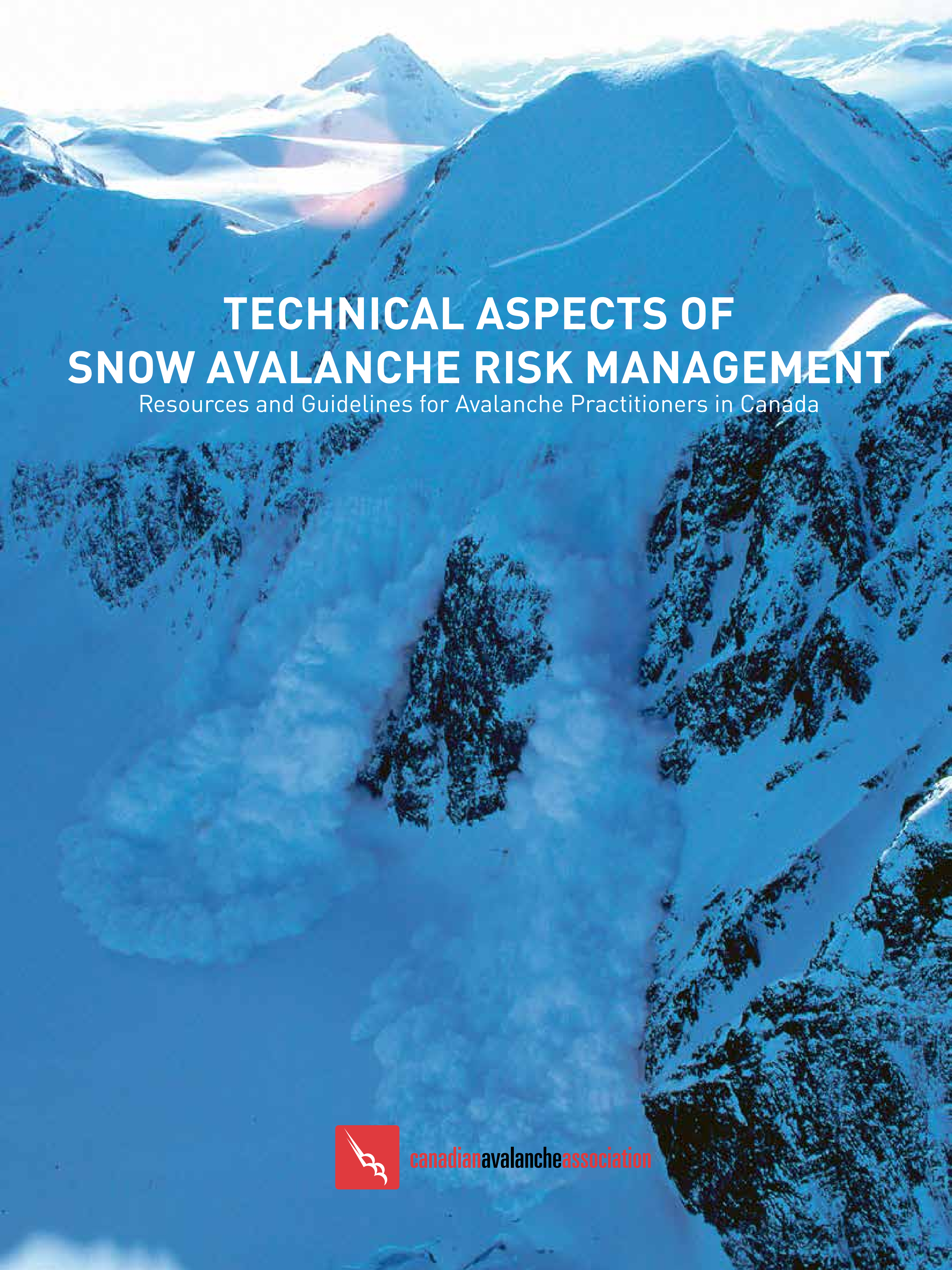
TECHNICAL ASPECTS OF SNOW AVALANCHE RISK MANAGEMENT

Resources and Guidelines for Avalanche Practitioners in Canada



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Resources and Guidelines for Avalanche Practitioners in Canada

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Technical Aspects of Snow Avalanche Risk Management
Resources and Guidelines for Avalanche Practitioners in Canada

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E. Neff photo.

Chapter 1 Outline

1 Introduction

1.1 Purpose

Technical Aspects of Snow Avalanche Risk Management provides a framework for avalanche risk assessment and mitigation, as well as resources and guidelines for avalanche practitioners in Canada. This publication describes best practices in the technical aspects of snow avalanche hazard and risk assessment and mitigation, and contains proposed guidelines for acceptable risk and typical assessment processes and mitigation options. This is the technical companion to the Land Managers Guide to Law, Ethics and Human Resources for Addressing Snow Avalanche Risk in Canada, also published by the Canadian Avalanche Association (CAA, in prep). Ideally, these guidelines will be adopted as minimum standard throughout Canada, resulting in more consistent decision making and greater safety.

1.2 Scope

This publication is intended to revise and expand upon two existing CAA technical guidelines: *Guidelines for Snow Avalanche Risk Determination and Mapping in Canada* (CAA, 2002a) and *Land Managers Guide to Snow Avalanche Hazards in Canada* (CAA, 2002b). This is a high-level overview of technical guidelines and typical applications for avalanche risk assessment and mitigation that includes:

- Managing uncertainty.
- Avalanche terrain identification, classification and mapping.
- Avalanche hazard and risk assessment concepts and systems.
- Assessment/decision aids.
- Mitigation options.
- Guidelines for use of avalanche terrain in Canada.
- Other considerations.
- Records and reports.

The focus of this publication is on what to do, not how to do it. Specific methods are referred to whenever possible, or included as an appendix.

1.3 Audience

This document is written for an audience of avalanche professionals that includes risk managers, consultants, engineers, geoscientists, foresters, avalanche forecasters, avalanche technicians, ski patrollers, mountain guides and ski guides. To a lesser extent, this publication is useful for land managers to understand the technical aspects of avalanche risk assessment and mitigation, especially as it would pertain to a commissioned report.

1.4 Impacts on Practice, Risk Management Limitations, Legislative Precedence

1.4.1 Impacts on Practice

At the time of publication, this document describes best practices in the technical aspects of avalanche risk management in Canada. The scientific understanding of snow avalanches, and the associated risk assessment and mitigation continues to evolve. It is the responsibility of the avalanche professional to keep current with accepted procedures and of the appropriateness of a particular method for a given assessment. New methods and refinements of existing methods should be expected. The responsible avalanche professional must assess and interpret the information provided in this document, identify any considerations not addressed, and determine appropriate requirements for a specific situation. Members of the CAA are expected to adhere to the practices detailed in this document, except where legislation takes precedence (see 1.4.3 below). Where a CAA member's risk assessment and mitigation practices significantly deviate from these guidelines, the member is required to document the specific challenges encountered and explain why these guidelines do not meet the needs of those challenges.

