency of (future) high intensity rainfall from the *High Intensity Rainfall Design System* (HIRDS), including climate-change scenarios of RCP 4.5 and 8.5		https://hirds.niwa.co.nz/
Regional / District Councils	Rainfall data	Triggering Factors	Regional and District Council contacts or websites
	Flood data		
	Historical landslide records	Landslide Inventory	
DOC	Traffic counts (both track counters and road counters)	Elements at Risk	Local DOC office or Visitor Safety Team (as specified in the contract)
	Staff exposure estimates		
	Geographic Information System (GIS) shapefiles of assets		
	Visitor user groups and where visitors congregate at/along DOC sites		
Other	Previous studies and reports, including journal papers and previous consultancy reports	Landslide Inventory Pre-Disposing Factors Triggering Factors Elements at Risk	-
	Local knowledge (interviews)		-
	Historic records		e.g. https://paperspast.natlib.govt.nz/

4.1.1 Pre-Disposing Factors

Information should be compiled on the factors that affect landslide susceptibility and hazard within the study area, as outlined in Table 4.2. This is undertaken by reviewing existing maps, reports and studies and analysing remote sensing datasets. See the Part 4 commentary report for more details on the various pre-disposing factors to be considered and associated potential errors in the data collection and analysis.

Table 4.2 Actions required to determine pre-disposing factors for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Collate information on geology, geological structures, soil, land use, hydrology and geomorphology from relevant maps, reports and studies (see Table 4.1) using the study area boundary as the reference for the information. • Document resolution of input data. • Document the information missing that may be of importance for landslide susceptibility and hazard analysis.	Same as for basic-level analysis, plus: • Transform information from reports and studies into an appropriate format within a GIS system.
Point		

4.2 Topographic Analysis

Topographic analysis should be undertaken as outlined in Table 4.3. The commentary provides more details on topographic analysis but, ideally, the higher the resolution of the topographic models the better, with the appropriate resolution adjusted for the different landslide types.

Table 4.3 Actions required to undertake topographic analysis for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Undertake topographic analysis (e.g. derive slope angle, aspect, curvature) using the national 8 m DEM model or higher-resolution topographic model, if available, at the appropriate scale for the site. The scale of the topographic analysis must be consistent with the study area and associated spatial scale of analysis and should be determined during the screening tool process and/or agreed with DOC when the scope of the study is confirmed.	• Obtain a higher-resolution topographic model of the study area and undertake detailed topographic analysis.* • For rockfalls or larger individual landslides, prepare digital surface models (DSMs) or digital elevation models (DEMs) and use hill shades developed from these to create maps of the source area(s) and the slopes between the source(s) and the elements at risk. This should be done using existing data or, where these are not available, from LiDAR or UAV surveys and structure-from-motion methods.
Point		

* An advanced-level risk analysis cannot be undertaken using the national 8 m DEM.

4.2.1 Engineering Geomorphological and Engineering Geological Mapping

The different types of landslide hazards affecting a site from within the study area should be identified and mapped. The purpose of the engineering geomorphological and engineering geological map is to:

- Provide information on the near-surface materials forming the landscape.
- Provide basic information on the surface geomorphic processes that may have formed the materials present at or near the surface.
- Locate areas of anthropogenically modified ground, comprising cut slopes and fill bodies.
- Use as an input for landslide and rockfall runout simulations.

Table 4.4 outlines the requirements for basic and advanced levels of risk analysis. *An essential component of this is field mapping to confirm and refine the geomorphological maps.* The Part 4 commentary report contains information on the methodology, terminology and suggested symbology to prepare an engineering geomorphological map.

Table 4.4 Actions required to undertake engineering geomorphological and engineering geological mapping for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• For *shallow rapid landslides*, prepare an engineering geomorphological map of the study area, including characterising dominant structural features, soil deposits, rock outcrops, basic hydrological information (e.g. stream and channel networks) and major breaks in slope. • Additionally, for *rockfalls* and *larger individual failures*, map geomorphic indicators of instability, such as cracks or partially detached blocks. • *For rockfalls*, map historic rockfall scars, as well as fallen blocks and talus deposits.	Same as for basic-level analysis, plus: • For *rockfalls* and *larger individual failures*, undertake detailed mapping of geological structure (i.e. with TLS or drone surveys), and geomorphic indicators of instability.
Point		

4.3 Landslide Inventory

The landslide inventory is an important component of many risk analyses as it informs magnitude-frequency, susceptibility and impact-area analysis. It is important that this activity of producing an inventory, through a compilation of existing data and/or mapping of new landslide data, is done thoroughly. Table 4.5 details the actions required to compile a landslide inventory for basic and advanced levels of risk analysis. For rockfalls and landslides from cuts and fills, the data will usually need to cover 10, 20 or more years so that several significant triggering events can be sampled in the inventory if it is to be used as the basis for landslide temporal probability assessment, as these more ‘recent’ engineered slopes may not have developed sufficient evidence (e.g. deposits of failure), unlike natural slopes.

In volcanic areas, previous records and observations of lahars and/or sector collapses should be identified. Sector collapses, the large-scale collapse of the top or flank of a volcano that produces a debris avalanche, can also occur. Geologic studies indicate 14 sector collapses at Taranaki in the past ~130,000 years (Zernack et al. 2009, 2012) and six sector collapses at Ruapehu (Tost et al. 2014; Conway et al. 2016). A lahar is defined as a flow of water-saturated, typically dense, volcanic material that resembles a flow of wet concrete, which can also be referred to as a debris flow. Lahars can occur at all volcanoes in New Zealand but are more likely at cone volcanoes and/or volcanoes with a crater lake. The formation of lahars requires a water source (e.g. crater lake, glacier or snow, precipitation).

In many cases, it will not be possible to create a large inventory from past records. Inventories can be improved over time if those responsible establish a system for gathering data that can then be incorporated in later risk analyses.

The minimum landslide area that can be mapped in practise and included in the landslide inventory for natural slopes should be noted and is likely to be in the order of 100 m². More detail on the creation, and associated limitations, of a landslide inventory are in the Part 4 commentary report.

Table 4.5 Actions required to compile and create a landslide inventory for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Prepare an inventory of landslides (including rockfalls) in the study area from aerial photographs and/or satellite imagery and from historic records. The inventory includes the location, classification, volume (or area) and, so far as is practicable, the date of occurrence of landsliding. • For *rockfalls,* boulder fields/talus can be used to define aerial extents, or a rockfall limit line can be used to show the downslope limit of mapped rockfall boulders. An estimate of the mean and largest rockfall boulder sizes and their shape are also needed.	Same as for basic-level analysis, plus: • Distinguish different parts of the landslides and map landslide features and boundaries. • Increase time and resources for data collection and desktop review and mapping, which will result in more rigorous coverage. • If possible, use advanced temporal cataloguing of periodic reactivations of the same hazard and temporal windowing of the specific triggering events to provide period inventory datasets, which can then be used in advanced validation approaches. This inventory should be presented in the form of a GIS landslide inventory map.
Point		Same as for linear advanced-level analysis, plus: • The study area boundaries may be slightly expanded to include more landslides within the immediate vicinity of the study area. This slightly enlarged area for mapping a landslide does not need to be any greater than double the size of the study area boundaries, as defined by the hazard zones and hazard footprints.

4.4 Triggering Factors

Information should be compiled on the factors that trigger landslides within the study area, as outlined in Table 4.6. Triggering factors need to be understood in order to develop risk-management strategies. Rainfall events can be planned for from forecasts, while earthquake events and landslides with no discernible trigger can only be responded to.

Table 4.6 Actions required to determine triggering factors for basic and advanced levels of analysis.

Site Type	Level of Analysis	
	Basic	**Advanced**
Linear	• Compile information on potential past triggering events from previous studies, reports, newspaper articles (print and online) and records (e.g. NIWA CliFlo database), including analysis of landsliding caused by historical earthquakes or associated with volcanic activity. The impact of climate change on triggering-event frequency and magnitude should be noted.	Same as for basic-level analysis plus: • More detailed analysis of past rainfall and earthquake events and future rainfall and earthquake predictions, including climate-change scenarios RCP 4.5 and RCP 8.5.
Point		

4.4.1 Rainfall

At the preliminary screening tool and basic levels of analysis, it is unlikely that landslide occurrence and severity (numbers of landslides produced and their volumes) will be able to be linked to the rain amount and duration that triggered them. Therefore, the number and size of landslides that could be triggered at a site by rain events will need to be estimated from historical records. This may be as simple as mapping the landslide distribution and their size (adopting volume classes) and estimating the period over which they are thought to have occurred. For advanced levels of analysis, it may be possible to link specific landslides to the rain event(s) that triggered them for various amounts and durations of rain.

These data should be recorded as the number of slides per unit area, or the percentage of the total of slopes that fail, so that the information can be used to estimate frequency of sliding for individual slopes.

In many cases, the landslide distributions identified at a site will be related to these past rain events – especially if the site has not been affected by strong ground shaking or human modification in the same period – and, in non-alpine and non-coastal sites, less affected by instability related to climate-warming or changes in wave environment. For example, the mapped landslides for a site may represent those that have occurred over, for example, a hundred-year period or more. However, allowance should be made for the likelihood that smaller slides will become less evident as vegetation re-grows, so are under-counted in the inventory.

For basic and advanced levels of analysis, it is therefore important to understand the amount and duration of rain that may have occurred at a site over this period and how representative the mapped landslides are with regards to what rain might occur in the future. The NIWA HIRDS model can be used to give an indication of the rainfall amount and duration to be expected at a given site for different annual return intervals (ARIs) based on past records for the site and region. An example of the 24-hour rain heights for the ARI of 0.01 (approximately equivalent to a 100-year return period) is shown for New Zealand in Figure 4.1.

4.4.1.1 Rainfall-Triggering Thresholds

The amount of rain needed to trigger a landslide is also important to understand. Linking landslide occurrence to rain amount and duration is complex and often not achievable. Rainfall-triggering thresholds for triggering shallow landslides in natural slopes resulting in debris flows have been collated for regions in New Zealand (e.g. Glade 1997, 1998). Information from global datasets is outlined in Guzzetti et al. (2008). Rosser et al. (in prep.) compiled a national database of landslides in New Zealand and recorded the daily (24-hour) rainfall for each landslide event to establish the magnitude and frequency of landslide-triggering storm events for different physiographic regions across the country. The frequencies of landslide-triggering rainfall thresholds are shown in Table 4.7.

It should be recognised that these data do not mean that, if the rain amount occurs, all slopes in the study area will fail. The rainfall depths represent the 2% triggering theshold for landslides, based on the method given in Guzzetti et al. (2008), where 2% of the population of known rainfall-induced landslides have occurred at or above the given rainfall intensity/duration. At larger rainfall amounts and intensities (larger than those given in Table 4.7), the number and size of landslides triggered will increase.

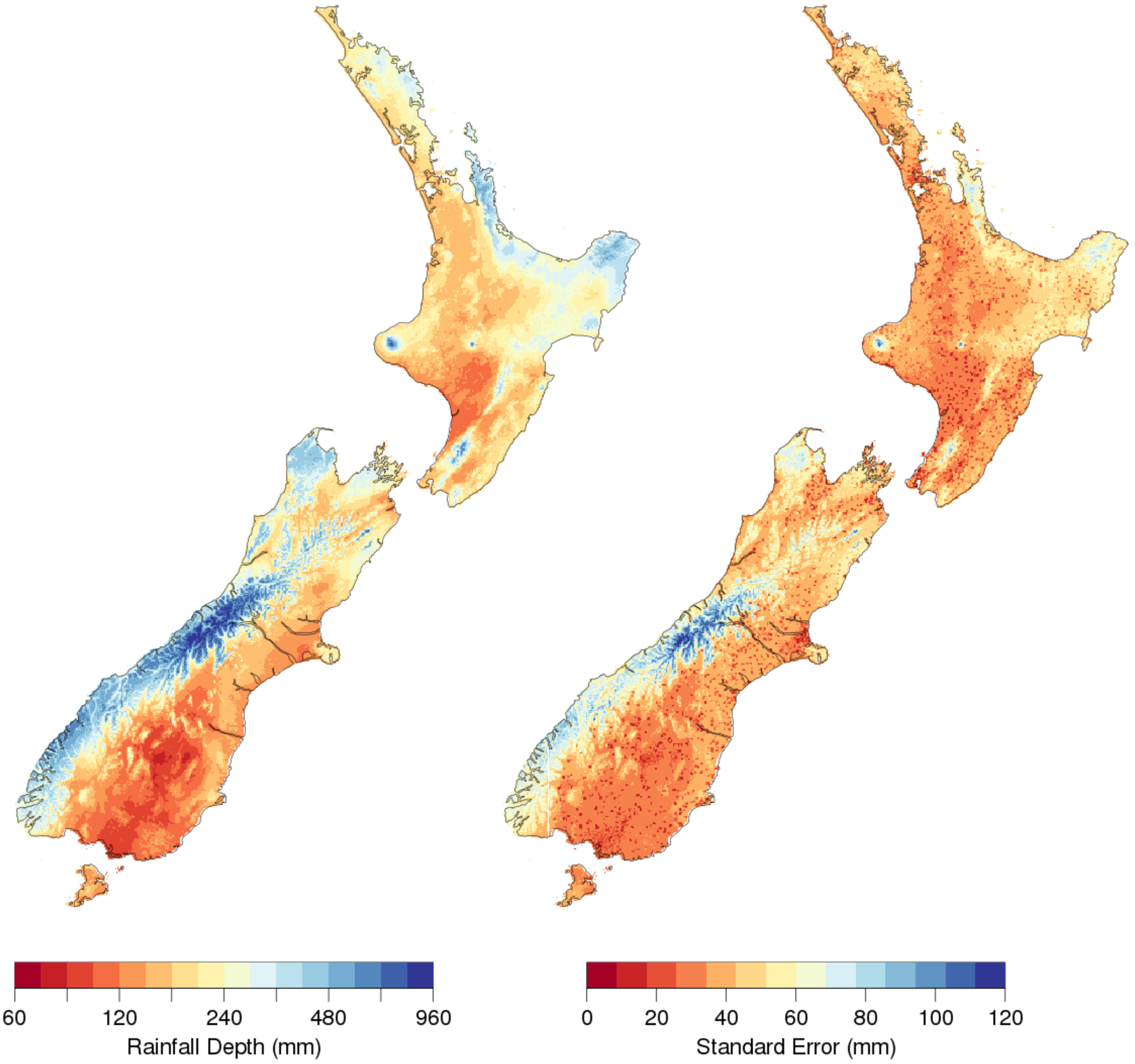

Figure 4.1 HIRDS rainfall forecast for New Zealand. The maps show the 24-hour rain heights and associated standard errors for an annual return interval of 0.01 (courtesy of NIWA).

Table 4.7 Landslide-triggering thresholds for rainfall-induced shallow landslides on natural slopes (after Rosser et al. [in prep.]). This dataset presented below is currently under review and will be published later in 2024. Note: these thresholds represent the triggering of either one or more landslides by the given rain amount.

Region	Mean 24-Hour Rainfall Depths for Triggering a Landslide (mm) Based on 2% Triggering Thresholds	Average Intensity (mm/hr)
Northland	110	5
Auckland	94	4
Waikato	94	4
Coromandel	290	12
Bay of Plenty	201	8
East Cape	166	7
Gisborne	94	4
Hawke’s Bay	132	6
Taranaki	94	4
Manawatū-Wanganui	130	5
Wairarapa	113	5
Wellington	76	3
Marlborough	148	6
Nelson/Tasman	166	7
Canterbury	96	4
Westland	100	4
Otago	73	3
Southland	60	3
Fiordland	326	14

4.4.2 Climate Change

Climatic changes and landsliding are intricately linked (e.g. Gariano and Guzzetti 2016; Crozier 2010; Jakob 2022). How landslide activity changes in response to climate change is not only dependent on climatic changes but also landslide type and geological and topographic setting. Despite complexities in the relationship between climate change and slope response, it is important to identify whether landsliding is likely to increase or change in the future.

For rainfall-induced landslides, it is important to understand the amount and duration of rain that may occur under different climate-change scenarios and how representative the mapped landslides are with regard to what rain might occur in the future. The NIWA HIRDS model can be used to give an indication of the rainfall amount and duration to be expected at a given site for different annual return intervals (ARIs) for different climate-change scenarios. This includes the RCP 4.5 and RCP 8.5 scenarios (see NIWA[4] for more information on the RCP scenarios), that DOC would specifically like assessed.

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[4] https://niwa.co.nz/climate-and-weather/climate-change-scenarios-new-zealand

For other landslide-trigger types, such as in coastal and alpine environments, it is important to understand how climatic changes may impact the rates and sizes of landslide events. Evaluation of historical changes in relevant environmental variables (e.g. temperature, wave height) in relation to landslide activity may provide an indication of how climatic changes may influence the rates and sizes of landslide events.

The potential impact of climate change on landslide hazard should be noted as a source of uncertainty in a basic-level analysis, while, for an advanced level of analysis, the impact should be quantified if possible.

4.4.3 Earthquakes

For earthquakes, it is important to determine whether earthquake-induced landslides are likely to affect the study area. As part of a basic-level risk analysis, this can be evaluated by using a Peak Ground Acceleration (PGA) hazard map of New Zealand (example in Figure 4.2) and the relationship between PGA and earthquake-induced landslide (EIL) (Table 4.8 and Figure 4.3). The representative PGA for the given study site can then be compared to the landslide and environmental criteria outlined in the commentary to identify the type and magnitude of the landslide impacts a site may potentially experience at the given levels of shaking. More example PGA hazard maps of New Zealand for different return periods are provided in the commentary and are available as kml files.

As part of an advanced-level risk analysis, the National Seismic Hazard Model (NSHM) may be used to generate a Peak Ground Acceleration Hazard curve. These can be generated for a given site in New Zealand from the NSHM. The process is set out NZS 1170.5:2004, ‘Structural Design Actions – Part 5: Earthquake Design Actions – New Zealand’. They give the annual exceedance probability of a given PGA occurring, which takes into account the influence of the various seismic sources that could affect the given site**.** PGA bands (from low to high) can be established, like those given in Table 4.8, which can be used to estimate the number and volume of landslides occurring within each PGA band. The PGA hazard curve can be used to give the annual exceedance probability of the representative PGA for each band, which can then be used in the risk analysis.

It should be noted that: (1) PGA may not be the best seismic parameter to use to assess the stability of a slope, as it typically represents higher frequency shaking. For example, initiation/ re-activation of larger landslides may require longer-duration shaking at lower frequencies; and (2) the PGA values given in Figure 4.2, represent ‘free field’ rock outcrop PGAs and thus do not account for local site effects, which could amplify or de-amplify the amount of shaking.