1.4.2 Risk Management Limitations

While avalanche risk in a given situation can sometimes be eliminated, it is often only reduced. Therefore, thresholds for tolerable risk for a variety of activities are provided in this publication. However, experience in Canada and other alpine regions (e.g. Europe, USA, and South America) shows that uncertainty is an inherent part of snow avalanche risk management. Accommodating uncertainty begins by first acknowledging its existence; then reducing it when practical; communicating the irreducible uncertainty; and, accommodating it in decisions.

1.4.3 Legislative Precedence

These guidelines do not replace any legislative requirements that may apply to a situation an avalanche professional may be dealing with in a particular jurisdiction. While every effort has been made to eliminate conflicts, where local legislation sets a different or higher standard than is set out in these guidelines, those legislative requirements supersede those in this publication. A professional should be aware of and follow all applicable legislation.

1.5 Background

A transportation corridor is one example of land use that may be exposed to snow avalanche hazard that can be assessed and mitigated by methods described in this publication. Consider Highway 3 in British Columbia (BC), across the divide of the Selkirk Mountains at Kootenay Pass. Prior to 1970, a number of vehicles were damaged by avalanches, and in 1976 three people were killed when an avalanche hit their moving vehicle. Later in 1976, the avalanche paths were mapped and the avalanche risk management program was enhanced. This program was upgraded over the years as traffic volume increased. There are higher taxpayer costs associated with highway closures, the forecasting and control program, and earthworks; however, these are worthwhile—there have been no avalanche fatalities on public roads since 1976.

Snow avalanche risk to forests, existing facilities, transportation corridors, community water supplies and fish-bearing streams may increase by harvesting forest on slopes above these elements at risk. In 1994, an avalanche started in a harvested block (cutblock) and ran into Airy Creek, BC, threatening a community water supply (Jordan, 1994). In 1996, an avalanche in Nagle Creek, BC, started in a cutblock (Bay, 1996) and caused an estimated CAD $400,000 damage to the forest below it (Figure 1.1). McClung (2001) estimated that avalanches had affected approximately 10,000 different cutblocks in BC. Along with CAA (2002a) and Weir (2002), this document describes best practices to identify potential avalanche hazards to forests caused by harvesting, to determine if and where modification of harvest plans are needed to reduce avalanche risk to a tolerable level.

Figure 1.1: *An avalanche that started in cutblock and damaged forest below it. Nagle Creek, B.C., March 14, 1996. J. Bay photo.*

Figure 1.2: *Avalanche damage to a school in Kangiqsualujjuaq, Quebec, Jan. 1,1999. Nine people were killed and 25 were injured when the avalanche struck the school during a New Year's Eve celebration. B. Jamieson photo.*

Snow avalanches can also threaten residential areas (Figure 1.2). Since 1950, there have been six fatal avalanches resulting in 31 fatalities in and near residential or public buildings in Canada (Stethem and Schaerer, 1979, 1980; Schaerer, 1987; Jamieson and Geldsetzer, 1996; Jamieson et al., 2010; Government of Quebec, 2000). Three of these avalanches and 16 of the fatalities occurred in Quebec and Newfoundland, indicating that avalanche problems are not confined to Western Canada. These incidents occurred in areas where no avalanche zoning (i.e. designation of land use that satisfies legislation, regulations or jurisdictional policies) had been applied. No fatalities have occurred in subdivisions zoned for avalanche hazard or risk.

The vast majority of avalanche fatalities in Canada occurred during backcountry travel. However, despite an increase in backcountry activity over the past two decades, fatality rates have not risen (Campbell et al, 2007). This can be attributed, at least in part, to advancements in risk assessment and mitigation systems for backcountry travel, many of which are described in this publication.

1.5.1 Risk Management Concepts

This document describes conventional risk management concepts that have relevance to the task of avalanche risk management. These concepts are taken from prevailing and established work in both general risk and avalanche-specific domains. This provides a useful structure and an understanding of this process by a wider audience.

Enterprise Risk Management

Enterprise risk management occurs on a broad organizational level and is a strategic business discipline. It supports the realization of an organization's objectives by addressing the full spectrum of its risks and managing the combined impact of those risks as an interrelated risk portfolio. Avalanche risk management commonly occupies only a small portion of an organization's enterprise risk management strategy. It focuses primarily on physical risk from snow avalanches (i.e. pure risk) and not other aspects of risk (e.g. speculative risk).

ISO 31000

The International Organization for Standardization (ISO) risk management standard known as the ISO 31000 *Risk Management—Principles and Guidelines*, is general risk management guidance that is intended to be pertinent in all sectors and risk management applications. This umbrella-like assistance is applicable for an entire organization, multiple areas or levels, at any time, or for specific functions, projects and activities.

The ISO 31000 risk management standard has three key components: *principles, framework*, and *process* (Figure 1.3) (CSA, 2010). The *principles* component describes the benefits and role that risk management plays within an organization. From this, the mandate and commitment of the organizational risk management program can be established. The *framework* component is informed by the principles and assists an organization to integrate risk management into it's overall management system. The framework makes risk management scalable to the organizational context and embeds a plan-do-check-revise cycle for risk management. While the "do" step (i.e. implementing risk management) commonly receives the most attention (e.g. this publication), it is important to consider the whole framework when establishing an avalanche risk management plan.

The framework contains the *process* component, which is composed of the following steps:

- Establishing the context (i.e. objectives and parameters where risk assessment and treatment are applied within the risk management process).
- Risk assessment (i.e. risk identification, analysis and evaluation).
- Risk treatment (i.e. risk control and mitigation).

These steps are embedded in a feedback loop that ensures continuous monitoring and review with updates, as well as both internal and external communication and consultation, incorporated at anytime throughout the process.

A risk management program can align with the ISO standard if it follows the framework, incorporates these principles, and is delivered via the process outlined. The avalanche risk assessment and mitigation framework described in this publication has been crafted in a manner that utilizes the ISO 31000 risk management terminology, principles and guidelines.

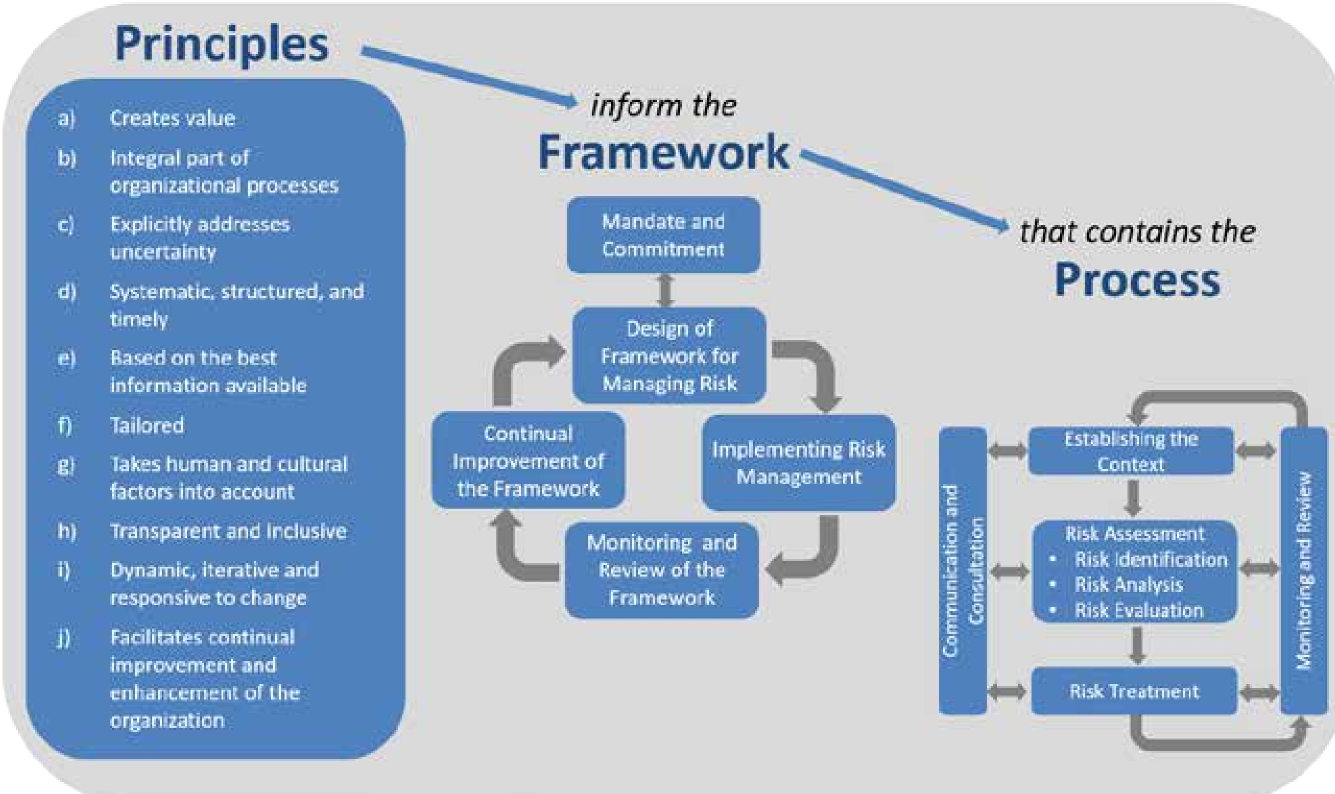


Figure 1.3: *Illustration of the three key components of the ISO 31000 risk management standard and their relationship in the structure (CSA, 2010).*

Foundations of Risk Assessment

Risk authorities make every effort to express the notion of risk in a uniform linguistic manner. The use of sets of questions in the risk assessment and evaluation process has proven successful. The following set of questions (Kaplan and Garrick, 1981) could be considered the fundamental beginning of the avalanche risk assessment process:

1. What can happen?
2. How likely is it that it will happen?
3. If it does happen, what are the consequences?

Consideration of these three questions results in the identification of a scenario or set of scenarios that describe (in a hypothetical sequence of events) the exposure of the element(s) at risk to the hazard. The sequence of events includes the initiating conditions through to one of the final states (e.g. reduction of hazard or loss to the element at risk).

A second set of questions (Ammann, 2006) builds on the general answers gained from the questions above (see *risk tolerance* and *risk acceptance* in Section 2.4):

1. What is tolerable?
2. How safe is safe enough (i.e. what is acceptable)?
3. What needs to be done?

This latter set of questions arrives at a choice of mitigation measures.

1.5.2 Avalanche Risk Management Process

Avalanche risk management is risk assessment and treatment of the snow avalanche hazard that includes the identification, assessment and mitigation of avalanche hazard. It occurs on both a planning and an operational scale. Figure 1.4 shows the core structure of the avalanche risk management process and how it fits within the ISO 31000 risk management process outlined in Section 1.5.1. Each element of the diagram are expanded upon in the following subsections.

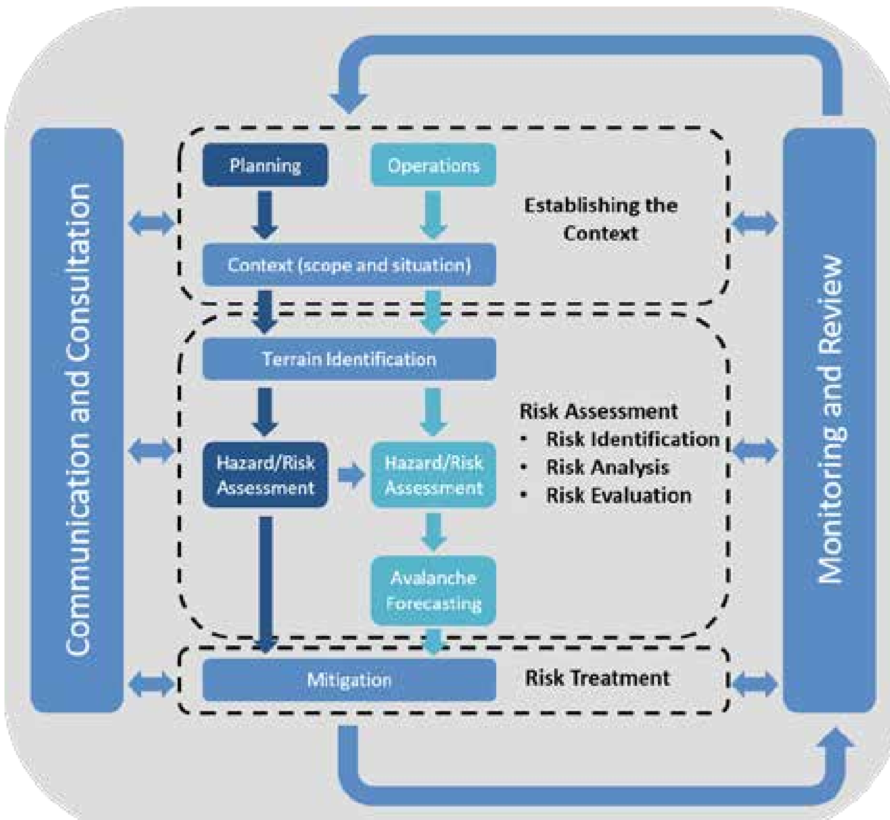


Figure 1.4: *The avalanche risk management process. The center of the diagram illustrates the parallel paths that focus on either planning or operational activities and identifies how this structure aligns under the ISO 31000 umbrella (CSA, 2010).*

Planning and Operations

At the onset of establishing the context of the hazard/risk assessment, a choice is made between two distinct stages in avalanche risk management activities: *planning* and *operations*.

Avalanche planning: Involves the study of avalanche hazard, risk, and/or mitigation for specific objectives. It is separate from avalanche operations in that the focus of the specific objectives are long-term, and result in maps, plans and reports. Avalanche planning is expanded upon in Chapter 5.