Earthquake ground motions of different amplitudes and duration can affect a slope in different ways depending on the frequency content of the earthquake, which is strongly influenced by earthquake magnitude and source-to-site distance, the shape and height of the slope and the nature of the materials forming the slope. Therefore, the amount of amplification and resultant permanent slope displacement and size of landslide initiated are likely to be larger when excited by earthquakes with predominant frequencies similar to the fundamental frequency of the slope. For more information relating to seismic amplification factors for slopes, refer to Eurocode 8, Part 5.[5]

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[5] https://eurocodes.jrc.ec.europa.eu/showpage.php?id=138

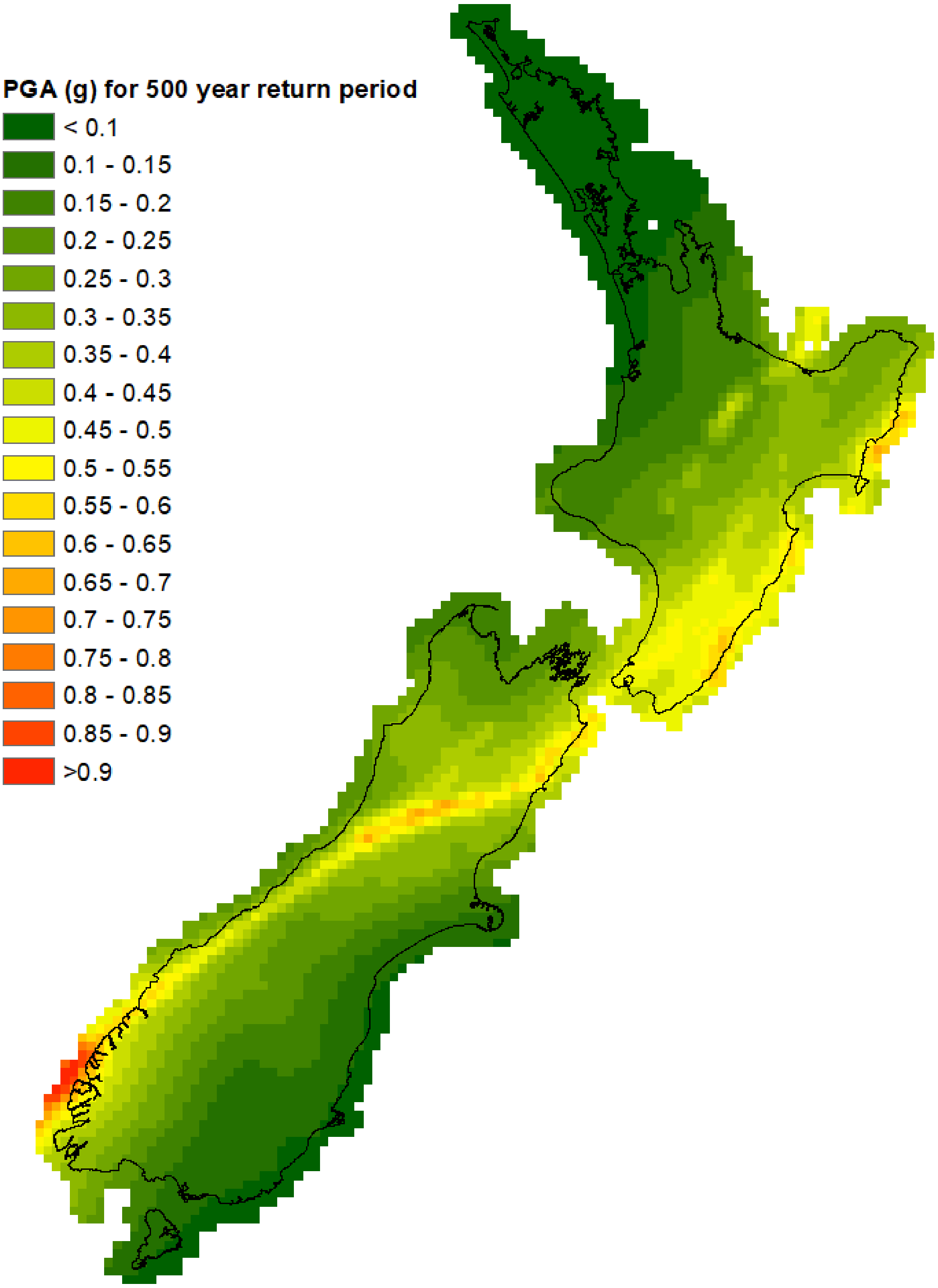


Figure 4.2 Example National Seismic Hazard Model map output for New Zealand, showing the Peak Ground Acceleration (PGA) with a 10% probability of being exceeded in 50 years. The PGA is calculated using a nation-wide map of V_{s30} (modified from Gerstenberger et al. [2020]). Note that these are free field PGA values and do not take into account the local site effects caused by topography and/or changes in geological materials.

Table 4.8 Landslide- and rockfall-triggering thresholds for earthquake-induced ground shaking, earthquake-induced landslide (EIL) opportunity (modified from Hancox et al. [2002]) and description of impacts.

Peak Ground Acceleration (PGA)*	Approximate MMI Range	EIL Opportunity	Description (Modified from Hancox et al. [2002])
<0.1 g	5–6	Very low	Very small rock and soil falls on the most susceptible slopes.
≥0.1–0.2 g	6–7	Low to moderate	Small landslides, soil and rock falls may occur on more susceptible slopes (particularly road cuts and other excavations), along with minor liquefaction effects (sand boils) in susceptible soils.
≥0.2–0.5 g	7–8	Moderate	Widespread small-scale landsliding expected, with a few moderate to very large landslides and possibly landslide-dammed lakes; many sand boils and lateral spreads likely in susceptible soils. Severe damage to roads, with many failures of steep high cuts and road-edge fills.
≥0.5–1.1 g	8–9	High	Widespread small-scale landsliding expected, with a few moderate to very large landslides and landslide-dammed lakes; many sand boils and lateral spreads likely. Severe damage to roads, with many failures of steep high cuts and road-edge fills.
>1.1 g	>9	Very high	Widespread landslide damage expected. Many large to extremely large landslides; sand boils and lateral spreads are widespread in susceptible materials and along stream and river banks. Landslide-dammed lakes are widespread in areas of steep terrain. Extensive very severe damage to roads – failures of steeps high cuts and road-edge fills are widespread.

* Adopts the PGA to MMI relationship of Moratalla et al. (2021).

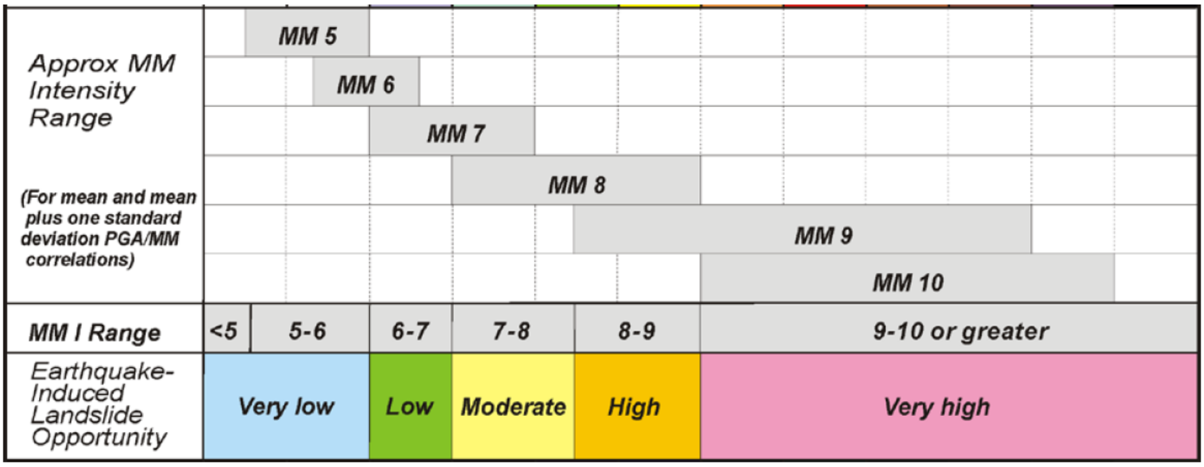


Figure 4.3 Example relationship between MMI and earthquake-induced landslide opportunity (after Hancox et al. [2002]).

4.4.4 Volcanic Activity

For volcanic activity, a primary lahar may be triggered by the rapid melting of ice or snow following an eruption or from an eruption ejecting crater lake water. A secondary lahar is unaccompanied by an eruption and can be caused by the collapse of a crater lake wall or crater lake dam, collapse of a lake wall or dam that has formed following an eruption or through remobilisation of volcanic material due to heavy rain. For secondary lahars, rainfall and/or crater lake water levels may therefore be the trigger for failure. Massey et al. (2010) contains a case-study of a secondary lahar from the Ruapehu crater lake. Refer to the Part 6 report (Deligne et al. 2020) for more information on volcanic activity and frequency for different volcanic areas in New Zealand.

5.0 FIELD INVESTIGATIONS

Field investigations are an essential part of all studies to characterise and validate the risk analysis. Table 5.1 outlines the requirements for basic and advanced levels of risk analysis. Following any stages of field investigation, potential changes in the scope of the hazards considered and spatial scale should be discussed with DOC.

Table 5.1 Actions required for fieldwork for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	For *shallow rapid* landslides: • Characterise and validate the landslide susceptibility and hazard identification process, the engineering geomorphological map and the landslide inventory, plus take photographs of relevant landslide and geomorphic features and record observations for rockfall and landslide runout. • For *rockfall and larger individual landslides*, carry out basic field engineering geological mapping sufficient to define the stratigraphy, structure and defects that control potential instability. For *rockfall*, identify areas with viable mechanisms for blocks to detach.	Same as for basic-level analysis, plus: • The field visit(s) may be a two- (or more) staged approach, whereby the initial field visit is conducted after the compilation of the data inputs, and the second field visit may be conducted after the data analysis is undertaken (i.e. analysis of landslide source, size, timing and runout).
Point		

6.0 DATA ANALYSIS

6.1 Landslide Source Susceptibility

Undertake landslide source susceptibility analysis for basic and advanced-level analysis, as outlined in Table 6.1.

Table 6.1 Actions required to undertake landslide source susceptibility analysis for basic and advanced levels of analysis.

Site Type	Level of Analysis	
	Basic	Advanced
Linear	• Investigate the factors that contribute to landslide susceptibility, such as material type (geology), slope angle, vegetation type, slope aspect, anthropogenic modifications, etc. and use these to develop landslide susceptibility classes; and/or • Estimate landslide density for each susceptibility class. This could be done using judgement or statistics, if a landslide inventory exists for the site. • Prepare a landslide susceptibility map showing the interpreted landslide susceptibility zoning classification areas.	• Perform data treatment analysis (discriminate, neural networks, fuzzy logic, logistic regression, etc.) and develop quantitative ratings and probabilities to obtain susceptibility classes. • Tailor the amount of analysis to the quantity and quality of data available. The susceptibility analysis may vary for trigger type, such as earthquake, rainfall or background (i.e. no discernible trigger), with separate susceptibility maps produced. • Prepare a landslide susceptibility map displaying the quantitative landslide susceptibility classes.
Point	• Where appropriate, determine the factors that contribute to landslide susceptibility and estimate landslide density for each susceptibility class. However, due to the lack of data, it may not be appropriate to apply susceptibility analysis for larger individual landslides or at the site-specific scale.	• Perform deterministic and/or probabilistic stability analysis. Implement the data and maps in GIS. The analysis should also be tailored, where appropriate, for earthquake- or rainfall-triggered landslides.