Avalanche operations: A phrase used to describe seasonal activities that include avalanche forecasting tasks and the direction and implementation of short-term mitigation measures in order to achieve specific organizational objectives. Avalanche operations is expanded upon in Chapter 6.

The distinction between these stages provides parallel paths through the avalanche risk management process, as well as in the structure and organization of this publication.

Scope and Situation

In addition to determining the stage of the process, two other components are addressed while establishing the context: *scope* and *situation*.

The *scope* identifies objectives, hazard/risk criteria, relevant factors (internal and external) of the activities, or parts of the organization where the risk management process is applied.

A *situation* is described by the intersection of three factors: *element(s) at risk, scale* and *avalanche risk scenario(s)*. An *element at risk* describes the population, properties, environmental elements, economic activities and services in the area affected by the avalanche(s) (after IUGS, 1997). *Scale* refers to the physical extent of terrain or geographic area (spatial scale) of the hazard, as well as the time span (temporal scale) over which the element at risk is exposed. *Scenarios* are a hypothetical sequence of events that answer the question "What could go wrong (or right) during the exposure of the element(s) at risk to the hazard?"

Scope and situation for avalanche planning and operations are expanded upon in Chapters 5 and 6 respectively.

Terrain Identification

Avalanche risk is a function of the natural and physical conditions of a geographic area. An inventory of the environment where avalanche risk may occur includes the cataloging of the natural and physical environment. This inventory is covered in Chapter 4.

Hazard and Risk Assessment

Assessment of avalanche hazard and risk are engaged separately. This follows from the essential notion that avalanche hazard is independent of any element at risk. Assessing the hazard separately from its effect on elements at risk is an important step in the avalanche risk management process. Two examples that help to understand this are:

1. In the planning stage, an initial avalanche terrain and snow supply assessment may conclude that there is no threat, and therefore no need to continue with the risk assessment process.
2. In an operational setting, a hazard assessment may conclude with an avalanche hazard forecast (e.g. as in a public recreational avalanche bulletin).

Both hazard and risk assessments follow the ISO 31000 steps of identification, analysis and evaluation. However, in an operational setting risk evaluation is often conducted in tandem with risk analysis where both are part of the same step in the risk assessment process.

Avalanche Forecasting

Avalanche forecasting is the prediction, over a specified scale of terrain, of current and/or future (e.g. with the range of a weather forecast) avalanche hazard/risk based on the expected likelihood of triggering, avalanche size and runout extent. The avalanche forecasting step can serve both as a process end point or the supporting step to mitigation. It may result in a detailed warning to a specific user group, a broad warning to a variety of user groups, or provide the basis for choice and application of operational mitigation measures. Avalanche Forecasting is expanded upon in Chapter 6.

Mitigation

Avalanche risk mitigation involves measures that modify the elements of avalanche risk. Specifically, measures that reduce the avalanche hazard, or the exposure or vulnerability of the element at risk. Types of mitigation and example measures are covered in Chapter 8.

Communication and Consultation

Ongoing internal communication and consultation throughout the risk management process helps to support and encourage accountability and ownership of risk within an organization (CSA, 2010). This includes an open and transparent risk management system that contains processes to consolidate information from a variety of sources. In an operational setting, this could include mechanisms that encourage reporting of "near-misses", which can be valuable data to validate the effectiveness of a risk management system.

Establishing mechanisms for communication with and reporting to external stakeholders can help build confidence in an organization. This includes avalanche professionals keeping stakeholders informed about the risk management process and stakeholders keeping avalanche professionals informed about concerns they may have. Both parties must also agree on tolerable and acceptable risk levels (see *risk tolerance* and *risk acceptance* in Section 2.4).

Monitoring and Review

In an operational setting, ongoing monitoring and review of avalanche risk, forecasting and mitigation effectiveness is used to revise the risk assessment, avalanche forecast and mitigation strategies in a real-time continuous feedback loop. Furthermore, daily review of the risk assessment, avalanche forecast and mitigation (e.g. during an evening guides meeting) helps inform the baseline risk assessment for the following day by summarizing the current hazard and confidence levels, and identifying deficiencies in data. In avalanche planning, periodic (e.g. annual or whenever operational conditions change) review and revision of risk control plans (e.g. avalanche safety plans) helps to ensure the effectiveness of risk management strategies. Revision of the plan often reflects experiences with implementation and associated operations.

Skier-triggered Size 1 soft wind slab avalanches. On that day high sensitivity to triggers was offset by specific spatial distribution and relatively harmless destructive potential to result in Moderate hazard at that location. C. Campbell photo.

Chapter 2 Outline

2 Definitions

2.1 Avalanche

Avalanche: Specifically refers to snow avalanche for the purpose of this publication.

Snow avalanche: A volume of snow, usually more than several cubic metres, moved by gravity at perceptible speed. Snow avalanches may contain rock, broken trees, soil, ice or other material.

Avalanche problem: A set of factors that describes the avalanche hazard and includes the elements of likelihood of triggering, avalanche size and character, aspect and elevation.

Avalanche character: Describes different types of avalanche regimes, each of which presents a general, repeatable pattern of potential or observed avalanche activity that suggests a distinct approach to risk treatment (e.g. wind slab, storm slab, persistent slab, deep persistent slab, wet slab, loose wet, loose dry, cornice fall and glide avalanche) (Statham et al., in prep).

Avalanche terrain: The area and topography within the physical boundary of the potential formation, movement and effect of an avalanche.

Avalanche forecasting: The prediction, over a specified scale of terrain, of current and/or future (e.g. with the range of a weather forecast) avalanche hazard/risk based on the expected likelihood of triggering, avalanche size and runout extent.

Avalanche area: A set of geographically associated avalanche paths (after Martinelli, 1974). These may affect a specific element at risk, or multiple elements at risk (e.g. a transportation corridor in which traffic is stopped behind a deposit from one path while being exposed to risk from one or more of the nearby paths).

Avalanche path: A fixed locality within which avalanches start, run and stop (McClung and Schaerer, 2006). Paths consist a starting zone, a track and a runout zone (Figure 4.2) and sometimes an air blast zone.

Starting zone: The part of an avalanche path where snow fails and begins to move down slope (Figure 4.2). Usually the slope angle in the starting zone exceeds 25°. Small avalanches may stop in the starting zone.

Track: The part of an avalanche path that connects the starting zone with the runout zone (Figure 4.2). In the track, large avalanches move with approximately constant speed. Usually the slope angle in the track is 15° to 30°. Secondary starting zones may also be present and small avalanches may stop in the track.

Runout zone: The part of an avalanche path where large avalanches decelerate rapidly and stop (Figure 4.2). On large avalanche paths the slope angle is usually less than 15° in the runout zone.

Avalanche size: A reporting system (Table 2.1) for observed avalanches based on the estimated potential destructive effects (McClung and Schaerer, 2006). An additional reporting system is used in U.S. operations (Greene et al., 2004 and Perla, 1975).

Table 2.1: Canadian classification system for avalanche size (McClung and Schaerer, 2006). For each size class, the table lists: typical impact pressures in kilopascals (kPa); typical mass in tonnes (t); typical path length in metres (m); and a description of the destructive potential, including the approximate forest area in hectares (ha) that could be destroyed.

Size and data code	Destructive potential	Typical mass	Typical path length	Typical impact pressure
1	Relatively harmless to people.	<10 t	10 m	1 kPa
2	Could bury, injure or kill a person.	10^2 t	100 m	10 kPa
3	Could bury and destroy a car, damage a truck, destroy a wood-frame house or break a few trees.	10^3 t	1,000 m	100 kPa
4	Could destroy a railway car, large truck, several buildings or a forest area of approximately 4 ha.	10^4 t	2,000 m	500 kPa
5	Largest snow avalanche known. Could destroy a village or a forest area of approximately 40 ha.	10^5 t	3,000 m	1,000 kPa

Return period: The expected average time between avalanches reaching or exceeding a given location. The return period of avalanches is typically expressed as either 1, 3, 10, 30, 100, or 300 years (per avalanche). This approximates a constant order of magnitude increase of 0.5 (i.e. 10^x where $x = 0.5, 1, 1.5, 2$ and 2.5). Mathematically, it is the reciprocal of the annual exceedance probability (e.g. every year the probability of an avalanche occurring with a specified return period is the reciprocal of that return period).

Frequency: The expected (average) number of avalanches per unit of time reaching or exceeding a location. Normally it has units of avalanche(s) per year(s) and is expressed as a ratio (e.g. 1:1, 1:3, 1:10, 1:30, etc.). This is determined from empirical evidence in the field, avalanche occurrence records, and/or a probability density function (CAA, 2002a).

Maximum event: The highest destructive potential at an avalanche location. Likely characteristics in maximum events include: a fast-moving, large (mass) and dry flowing avalanche; a smooth running surface; a long return period (e.g. ≥ 100 years); and an extreme runout distance (CAA, 2002a).

Extreme runout: The maximum event runout distance and lateral extent.

2.2 Hazard

Avalanche hazard: A source of potential harm or loss. The potential for an avalanche(s) to cause damage to something of value. It is a function of the likelihood of triggering or frequency, and the avalanche size or magnitude. (Statham, 2008).

Avalanche danger: Synonymous with avalanche hazard; commonly used to represent avalanche hazard in public avalanche bulletins.

Avalanche hazard assessment: A process that includes the steps of avalanche hazard identification, analysis and evaluation (after CSA, 2010).

Avalanche hazard identification: A process that includes the identification of avalanche terrain, recognition of avalanche potential, and recording and representing its location.

Avalanche hazard analysis: The data collection and study of the environmental conditions that contribute to the hazard. In planning, it includes an estimation of the probabilities and the dimensions of the physical impact of potential avalanches. In operations, it involves the systematic observation, monitoring, and investigation of avalanche activity, snowpack and weather conditions.

Avalanche hazard evaluation: Entails comparing the results of the analysis against evaluation criteria that rate or rank the hazard.

2.3 Risk and Uncertainty

The choice of definition for risk is fundamental to risk management. Both a hazard-based definition, “a function of likelihood of adverse occurrences and its consequences” (Vick, 2002), and the ISO 31000 definition, “the effect of uncertainty on objectives” (CSA, 2010), have application to technical aspects described in this document.

Uncertainty: The state (even partial) of deficiency of information related to understanding or knowledge of an event, its consequence or likelihood (ISO, 2009).

Avalanche risk: The probability of harm or cost resulting from interaction between avalanche hazard and a specific element(s) at risk (after Statham, 2008). A first level mathematical definition comes from Kaplan and Garrick (1981):

$$Risk = \{(s_i, p_i, x_i)\}$$

where:

s_i is a scenario description for a given element at risk,

p_i is the combined avalanche likelihood and probable exposure of the element at risk for that scenario, and

x_i is a function of the avalanche magnitude and element at risk’s vulnerability.

In other words, avalanche risk is a function of the likelihood (L) and magnitude (M) of the avalanche, and the exposure in space and time (E) and vulnerability (V) of the element at risk, such that:

$$Risk = \mathrm{f}(L_{ai}, E_{ji}, M_{ai}, V_{ja})$$

given scenario i, element at risk j and avalanche a.

Element at risk: The population, properties, environmental elements, economic activities and services in the area affected by the avalanche(s) (after IUGS, 1997).

Vulnerability: The fraction of loss given that the element at risk is hit by or caught in an avalanche with specified magnitude. When people are affected by avalanches, vulnerability is the probability of death (after IUGS, 1997).

Consequence: The outcome of an event affecting objectives (CSA, 2010). Consequence is a function of the avalanche magnitude and the vulnerability of the element at risk.

Avalanche risk assessment: A process that includes the steps of avalanche risk identification, analysis and evaluation (after CSA, 2010).

Risk scenarios: Descriptions or mental visualizations of a hypothetical sequence of events that occur during the exposure of the element(s) at risk to the hazard.

Avalanche risk identification: Connects the hazard assessment to the element(s) at risk through risk scenarios.

Avalanche risk analysis: Determines a level of risk through examination of probability of an event, exposure of the element at risk, consequence and existing mitigation measures. It provides an estimation of the uncertainties associated with the risk scenario.

Avalanche risk evaluation: Compares the analysis results to criteria to determine whether the risk is tolerable (see *risk tolerance* in Section 2.4), and determine a choice of action or mitigation.

Support tool: Tools that increase the quality and efficiency of risk management processes by enhancing objectivity and consistency, and reducing the influence of unwanted human factors.

Assessment/decision aid: A particular support tool that explicitly helps decision makers combine multiple observations and produce a concrete assessment and/or decision in regards to risk mitigation.

Public risk: Risk to the public interest where the organization is neither the source nor the bearer of the risk (CSA, 2011).

Risk owner: Person or entity with the accountability and/or authority to manage a risk (ISO, 2009).

2.4 Mitigation

Mitigation: Risk treatment that reduces negative consequences (CSA, 2010). Mitigation includes preventative and protective measures that limit or lessen the likelihood or severity, or both (after CSA, 2012). Specific types of avalanche mitigation are defined in Chapter 8.

Risk tolerance: An organization or society's readiness to accept the uncertainty and potential outcomes after the mitigation in order to achieve objectives (after CSA, 2011; ISO, 2009). Risk tolerance is a condition in that it represents expectations. CAA (in prep) discusses the social context and the non-regulatory environment that influences risk tolerance.

Risk acceptance: The informed decision to take a particular risk (ISO, 2009). Risk acceptance is an action in that it represents a decision. Guidelines for acceptable risk are provided in Chapter 9. CAA (in prep) discusses risk acceptance and it's determining factors.