For basic-level analysis, areas of higher landslide density can be determined using either absolute or relative ranking scale descriptors. Relative susceptibility applies only within the study area and may represent quite different absolute susceptibilities in different areas being zoned. For the relative susceptibility descriptors, the objective is usually to include the largest number of landslides in the higher-susceptibility classes while trying to achieve the minimum spatial area for these classes. So, the higher-susceptibility classes should have the greatest density of landslides, even though the density is not assessed. It is important to note that landslide susceptibility mapping does not quantify the number of rockfalls or small landslides that may occur in a given time period, nor for large landslides the annual probability that landsliding will occur, which is done in hazard mapping.

These ranking scale descriptors are then correlated with pre-disposing factors (Table 6.2) via the frequency or proportion of landslides per pre-disposing factor unit. Descriptions of landslide susceptibility are difficult to standardise, as the geological, topographical, geotechnical and climatic conditions judged to be conducive to landsliding are often subjective and not readily quantified.

For a basic analysis, document the factors involved in determining landslide susceptibility, the mapping unit that susceptibility assessment is applied to and the landslide susceptibility descriptors that are used. See the Part 4 commentary report for more detail.

For an advanced-level analysis, document the data inputs used in the statistical analysis and the resulting statistically significant data inputs. Where the data permits, test the quality of the susceptibility model by: goodness of fit metrics, sensitivity to input parameter metrics and prediction ability of landsliding included within the dataset. The Part 4 commentary report contains more detail on the creation of a logistic regression model based on the 2016 Kaikōura earthquake-induced landslide dataset. For both basic- and advanced-level analysis, incorporate expert judgement in assessing the data and limit detailed analyses to those which are reasonable and appropriate given the potential consequences and data available.

Table 6.2 Examples of landslide susceptibility mapping descriptors (from AGS [2007c]).

Susceptibility Descriptors	Rockfall	Landslides
	Probability that rockfall will reach the area given rockfall occurs from a cliff	**Proportion of area in which landslides may occur**
High susceptibility	>0.5	>0.5
Moderate susceptibility	>0.25–0.5	>0.25–0.5
Low susceptibility	>0.01–0.25	>0.01–0.25
Very low susceptibility	0–0.01	0–0.01
	Proportion of the total rockfall population in the study area	**Proportion of the total landslide population in the study area**
High susceptibility	>0.5	>0.5
Moderate susceptibility	>0.1–0.5	>0.1–0.5
Low susceptibility	>0.01–0.1	>0.01–0.1
Very low susceptibility	0–0.01	0–0.01

6.2 Landslide Size

The range of landslide sizes (area or volume) that can be generated within the study area need to be defined, as outlined in Table 6.3. This is determined via two sources of information: (1) analysis of the landslide inventory; and (2) topographic, geological and geomorphic controls, and rock structure controls for rockfall, on potential landslide size.

Analysis of the landslide inventory will reveal the size of the landslides that have occurred in the past within the study area, or within landslide inventories from similar geological, geomorphological and topographic regions. This is particularly important for earthquake-induced landslides, where historical records and inventories may not exist.

Engineering geomorphological mapping, slope angle analysis and topographic controls can all be used to determine the maximum credible landslide volume. This is important to evaluate as the volume that can be produced from a slope will ultimately be limited by the size of the slope and, in many cases for shallow slides, the depth of accumulated colluvium and completely weathered rock. The Part 4 commentary report provides information on understanding the topographic controls on landslide size.

As part of determining landslide size, the mapped area of landslides needs to be converted into volumes. This is often undertaken by using area to volume scaling relationships published in the literature. The Part 4 commentary report contains more information about converting landslide areas to volumes. Table 6.4 outlines qualitative and quantitative landslide volume classes for describing landslide size.

Table 6.3 Actions required to determine landslide size for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Determine the most likely volume(s) and maximum credible volume for both event (e.g. earthquake and rainfall) and non-event triggers for identified source areas (incorporating the susceptibility mapping results) in the study area.	• Determine the range of landslide volumes possible within the study area and link these landslide volumes to a range of source areas as determined by geomorphic and topographic constraints, as well as susceptibility analysis. This may utilise existing relationships such as landslide frequency (number) and source area (magnitude) relationships for event (e.g. earthquake and rainfall) and non-event triggers.
Point		

Table 6.4 Landslide size classification (based on McColl and Cook [2024]).

Class	**Descriptor (with m^3 Quantity)**	**Minimum Volume (m^3)**	**Minimum Area (m^2)**
14	Monster (trillions)	≥ 100,000,000,000,000	≥ 500,000,000,000
13		≥ 10,000,000,000,000	≥ 100,000,000,000
12		≥ 1,000,000,000,000	≥ 10,000,000,000
11	Giant (billions)	≥ 100,000,000,000	≥ 1,000,000,000
10		≥ 10,000,000,000	≥ 500,000,000
9		≥ 1,000,000,000	≥ 100,000,000
8	Large (millions)	≥ 100,000,000	≥ 10,000,000
7		≥ 10,000,000	≥ 1,000,000
6		≥ 1,000,000	≥ 500,000
5	Medium (thousands)	≥ 100,000	≥ 100,000
4		≥ 10,000	≥ 10,000
3		≥ 1000	≥ 1000
2	Small (ones)	≥ 100	≥ 500
1		≥ 10	≥ 100
0		≥ 1	≥ 10
-1	Very small (thousandths)	≥ 0.1	≥ 1
-2		≥ 0.01	≥ 0.5
-3		≥ 0.001	≥ 0.1

6.3 Landslide Frequency

Landslide frequency is determined from the assessment of the recurrence interval (average time between events of the same magnitude) of the landslides. This is often determined from the landslide inventory. However, given limited data, this is often approximated. As such, the resulting estimation of frequency represents a best estimate. It is important to not infer greater accuracy than is reasonably possible.

Estimation of the annual probability (frequency) of each landslide is the $P_{(H)}$ component in the risk equation (Equation 2.1). This may involve the analysis of landslide magnitude-frequency relationships, which are often expressed as the expected annual frequency of landslide events of a given magnitude occurring within a certain area (e.g. landslides per km² per year). Table 6.5 outlines the actions required to determine landslide frequency for basic and advanced levels of risk analysis.

These magnitude-frequency relationships can also be determined for each trigger event (e.g. earthquake, rainfall, ‘background’ landsliding rate). This is calculated by multiplying the annual probability of trigger event by probability of landsliding given the event. The Part 4 commentary report provides more detail on determining magnitude-frequency analysis at an advanced level for a specific trigger event by providing an example for generating landslide magnitude-frequency scaling relationships for different levels of earthquake shaking.

For individual slopes, the frequency may be assessed by expert elicitation, taking account of the frequency of triggering events such as rainfall and seismic loading and their assessed impact on the slope, should they occur at the site. Where possible, relate landslide occurrence to triggering event, such as daily rainfall or seismic events. Where landslide occurrence cannot be related to a past triggering event, then the number of landslides and/or rockfalls that have occurred over a period of time, and their volume, could be used to establish a relationship between landslide frequency and volume.

Table 6.5 Actions required to determine landslide frequency for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Establish landslide frequency based on the interpretation of the number of landslides that may have occurred within the study area (the landslide inventory) or on similar slopes (to those in the study area) but are outside of the study area. • For *earthquake-triggered landslides*, use Figures 4.2 and 4.3, plus Table 4.8, to provide an expert-judgement-based estimate of the frequency of landsliding. • For *rainfall-triggered landslides*, use Figure 4.1 and Table 4.7 to provide an expert-judgement-based estimate of the frequency of landsliding. Note any potential uncertainty and changes related to climate change.	Same as for basic-level analysis, plus: • Spend more time and resources establishing landslide frequency for the different assessed landslide volumes. • For *earthquake-triggered landslides*, where appropriate data is available, determine landslide frequency and magnitude for different amounts of ground shaking (PGA). • For *rainfall-triggered landslides*, where appropriate data is available, determine landslide frequency and magnitude for different levels of rainfall intensity and duration, including climate-change scenarios RCP 4.5 and RCP 8.5.
Point		

6.4 Landslide Impact Area

Table 6.6 outlines the actions required for each stage of basic- and advanced-level analysis to assess the landslide impact area for (using the terminology for slippage and falling debris from the Building Act 2004):

- **slippage**, which includes the movement or loss (including partial loss) of land from a slope when it occurs beneath it e.g. a structure, path, road, car park, etc.; and
- **falling debris**, which includes soil, rock, vegetation and snow or ice that may slide, fall, flow or avalanche onto a site from upslope (the landslide source area), inundating the site.

For slippage*,* if the site is upslope of, or within the landslide feature, the amount of slippage (movement) and area affected are estimated in order to assess if the extent and velocity of any landslide movement could credibly affect people at the site.

The landslide slippage probability is the probability that a specified landslide will affect a specified area. The amount of slippage and area affected should be assessed from:

- The landslide hazard on the slope below, including the approximate volume of the landslide and type of landslide. The failure mode of the landslide, such as translation or rotation, may affect the magnitude of slippage.
- Evidence of slippage, including active or incipient foundation failure of infrastructure and geomorphic indicators, such as tension cracks (Hancox 2008).
- Proximity to slope edge. For example, a point location located within 20 m of a steep slope edge may be more susceptible than a point location situated on broad ridges and terraces that are 50 m to 100 m from the slope edge (Hancox 2008).

Slippage might include extremely rapid (5 m/s) to extremely slow (<16 mm/year) debris movement velocity. To determine if a life-safety risk exists from slippage, an assessment needs to be made of the potential for the landslide mass to fail rapidly – under certain conditions, such as an earthquake or undercutting/erosion of the toe, etc. – and without usable warning time. Expert elicitation should be used to determine if this is a credible scenario for a site affected by slippage. The uncertainty around this expert judgement should be clearly noted.

For falling debris, the method is used to assess if there is a credible debris path from the landslide source area(s) downslope to the site and therefore if people at the site are exposed to landslide hazards.

The landslide runout probability is the probability that a specified landslide will reach a certain distance downslope, or affect a specified area (Corominas et al. 2015). Landslide runout probability therefore represents the conditional probability that if a landslide of a given size occurs, it reaches the element at risk $P_{(T:L)}$ (Equation 2.1). This may involve the landslide source encompassing the element at risk, or debris or rock falls from the source reaching the element at risk. For falling debris, $P_{(T:L)}$ can be estimated using the following base equation:

$$\frac{D + d}{L}$$

where *D* is diameter of the landslide event (e.g. rockfall size), *d* is the diameter of a person and *L* is the length of track along which the landslide could occur. The equation can be modified for different settings.

Information on travel distance from previous events on or near the site may be collected during the field visit. Predictions of travel distance and travel direction should be based on the assessed mechanism of future events and site characteristics. Allowance should be made for the uncertainty in predicting travel distances. The Part 4 report contains: (1) empirical datasets that can be used to determine landslide runout for different landslide types, (2) debris flow runout path estimation and (3) an example calculation route of $P_{(T:L)}$.

Table 6.6 Actions required to determine landslide travel distances, slippage geometry and slippage velocities for basic and advanced levels of analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Assess limiting travel distances from geomorphologic data and old landslide deposits and rockfall boulders using empirical methods. • Assess the likely travel distance and velocity for the maximum credible volume from consideration of the classification of the potential landslides, geology and topography and use these data to assess travel distance and rockfall trajectories. • Assess the potential for slippage to occur, including the amount of slippage, the area affected from geomorphologic data and any evidence of slippage. • Assess the likely velocity of landslide movement (slippage), including the potential for the landslide mass to fail rapidly.	Same as for basic-level analysis, plus: • Use empirical and, where appropriate, numerical methods to forecast runout for different landslide volumes and rockfall trajectories to delineate with more accuracy the hazard footprints, along with the velocity and height of the debris/rockfalls, which can be linked to the vulnerability variables adopted. • Where appropriate, apply the decision tree framework of Glastonbury and Fell (2008) and Fell et al. (2007) to determine the likely velocity of movement or conduct numerical analyses to assess the likely velocity of movement and amount of permanent displacement of slippage.
Point		

6.4.1 Landslide Intensity

Landslide intensity describes the destructiveness of a landslide (Hungr 1997). Measurements of landslide intensity include the velocity of sliding (coupled with slide volume), kinetic energy, total and/or differential displacement and peak discharge per unit width (for debris flows; Fell et al. [2008b]). The intensity and runout of a landslide will determine its impact on the elements at risk and the vulnerability of persons.

The Part 4 commentary report provides advice on using empirical methods and access to relevant empirical datasets. Numerical methods require back analysis to calibrate the numerical models and simulations. The outputs from these numerical methods should include landslide intensities such as rockfall kinetic energy or bounce height, or, for debris avalanches and debris flows, the volume of debris passing and its velocity. Given the scatter of data for empirical estimates, as well as variations in input model parameters for numerical simulations, sensitivity analysis is recommended to be undertaken.

7.0 CONSEQUENCE ANALYSIS

7.1 Elements at Risk

The information about elements at risk should be provided from DOC observations and records (e.g. track counters, traffic counts, walking times), as outlined in Table 7.1. Additionally, where appropriate, DOC should provide GIS data (and associated metadata) for track, hut and road positions.

Table 7.1 Element of Risk information required for risk analysis.

Site Type	Level of Analysis
Linear	The elements at risk consist of: 1. Workers walking along tracks and driving along roads. 2. Visitors walking along tracks and driving along roads. As part of Section 4 (data compilation), information should be collected on: 1. The number of visitors walking the tracks, including: a. The seasonality of this number, for example, peak-season versus off-season visitor numbers. b. The average time spent walking the tracks. 2. The number of visitors driving along the road, including: a. The length of time it takes them to drive the road. b. The composition of vehicles, for example, cars versus buses. 3. The number of hours spent by workers walking along the tracks or driving along the roads. 4. Any locations along the tracks or roads that visitors and/or workers may spend longer at (such as a picnic area or viewing point).
Point	The elements of risk consist of: 1. Workers occupying a point site, such as a hut. 2. Visitors occupying a point site, such as a hut or viewing area. As part of the data gathering, information should be collected on: 1. The number of visitors staying at a hut, including: a. The seasonality of this number, for example, peak-season versus off-season visitor numbers. b. The average length of the stay. 2. The number of visitors at other point sites, such as picnic areas or carparks, including the length of time the visitor spends at the locations. 3. The number of hours spent by workers at each point site.

7.2 Exposure

If the elements at risk are mobile (e.g. persons on foot or in vehicles), it is necessary to make allowances for the probability that persons (or a particular number of persons) will be in the area affected by a landslide at the time the landslide occurs. This is the spatio-temporal probability $P_{(S:T)}$ (Equation 2.1). Table 7.2 outlines the type of risk analysis required for basic and advanced levels.

For assessing risk to assets (e.g. huts and bridges), assume a $P_{(S:T)}$ of 1.

Table 7.2 Spatio-temporal probability analysis for basic and advanced levels of risk analysis for mobile elements at risk (i.e. people).

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Use the individual of interest who, for visitors, is the maximum (slowest) recorded time to complete a section of track, and, for workers, is the person spending the longest amount of time along the track or road each year.	Same as for basic-level analysis, plus: • Include analysis of different times taken to walk the tracks (from slow to fast). Incorporate slower walking speeds along steeper sections of track, as well as any other identified factors that may influence exposure.
Point	• Use the individual of interest who, for visitors and workers, is the person with the longest occupancy at a point site.	Same as for basic-level analysis, plus: • Include analysis of different occupancy times, as well as changes in the seasonality of occupancy. The changes in the number of visitors occupying a point site between high and low season is important for multiple fatality risk calculations.

7.3 Vulnerability

Vulnerability is defined as the degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is often expressed on a scale of 0 (no loss) to 1 (total loss) (Corominas et al. 2015). For life loss estimates, it is the probability that the person at risk will be killed, given that they are impacted by the landslide. This is dependent on the landslide volume and velocity, and, for roads, whether the person(s) is in a vehicle but should also incorporate whether there is sufficient warning time for the person to take avoidance measures to get out of the path of the landslide.

There is published empirical information on vulnerability which should be used for basic- and advanced-level analysis. Estimates of whether the person at risk can get out of the path of the landslide should be done by expert elicitation. The Part 4 commentary report provides more information on vulnerability values to be used for both basic- and advanced-level analysis.

8.0 RISK ESTIMATION

8.1 Local Personal Risk (if Requested by DOC)

Local Personal Risk (LPR) should usually only be calculated for advanced risk analysis of linear sites. DOC may request it be done for basic analyses. Calculations of LPR assume a person is present in the path of the landslide 100% of the time, and it is assumed that the spatio-temporal probability is 1.0. LPR should be calculated separately for trigger events, such as earthquakes or rainfall (where applicable), and annual landslide rates (where no triggering event is discernible) and then combined to produce a total LPR. LPR will vary along linear sites such as tracks and roads, and the track or road should be sub-divided into lengths of similar LPR based on the hazard. The Part 4 commentary report contains more detail on calculating LPR for these different trigger and non-trigger types.

For linear sites, this will allow ready visualisation of the sections with highest risk. Where applicable, the GIS output, shapefiles and metadata should be delivered to DOC as part of the project reporting.

8.2 Visitor Risk per Day or per Experience of up to One Day

The individual risk for a person on any given track or road is calculated taking into account the landslide frequency, travel distance and spatio-temporal probability of the person for each potential landslide hazard along the linear site. These probabilities for each section of road or track are summed to calculate the total probability of death from walking or driving the whole route. For point sites, which might include a particular section of the track or road, only the risk for that section of road or track is considered. Table 8.1 outlines the requirements for the presentation of risk estimates for basic- and advanced-level risk analysis. An example calculation route for a basic analysis of a visitor walking a track is provided in the Part 4 report.

Table 8.1 Requirements for the presentation of risk for basic- and advanced-level risk analysis.

Site Type	Level of Analysis	
	Basic	**Advanced**
Linear	The resulting output should be a best estimate of the risk per day or per experience of up to one day. List the source of the main uncertainties in the analyses.	The resulting output should be reported as a range, based on a reasonable lower and upper estimate of the risk levels. This could be done by simply estimating the risk, using judgement to adopt values for a given variable (e.g. frequency of landsliding) that represent the lower and upper ends of a range thought to be reasonable. These ranges could be estimated and the risk calculated, for example, by changing each input variable one at a time in the risk equation. Such an approach is called a sensitivity factor analysis.*
Point		

* The Part 4 commentary report provides more information on undertaking sensitivity factor analysis.

8.3 Annual Individual Fatality Risk

The Annual Individual Fatality Risk (AIFR) for the worker along a linear site is calculated from the risk per trip, allowing for the total number of trips in a year. For point sites such as huts, estimate the risks using the spatio-temporal probability by dividing the worker's total exposed hours during a year by the number of hours in a year.

If required and requested by DOC, estimate the AIFR for the most exposed visitor (i.e. a visitor that undertakes multiple trips per year). The AIFR information is presented in the same way for both basic- and advanced-level analysis. as detailed in Table 8.1.