2.5 Scale

Scale plays a vital role in the avalanche risk management process. It is addressed in several contexts: measurement, assessment, reporting and monitoring. It has relevance across many .of the chapters in this publication; hence, the definitions for these various uses of scale are compiled here for easy reference.

Scale: A graduated means (i.e. nominal, ordinal, interval or ratio) of measuring the magnitude of an object, mechanism or process (Whittow, 1984). For example, the North American Avalanche Danger Scale (Statham et al., 2010).

Assessment scale: The spatial extent or separation between individual ratings of avalanche hazard or avalanche risk. Table 2.2 illustrates the assessment scale recommended in this publication.

Monitoring scale: The time separation or period length over which observations or measurements are taken, or ratings are valid.

Cartographic (map) scale: The ratio of the distance on a map or other representation to the actual distance on the ground (e.g. representative fraction) (Whittow, 1984).

***Table 2.2:** Assessment scale names, descriptions and examples (Statham et al., in prep).*

Spatial extent	Description	Example	Scale
Terrain feature	Individual geographic features contained within a larger slope.	Convex rolls, gullies and terrain traps.	
Slope	Large, open, inclined areas with homogeneous characteristics bounded by natural features such as ridges, gullies or trees.	Typical avalanche starting zone or wide open areas on ski runs.	Micro < 1 km^2
Path or run	Multiple interconnected slopes and terrain features running from near ridge crest to valley bottom.	Traditional avalanche paths with a start zone, track and runout zone. Typical long backcountry ski run.	
Mountain	An area rising considerably above the surrounding country with numerous aspects and vertical relief running from summit to valley bottom.	Ski area (e.g. Whistler mountain) or typical single operating zone in a cat skiing tenure.	Meso $> 10^2$ km^2
Drainage	An area with a perimeter defined by the divide of a watershed.	Typical single operating zone in a helicopter skiing tenure (e.g. Crawford Creek).	
Region	A large area of multiple watersheds defined by mapped boundaries.	Typical public forecasting area, or park land (e.g. North Columbia region or Glacier National Park).	Synoptic $> 10^4$ km^2
Range	A geographic area containing a chain of geologically related mountains.	Mountain ranges or sub-ranges (e.g. Coast, Purcell or Rocky Mountains).	

Chapter 3 Outline

3 Uncertainty

Uncertainty is an inherent part of avalanche hazard/risk assessment that cannot be eliminated. It is intrinsic in data collection, analysis, assessment and decision making (Morgan and Henrion, 1990; Vick, 2002). This necessitates uncertainty to be identified, reduced when practical, clearly communicated and accommodated. This chapter provides an overview of uncertainty in avalanche hazard/risk assessment. See Jamieson et al. (2015) for more detail.

3.1 Types of Uncertainty

Uncertainty is defined as the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence or likelihood (ISO, 2009). Vick (2002), Ang (2011) and others further divide uncertainty into two types: natural (aleatoric) and knowledge source (epistemic).

Natural uncertainty: Inherent to a system due to natural variability or randomness (e.g. the difference in weather and snowpack over variable mountain terrain). Natural uncertainty is due to random variability, such as 24-hour snowfall height over terrain, and cannot be reduced. Therefore, it should be considered in assessments.

Knowledge source uncertainty: Arises from limited information or understanding (e.g. the presence of a layer of depth hoar at the base of a deep snowpack is unknown). Knowledge source uncertainty can be reduced, although the benefit in doing so varies.

3.2 Sources of Uncertainty

Uncertainty in avalanche hazard/risk assessment and mitigation arises from a variety of internal and external sources, as listed below.

3.2.1 Weather and Climate

Forecasted weather, which in itself involves uncertainty, is the basis for avalanche forecasting. Furthermore, larger forecast areas and longer lead times, leads to greater uncertainty.

Changes in climate are altering the snowpack in mountain areas of the northern hemisphere (Bellaire et al., 2016; Eckert et al., 2013; Sinickas et al., 2015). Records from the past 40 to 70 years show the length of the snow season in some alpine regions is shortening, and snowpack depths are decreasing, especially at lower elevations. When run for the next 35 to 85 years, combined climate and snowpack models suggest these trends will continue (Castebrunet et al., 2014).

3.2.2 People

Human behaviour generates uncertainty. For example, individuals may be in unexpected places at the time of an avalanche (e.g. closed areas, no-stopping zones or areas where a ski guide directed them away from. Also, people's perception of the relevant environmental factors including terrain, their assessment of the conditions (McClung, 2002; McCammon, 2002) and subsequent actions are sources of uncertainty.

3.2.3 Terrain

At any point in time terrain can be considered constant with no associated uncertainty. However, over time terrain can be modified by fire, slope mass movement, glacial ablation or advance, construction, mining, deflectors or dams of hardened snow, etc., potentially adding uncertainty regarding future avalanche motion including estimates of extreme runout. Also, the seasonal snowpack can smooth ground roughness, reduce the angle of short cliffs, etc. affecting the release and motion of avalanches.

Furthermore, there is variability in terrain severity, thus uncertainty, when considering a route through avalanche terrain that a skier is exposed to over the course of a day.

3.2.4 Snowpack

Snowpack properties, including stability, can vary considerably over terrain (Figure 3.1) (Schweizer et al., 2008). As a result, snowpack is a major source of uncertainty for avalanche forecasting. Snowpack properties are also a source of uncertainty for land-use planning. For example, estimates of the maximum slab height or snowpack height for return periods of 10 to 300 years are uncertain.

Figure 3.1: *Complex processes resulted in variable crown height and bed surface for this slab avalanche and, hence, contributed to natural uncertainty in snowpack properties and stability within a single avalanche starting zone. B. Jamieson photo.*

3.3 Strategies to Reduce Knowledge Source Uncertainty

Avalanche hazard/risk assessment and some aspects of mitigation involve reducing knowledge source uncertainty. Specifically, McClung and Schaerer (2006) define the goal of avalanche forecasting in terms of minimizing uncertainty about the instability of the snowpack.

Knowledge source uncertainty can potentially be reduced through these general strategies:

- Identify knowledge gaps early in the assessment process and seek targeted information. This is an example of the monitoring and review element in the risk management process (Section 1.5.2).
- Apply independent methods in the same assessment. For example, vegetation analysis, topographical-statistical models and physical-dynamic models (Chapter 4) are combined to estimate runout.
- Seek independent expert opinions of hazard/risk, or access guidance from other sources, such as assessment/decision aids (Chapter 7).
- Stay informed about advances in understanding regarding sources of uncertainty (e.g. climate change) and their effect on avalanche hazard/risk.

3.4 Strategies for Considering Uncertainty

While natural uncertainty cannot be reduced, it must be considered along with any knowledge source uncertainty, in avalanche hazard/risk assessment. However, fundamental limitations in knowledge of weather, climate and avalanches may result (on rare occasions) in magnitudes or runouts that exceed levels stated in thorough assessments. This section summarizes strategies for considering uncertainty and reaching appropriate decisions and designs for mitigation (see risk tolerance and acceptable risk in Chapter 2).