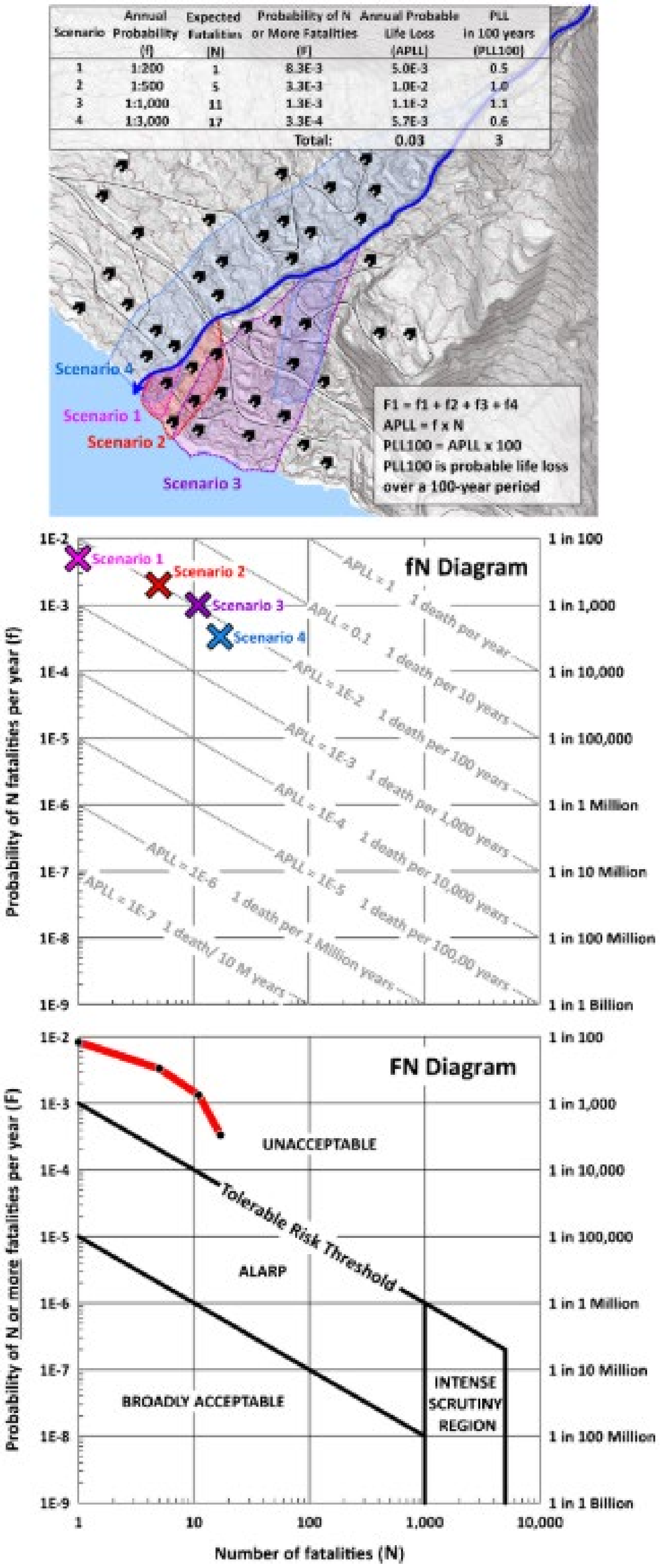
8.4 Multiple Fatality Risk (if Requested by DOC)

Multiple fatality risk, in terms of the frequency of an accident killing N or more people in a single event, should be used to show DOC the potential for multiple fatality events (Lee and Jones 2014). At some sites, a key issue could be that a large landslide, or several smaller landslides triggered by a single event such as an earthquake, could cause multiple fatalities in a single event. *Multiple fatality risk is scenario-based*. Two broad risk metrics are considered for multiple fatality risk, which are fN pairs and annual probability of lives lost (APPL).

To ensure a correct estimation of multiple fatality risk, the scenarios chosen for analysis (e.g. the f/N pairs) must be both mutually exclusive and conceptually exhaustive. In other words, they cover all possible scenarios and outcomes (conceptually exhaustive) and do not overlap (mutually exclusive).

Table 8.2 Requirements for the presentation of multiple fatality risk for basic- and advanced-level risk analysis.

Site Type	**Level of Analysis**	
	Basic	**Advanced**
Linear	• Identify the potential for an individual landslide, or landslides triggered by a single event such as an earthquake or rain storm, to kill multiple people. • If there is a potential for multiple people to be killed, then the frequency (f) of the landslide/landslide-triggering event killing a number (N) or more people should be estimated for both the most likely and maximum credible landslide volumes. These **f/N pairs** should be calculated and tabulated for visitor groups. • Multiply the numbers of deaths (N) by the annual frequency (f) of the landslide event that results in the given number of deaths. Do this for events that result in: (a) 1 or more fatalities, (b) 5 or more fatalities and (c) the worst-case scenario, to calculate the annual probability of lives lost for 1 or more, 5 or more, or the worst-case number of fatalities.	Calculate multiple f/N pairs for the full range of landslide volumes and plot the f/N pairs on an FN diagram to create an FN curve, where 'f' represents the frequency of a specific scenario occurring and 'F' represents the frequency of any/all scenarios with greater than or equal to N fatalities occurring. The area under the curve calculates the total multiple fatality risk.
Point		



Scenario	Annual Probability (f)	Expected Fatalities (N)	Probability of N or More Fatalities (F)	Annual Probable Life Loss (APLL)	PLL in 100 years (PLL100)
1	1:200	1	8.3E-3	5.0E-3	0.5
2	1:500	5	3.3E-3	1.0E-2	1.0
3	1:1,000	11	1.3E-3	1.1E-2	1.1
4	1:3,000	17	3.3E-4	5.7E-3	0.6
			Total:	0.03	3

Figure 8.1 A hypothetical example of multiple fatality landslide risk at a debris flow fan. The spatial map displays the different debris flow events (Scenarios 1–4) that can result in one or more fatalities. The APPL is calculated for each scenario and then summed to give the total APPL. In this example, the annual probability of the scenario occurring is calculated as 1 divided by the return period. Normally, the annual probability should be calculated as the annual exceedance probability, although there may be minor/limited differences between both numbers. The scenario f/N pairs can be plotted on an fN diagram and used to create an FN curve that can be plotted on an FN diagram. The FN diagram displays the Hong Kong risk evaluation criteria for multiple fatality risk (GEO 1998) and therefore is not applicable to a DOC context (figure from Strouth and McDougall [2021]).

Figure 8.1 displays a hypothetical example of multiple fatality risk on a debris flow fan. The APPL is calculated for each scenario and then summed to give the total APPL. In Figure 8.1, the x axis of the fN diagram represents the number of fatalities (N) that can occur for a particular landslide risk scenario, and the y axis represents the probability of the landslide occurring. Each fN pair can be calculated and plotted on such a diagram. This can help display the relative contribution of each scenario to risk. The fN pairs can be combined to create an FN curve; ‘f’ represents the frequency of a specific event occurring, while ‘F’ represents the frequency of any/all scenarios with greater than or equal to N fatalities occurring. The equations are as follows:

N = the number of people expected to be killed if impact occurs:

$$= e_s \text{ x } P_{(T:S)} \text{ x } V_{(D:T)}$$

where e_s is the maximum number of people that could be present when the hazard event occurs (usually the maximum number that can occupy the element at risk – hut, lookout, section of track, etc.).

f = the probability that the expected number of people are killed:

$$= P_{(H)} \text{ x } P_{(S:H)}$$

APPL = the annual probability of life lost for each scenario:

$$= f \text{ x } N$$

Refer to the Commentary (Part 4 report) for a worked example.

8.5 Asset Impact

The potential for a landslide hazard to impact an asset (such as hut) should be noted. For both basic- and advanced-level analysis, if an asset lies within the footprint of a landslide hazard, then the asset impact value should be 1, otherwise the asset impact value should be 0.

Additionally, note and explain any potential mitigation options that may prevent damage to the asset occurring.

8.6 Risk-Sensitivity Analysis

For a basic-level risk analysis, areas of limited or missing information where the consultant has the lowest qualitative confidence in the quality and/or accuracy of the input data and data analysis should be documented. This includes uncertainty related to the impacts of climate change.

An advanced level of risk analysis requires, in addition to the above, a sensitivity analysis of the estimated risk via factor analysis. An example of this factor analysis is provided in the Part 4 commentary report.

9.0 RISK MITIGATION

Risk-mitigation strategies include but are not limited to:

1. **Accept the risk**, subject to the criteria set by DOC.
2. **Avoid the risk**, such as relocation of the tracks or roads or, in some cases, the abandonment of particular tracks and roads.
3. **Reduce the frequency of landsliding** using stabilisation measures to control the landslide-initiating circumstances, such as by re-profiling the ground surface to reduce the slope gradient; provision of improved surface-water drainage measures; provision of subsurface drainage schemes; provision of retaining structures such as retaining walls, anchored walls or ground anchors; or afforestation.
4. **Reduce the consequences** by provision of defensive stabilisation measures or protective measures, such as a boulder catch fence, amelioration of the behaviour of the landslide, relocation of the track or road to a more favourable location or having ‘no stopping’ signage on high-risk areas of track.
5. **Manage the risk by establishing monitoring and warning systems**, such as by regular site visits or survey, which enable the risks to be managed as an interim or permanent measure by alerting persons potentially affected to a change in the landslide condition. This may be also done by closing tracks in periods of the year that are known to be associated with a higher hazard. Such systems may be regarded as a method of reducing the consequences, provided it is feasible for sufficient time to be available between the alert being raised and appropriate action being implemented.
6. **Transfer the risk**, such as by requiring another authority to accept the risk (possibly via a court appraisal) or by provision of insurance.
7. **Postpone the decision** where there is sufficient uncertainty resulting from the available data, provided that additional investigations or monitoring are likely to enable a better risk assessment to be completed. Postponement is only a temporary measure and implies that the risks are being temporarily accepted, even though they may not be tolerable.

It is expected that the consultant will confer with DOC to consider suitable risk-mitigation options, as determined due to the Management Plan, Conservation Management Strategy rules or acceptability by iwi. Subject to the scope of the brief from DOC, the study may include estimates of the risk reduction for each mitigation option and residual risks.

For a basic-level risk analysis, the DOC risk-tolerability criteria will be provided to the consultant, against which they can plot the results from their basic-level analysis. The consultant can identify and recommend feasible risk-mitigation options, but this should be high-level recommendations for DOC to consider rather than granular and specific mitigation options. The proposed risk-mitigation options should be able to reduce the risk significantly (e.g. by an order of magnitude to result in a shift in risk tolerability). This should also include a comment on where the greatest uncertainty exists in the risk analysis and therefore where it may be helpful for DOC to collect more information (e.g. create a system for recording rockfall or debris flow occurrences).

For an advanced-level risk analysis, the DOC risk-tolerability criteria will be provided to the consultant, against which they can plot the results from their advanced-level analysis. Following this, the consultant can identify and recommend feasible risk-mitigation options and the resulting risk reduction and residual risks. This includes providing more detail on mitigation options that may require design and construction of stabilisation measures, as well as monitoring and early warning systems.

Adoption of particular risk-mitigation measures needs to be documented by DOC so that the decisions are transparent. Documentation will need to make it clear whether there is ongoing maintenance required or not. Responsibility for implementation of the risk-mitigation measures (including auditing and reporting) resides with DOC, particularly where ongoing maintenance is required.

Included within assessment of mitigation strategies is advice surrounding when re-assessment of the risk analysis may be needed and what might constitute a trigger for risk analysis re-assessment. This re-assessment trigger may include, but is not limited to:

- An increase in overall landslide rates in the study area.
- An increase in landslide rates of activity from a particular location in the study area.
- A significant earthquake event (e.g. M >6 and ground shaking >0.2 g), as rates of landslide activity are likely to be elevated in future years to decades.
- A significant change in visitor numbers or exposure.

The consultant should also indicate and note the potential for secondary or cascading hazards. For example, the potential for the formation of a landslide dam and associated dam break flood hazard or the potential for landslide-generated tsunami should be noted. These secondary and cascading risks are not quantified within the scope of this analysis methodology, as there is currently no standardised methodology for undertaking such risk analysis. However, they can be incorporated within more detailed risk analysis, if DOC requires this.

10.0 REPORTING REQUIREMENTS

The report on the landslide risk analysis should document the data gathered, assumptions made, sources of uncertainty, logic applied, limitations of the methodology and conclusion reached in a defensible manner. The consultant will gather relevant data, assess the relevance of the data and reach conclusions as to the appropriate geotechnical model and basic assessment of the slope forming processes and rates. Full documentation of these results provides evidence of completion and transparency in the light of uncertainty, enables the analysis to be re-examined or extended at a later date and enables the analysis to be defended against critical review. For the basic- and advanced-level analyses, the general data to be presented include:

1. An executive summary that outlines the following:
    a. Summary of findings from the report.
    b. Calculated risk metrics.
    c. Risk metrics shown relative to DOC's risk-tolerability chart (Figure 2.2), except for multiple fatality risk (if requested by DOC). Multiple fatality risk values should be presented but not plotted against risk-tolerability criteria.
    d. Assumptions and uncertainty associated with the findings.
    e. If applicable, assessment of potential risk-mitigation measures and options.
2. List of data sources.
3. Discussion of investigation methods used and any limitations thereof.
4. Description of potential landslides within the study area, discussed in terms of the classification, volume or area and location in relation to the element at risk. Also describe the geomorphic model, relevant slope forming process and, where applicable, process rates.
5. Study area maps with locations of study area extent, point and linear sites, hazard zones and hazard footprints.
6. Engineering geomorphological mapping results (and any associated GIS and metadata).
7. Map of the landslide inventory with assessed trigger events, if applicable.
8. Description of field visits and validation of remote sensing information.
9. Description and/or map of landslide susceptibility classes.
10. Frequency-magnitude scaling relationships for landslides for each trigger type.
11. Map of the landslide source areas explicitly considered in the study area and the resulting potential landslide runout or slippage from these source areas.
12. Assessed consequence to life.
13. Assessed damage to assets.
14. The resulting risk for each landslide trigger type and overall landslide risk. If applicable, this includes LPR maps (with associated GIS metadata) for each trigger type and overall landslide hazard. For point and linear sites, the AIFR and risk per trip should be reported. If required for advanced-level analysis, an fN curve of multiple fatality risk.
15. If applicable, assessment of potential risk-mitigation measures and options.
16. If applicable, sensitivity factor analysis of estimated risk values should be reported.

Where any of the above is not or cannot be completed, the report should document the missing elements and include an explanation as to why.

10.1 Peer-Review Requirements

For a basic-level analysis, an internal review by a competent consultant is required. As part of the expert panel, DOC will provide a ‘high-level’ quality check on the report.

For an advanced-level analysis, external peer review is required. This provides DOC with greater confidence that the risk analysis is of sufficient quality and fit for purpose. This peer-review process should be ongoing from the risk-analysis investigation through to the closure of the project. The external peer-review process may require a field visit.

11.0 CONCLUSION

The guideline report presents a methodology for quantitative risk analysis (QRA) from landslide hazards at point sites (such as at huts and car parks) and linear sites (such as tracks and roads) within public conservation lands and waters (Department of Conservation land). The methodology quantitatively assesses life-safety risk to visitors and workers on public conservation lands and waters by calculating, where requested by DOC, four risk metrics that include:

1. **Local personal risk (LPR)**, which represents the annual probability of death for a theoretical imaginary person present at a particular location for 100% of the time (24 hours a day and 365 days of the year).
2. **Risk per trip per day** for visitors, which is expressed in terms of the fatality risk experienced by an individual (probability of death) per day or per experience, if the walk takes several days, along a track and/or road within the given study area.
3. **Annual individual fatality risk (AIFR)**, which is expressed in terms of the fatality risk experienced by an individual (probability of death) over one full year of working in a given study area. The risk is calculated for: (1) the worker(s) most exposed on public conservation lands and waters, which may include DOC staff, contractors, volunteers and concessionaires; and, if requested by DOC, (2) the visitor most exposed, for example, a person who may do a walk several times a year.
4. **Multiple fatality risk**, which is the relationship between the frequency of occurrence of a specified hazard and one or more people being killed if that hazard were to occur. Two broad risk metrics are considered for multiple fatality risk, which are fN pairs and annual probability of lives lost.

Additionally, the methodology assesses whether a hut or other similar significant infrastructure or assets can be impacted by a landslide hazard, and, if so, what the potential mitigation options may be.

The methodology is based on the AGS (2007a–d) and the JTC-1 guidelines (Fell et al. 2008b). It has been modified where appropriate to provide guidance specific to a New Zealand context and for analysing the risk to point sites (e.g. huts and viewing areas) and linear sites (e.g. tracks and roads) present within the public conservation lands and waters from landslide hazards.

The guideline outlines two levels of analysis: basic and advanced. The basic level of analysis represents an initial estimation of the landslide risk workers or visitors are exposed to using simple and limited input datasets and data analysis. The advanced level of analysis involves greater time and resources dedicated toward data collection, input datasets, data analysis and peer review of the risk calculation process. The spatial scale at which the basic- or advanced-level risk analyses methods are undertaken will vary for the type of site, linear or point, and, in particular, the length of a linear site. For example, risk analysis of a multi-day tramp along a linear route may require a more regional-scale analysis than that of a single-day tramp along a linear route. The guideline outlines for the various spatial scales, resolution and type of data inputs and subsequent data analysis required. Practically, the QRA workflow involves:

1. Determining the different types of landslides that could occur within the study area, i.e. landslide susceptibility analysis.
2. Considering the full possible range of triggering events (e.g. earthquakes, rain) in terms of a set of earthquake, rainfall or background (i.e. no discernible trigger) events.

3. For basic analysis, choosing the maximum credible and most likely volumes for each type of trigger. For advanced analysis, choosing a small set of representative events for each type of trigger spanning the range of severity of events from smallest to largest.
4. For each of the representative events and landslide types, estimating the:
   a. Annual probability of the landslide occurring ($P_{(L)}$).
   b. Probability of the landslide (e.g. debris from a landslide of a given type) reaching the element at risk (e.g. the person, track, road, hut) ($P_{(T:L)}$).
   c. Spatio-temporal probability that the person is in the path of the landslide when it reaches or passes the elements at risk ($P_{(S:T)}$).
   d. Vulnerability of the element at risk ($V_{(D:T)}$).
   e. Exposure of assets to landslide damage (1 = exposed, 0 = no exposure).
5. Combining 4(a)–(d) for all landslide types to estimate the risk per trip or AIFR for individuals at linear or point sites within public conservation lands and waters.
6. Summing the risk from all events to estimate the overall risk.

Various data inputs and analysis are required for the calculation of each of the elements of the risk equation (Equation 2.1). This guideline report therefore provides an overview and technical guidance on how to carry out a QRA for landslide hazards within a given DOC study area and outlines the minimum data inputs, data analysis, reporting and peer-review requirements for both basic and advanced levels of QRA.

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APPENDICES

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APPENDIX 1 RISK TERMINOLOGY

The landslide hazard and risk terminology of the ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering), ISRM (International Society for Rock Mechanics) and IAEG (International Association of Engineering Geologists) Joint Technical Committee working group (JTC1) has been adopted. Table A1.1 contains the main terms used within the report and is adapted from Corominas et al. (2015) and Fell et al. (2008b). Each of the terms, such as landslide risk, landslide susceptibility and landslide hazard, have a specific definition, cannot be used interchangeably and should be used for landslide risk studies.

Table A1.1 Glossary of terms on landslide hazard and risk (adapted from Fell et al. [2008b] and Corominas et al. [2015]).