3.4.1 Safety Factor

The safety factor is the ratio of design strength (or structural capacity) to the design load. It is widely used in geotechnical assessments of slope stability. Higher ratios are safer in that they allow for greater uncertainty in the load and design strength, including variations over time and space. While safety factors based on slope failures and laboratory tests have been published in design codes for soil and rock slopes, they have not been published for snow slopes, likely because snowpack properties vary more strongly over space and time.

Safety factors for static snow loading and avalanche impact on structures are needed, but few have been published (e.g. Margreth, 2007a). In some cases, a conservative value is used for an uncertain variable in order to account for uncertainty. For example, Jóhannesson et al. (2009) propose a high flow density for safety when estimating impact pressures.

3.4.2 Non-exceedance Probabilities

When the statistical distribution of a random variable used in risk/hazard assessment is modeled, 50 percent (%) of its values will be less than or equal to the median (which is close to the mean or expected value for approximately symmetric distributions). Hence, the median has a non-exceedance probability of 0.5. In hazard/risk assessments with higher uncertainty, it may be advantageous to apply a higher non-exceedance probability to a particular variable. For example, a non-exceedance probability of 0.8 may be applied for topographical-statistical runout estimation, which means that only 20 % of the paths in the range have relatively longer maximum runouts (e.g. McClung and Mears, 1991). When hazard/risk is modeled as a statistical distribution such as in Monte Carlo simulations, a higher non-exceedance probability corresponds to lower hazard/risk.

3.4.3 Margin of Safety

While margin of safety is also defined in engineering, it is used qualitatively in this publication to refer to the additional caution due to the uncertainty that lies beyond the expected avalanche hazard or risk. For example, when the snowpack variability increases uncertainty in the triggering probability and, hence, avalanche risk, a greater margin of safety is applied to the risk treatment (e.g. terrain selection). Since the uncertainty cannot be fully known or quantified, it is sometimes managed by adding a margin of safety that can decrease the frequency and/or severity of avalanche accidents but not eliminate them. This margin of safety may be described in terms of space or time (e.g. waiting an extra day for the storm snow to stabilize, or traveling 20 m back from the (uncertain) top of the slope). Sometimes the margin of safety is labeled in relative terms like low, moderate or high. Margin of safety is the qualitative analogue to choosing a non-exceedance probability > 0.5.

3.4.4 Team Decision Making

Teams of experts can seek a consensus or risk options can potentially be vetoed in order to make conservative decisions that account for some uncertainty. For example, when creating a list of open (i.e. green) and closed (i.e. red) runs for the day, lead guides at a helicopter-skiing operation may only list runs as open if everyone agrees.

3.5 Strategies for Communicating Uncertainty

Uncertainty is an important part of hazard/risk assessments. Hence, it should be explicitly communicated to the risk owner (CSA, 2010) and others involved in assessing hazard and risk (Morgan and Henrion, 1990). Uncertainty in a qualitative variable can only be expressed qualitatively; however, uncertainty in a quantitative variable can be expressed quantitatively or qualitatively (e.g. you cannot have 10 % uncertainty in a moderate risk rating, you can only have "low uncertainty", but you can have "low" or 10 % uncertainty in a risk level of 0.3).

3.5.1 Qualitative Uncertainty

Methods to communicate qualitative uncertainty:

- Use a finite ordered list of levels or classes, in which fewer classes (i.e. lower resolution) implies greater uncertainty. For example, likelihood of triggering (very unlikely, unlikely, possible, likely, almost certain) or avalanche size (1, 2, 3, 4, 5). More classes (i.e. greater resolution) imply less uncertainty. Also, the individual classes can be labeled with words like "typical" or "nominal" to further highlight the deficiency in knowledge and, hence, classification.
- State or display the applicable range of a variable. For example, avalanches that range from Size 2 to Size 3 can be displayed graphically as a whisker, or the length (or width) of a rectangle or ellipse, keeping in mind that the axes represent ordinal variables (Figure 3.2).
- List possible outcomes (e.g. wind slab or storm slab avalanches could occur today).

Qualitative uncertainty is often simply expressed in terms of confidence levels in which high confidence is associated with low uncertainty and vice versa (Willows and Connell, 2003). For example, for a short-term qualitative hazard assessment: if a slab avalanche releases above the highway corridor today, confidence is high that it will not exceed Size 2.

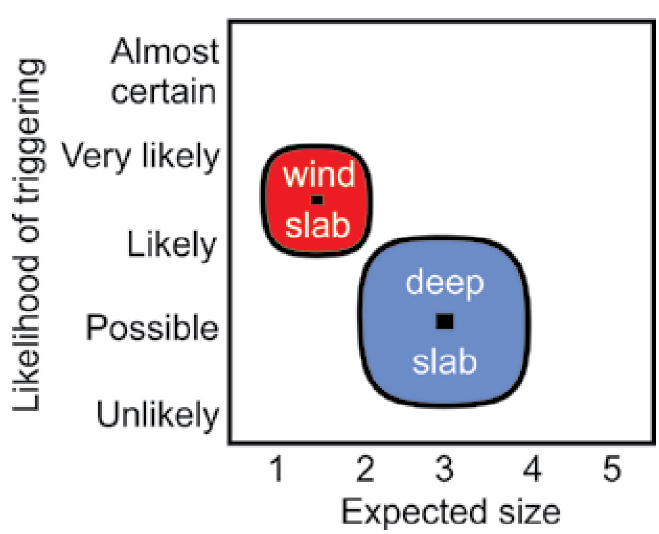


Figure 3.2: *For a given forecast area, day, and character of avalanche, this avalanche hazard chart displays the qualitative uncertainly and variability in expected avalanche size (1 to 2 for wind slabs and 2 to 4 for deep slabs) and in the likelihood of triggering (likely to very likely for wind slabs and unlikely to likely for deep slabs) (after Statham et al. 2010 and in prep.).*

3.5.2 Quantitative Uncertainty

Expressing uncertainty quantitatively requires error estimation (e.g. determining the accuracy of measurements through an analysis of equipment and observer bias). Uncertainty in a quantitative variable can be expressed as a confidence interval, as it is in traditional statistical analysis. For example, Haegeli et al. (2014) found that airbags increase the probability of survival by an average of 11 percentage points (from 78 to 89 %), and the 95 % confidence interval for the increase is four to 18 percentage points. Confidence intervals can also be displayed graphically, typically as whiskers (e.g. Figure 3.3). Uncertainty can also quantitatively expressed as a standard deviation. For example, with a specific thermometer, the temperature measurement has a standard deviation of 0.5°C.