Term	Definition
Conditional probability	The probability of an outcome, given the occurrence of some event.
Consequence	In the context of risk analysis, the outcome or result of a hazard being realised.
Danger (threat)	The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as a menacing block). The characterisation of a danger or threat does not include any forecasting.
Elements at risk	Population, buildings and engineering works, infrastructure, environmental features, cultural values and economic activities in the area affected by an event (e.g. landslide).
Exposure	People, property, systems or other elements present in hazard zones that are thereby exposed to potential losses.
Extreme event	An Event, which has a very low annual exceedance probability.
Forecast	Definite statement or statistical estimate of the likely occurrence of a future event or conditions for a specific area.
F–N curves	Curves relating the probability per year of causing N or more fatalities (F) to N. This is the complementary cumulative distribution function. Such curves may be used to express multiple fatality risk criteria and to describe the safety levels of particular facilities.
Fragility curve	A curve that defines the probability of failure as a function of an applied load level.
Individual risk to life	The increment of risk imposed on a particular individual by the existence of a hazard. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the hazard did not exist.
Landslide hazard	A condition that expresses the probability of a particular threat occurring within a defined time period and area.
Landslide inventory	A record of recognised landslides in a particular area. The landslides can be distinguished by typology, geometry and activity.
Landslide intensity	A set of spatially distributed parameters related to the destructive potential of a landslide. The parameters may be described quantitatively or qualitatively and may include maximum movement velocity, total displacement, differential displacement, depth of the moving mass, peak discharge per unit width or kinetic energy per unit area.
Landslide magnitude	The measure of the landslide size. It may be quantitatively described by its volume or indirectly by its area. The latter descriptors may refer to the landslide scar, landslide deposit or both, but this must be specified.

Term	**Definition**
Landslide probability	In the framework of landslide hazard assessment, the following types of probability are of importance: (i) Spatial probability – the probability that a given area is affected by a landslide. (ii) Temporal probability – the probability that a landslide will occur in a given period of time in a specified area. (iii) Size/volume probability – the probability that any given landslide has a specified size/volume. (iv) Runout probability – the probability that any given landslide will reach a specified distance or affect a specified area downslope.
Landslide susceptibility	A quantitative or qualitative assessment of the volume (or area) and spatial distribution of landslides, which exist or potentially may occur in an area. Susceptibility may also include a description of the velocity and intensity of the existing or potential landslide.
Landslide susceptibility map	A map showing the subdivision of the terrain in zones that have a different probability that landslides of a given type may occur.
Mitigation	Measures undertaken to limit the adverse impact of, for instance, natural hazards, environmental degradation and technological hazards.
Multiple fatality risk	The risk to society of widespread or large-scale detriment from the realisation of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio-political response.
Recurrence interval	The recurrence interval, or return period, is the long-term average elapsed time between landslide events at a particular site or in a specified area.
Risk	Measure of the probability and severity of an adverse effect to life, health, property or the environment. Quantitatively, $Risk = Hazard \times Potential\ Worth\ of\ Loss$ This can be also expressed as ‘Probability of an adverse event times the consequences if the event occurs’.
Risk analysis	The use of available information to estimate the risk to individuals, populations, property or the environment from hazards. Risk analyses generally contain the following steps: definition of scope, danger (threat) identification, estimation of probability of occurrence to estimate hazard, evaluation of the vulnerability of the element(s) at risk, consequence analysis, and their integration.
Quantitative risk analysis	An analysis based on numerical values of the probability of occurrence of a potentially damaging event and vulnerability of the exposed elements and consequences that results in a numerical value of the risk.
Reach probability / runout probability	Probability that a specified landslide will reach a certain distance downslope or affect a specified area.
Risk assessment	The process of making a recommendation on whether existing risks are acceptable and present risk control measures are adequate, and, if not, whether alternative risk control measures are justified or will be implemented. Risk assessment incorporates the risk-analysis and risk-evaluation phases.

Term	Definition
Risk evaluation	The stage at which values and judgement enter the decision process, explicitly or implicitly, by including consideration of the importance of the estimated risks and the associated social, environmental, and economic consequences in order to identify a range of alternatives for managing the risks.
Risk management	The systematic application of policies, procedures and practises to the tasks of identifying, analysing, assessing, monitoring and mitigating risk.
Risk mitigation	Application of appropriate techniques and principles to reduce either probability of an occurrence or its adverse consequences or both.
Spatio-temporal probability of the element at risk	The probability that the element at risk is in the landslide path at the time of its occurrence. It is the quantitative expression of the exposure.
Tolerable risk	A risk within a range that society can live with so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.
Vulnerability	The degree of loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude/intensity. It is often expressed on a scale of 0 (no loss) to 1 (total loss).

APPENDIX 2 LANDSLIDE CLASSIFICATION

The report uses the Cruden and Varnes (1996) update of the Varnes (1978) landslide classification system. Table A2.1 outlines that landslides are classified based on the type of movement and material type. For more information on the basis of the classification system, and associated definitions for each landslide type, see Cruden and Varnes (1996). Figure A2.1 contains the main types of landslides. More information on failure mode, speed of failure and material type is in Cruden and Varnes (1996).

Table A2.1 Summary of the landslide classification system (Cruden and Varnes 1996).

Type of Movement	**Type of Material**		
	Bedrock	**Engineering Soils**	
		Predominantly Coarse	**Predominantly Fine**
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock topple	Debris topple	Earth topple
Slide	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow

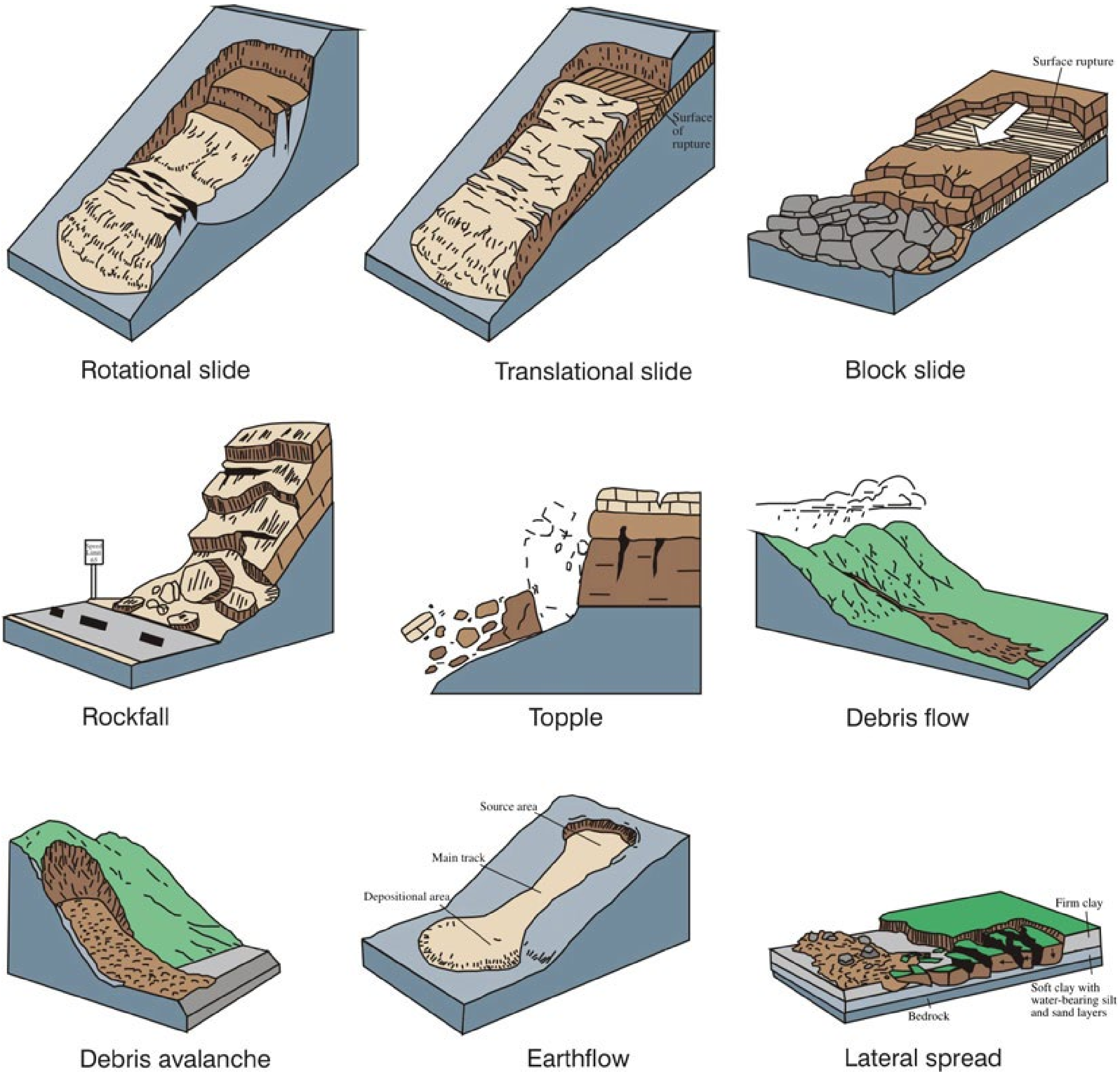

Figure A2.1 The main types of landslides (generalised after Cruden and Varnes [1996]).

APPENDIX 3 RISK-MANAGEMENT WORKFLOW

DOC Natural Hazard Risk Analysis Workflow

Natural Hazard Occurs

Natural hazard event occurs, or a natural hazard is identified at a visitor site

Natural hazards relating to landslides, tsunamis and volcanoes potentially affect the visitor site and require quantitative risk analysis

Contact the Visitor Safety Team.

Setting the Scope

Review study area boundary with DOC staff to ensure that it captures all known and unknown hazards.
For example, study area boundary is extended if it only covers half of the track but landslides could occur along the whole track

Refine study area boundary to capture all known and unknown natural hazards

Risk Analysis

Provide data to consultants: visitor site risk tolerance (low, medium, or high), asset locations, visitor numbers, worker exposure, historical data etc.

Report provided to DOC

Provide:
Summary of findings, calculated risk metrics, risk shown on DOC's risk threshold chart, assumptions and uncertainty associated with the findings, any high level potential risk mitigation measures and options

DOC Expert Panel

Partcipate in DOC Expert Panel outlining report results, uncertainities and any possible mitigation options that significantly reduce the risk

DOC organises expert panel

Representatives from: Visitor Safety team, DOC Staff with knowledge of the site, any other relevant DOC staff, experienced technical expert(s).

DOC makes risk management decisions, or decides whether further analysis/ investigation is required.

● Consultant's role
○ DOC's role

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