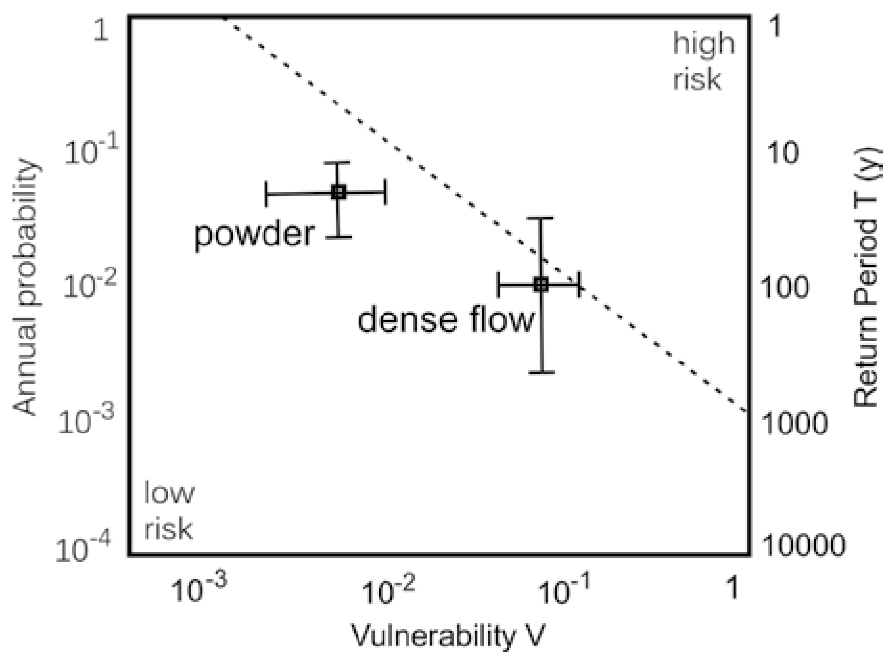
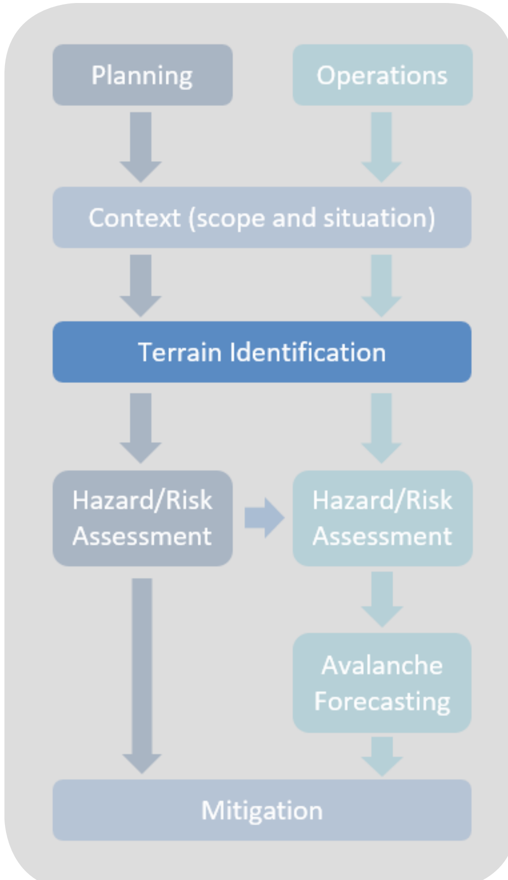


Figure 3.3: *This example risk graph shows the quantitative uncertainty in annual probability and vulnerability as whiskers (confidence intervals) for two hypothetical scenarios: a dense flow avalanche and a powder avalanche that threaten a ski lift tower. The dense flow scenario has lower probability of impact and greater vulnerability, whereas the powder avalanche scenario has higher probability and lower vulnerability. Since diagonal lines such as the dashed line represent a constant level of risk (product of probability of impact and vulnerability), the dense flow scenario – especially considering its uncertainty – constitutes higher risk to the tower.*

3.5.3 Knowledge Base

Knowledge source uncertainty arises from the assumptions behind a model or process, and the limitations of the underlying data (Aven and Renn, 2014). These sources of uncertainty should be communicated to the risk owner. For example, consider a 10-year runout extent that is based on an analysis of vegetation and 20 years of historical records. In this case, the risk owner should be advised that uncertainty rises from a limited record of history.

D. Bryan photo.



Chapter 4 Outline

4 Avalanche Terrain Identification, Classification and Mapping

Understanding and communicating the subject of avalanche terrain are important components in both the planning and operational stages of avalanche risk management. In comparison to snowpack properties, terrain can be analyzed more objectively given that its geographic parameters are measurable and can be considered mostly static, at least over the short term.

Avalanche terrain identification involves the analysis of topography, vegetation and surficial materials, observations and records of avalanche activity, snow supply and climate characteristics, and/or numerical runout modeling to identify the location and extent of avalanche terrain.

Mapping, which is closely linked to avalanche terrain identification, is the process of analyzing terrain information and data, and presenting the results on a map. It provides the basis for understanding and communicating location and runout extent, and specific terrain parameters (e.g. slope angle, slope shape, elevation and aspect). As in terrain identification, mapping is also undertaken at a variety of scales and levels of detail, depending on the objective of the assessment.

Terrain is often classified into distinct categories based on pre-determined criteria. This is used for several applications, including land-use planning and backcountry travel, and helps to standardize risk assessment methods, communicate the complexities of avalanche terrain, and streamline actions to mitigate the risk. Terrain classification sometimes leads to zoning, which is a type of avalanche mitigation (Chapter 8) that utilizes mapped boundaries to designate specific policy or regulation for land use.

This chapter outlines the methods and elements of terrain identification, mapping and classification that may be required in a hazard/risk assessment. These methods may be incorporated at the planning or operational stage, although any formal documentation (e.g. maps) is usually produced in the planning stage. Guidance for the use of specific terrain identification, classification and mapping techniques is outlined in Chapter 9.

4.1 Avalanche Terrain Identification

4.1.1 Methods

The method(s) used and level of effort put into avalanche terrain identification depend upon the context (i.e. stage, scope and situation) and the resulting level of detail required. Specific examples of avalanche terrain identification methods for planning and operations can be found in Chapter 5 and Chapter 6 respectively.

In general, avalanche terrain identification methods can be categorized as those that take place either in an office (i.e. *desktop*) or in the *field*, as outlined in Table 4.1 and summarized in the following subsections.

Table 4.1: *Methods for avalanche terrain identification.*

Method		Description
Desktop		Desktop study of photographs, imagery and topographic maps, as well as digital elevation models and other data using Geographical Information Systems (GIS), at various scales. Collection and analysis of avalanche activity records and climate data.
Field	Ground-based survey	On-the-ground mountain travel to observe and/or measure characteristics of terrain, vegetation and surficial materials, as well as current avalanche activity or recent avalanche deposits.
	Aerial reconnaissance	Observations similar to those made from the ground, but made from an aircraft (helicopter or airplane), so often involve more estimation. Limited reconnaissance may also be accomplished using Unmanned Aerial Vehicles (UAVs or “drones”).

Desktop

Desktop investigations during both the planning and operational stages often begin with analysis of terrain photographs and imagery, topographic maps, oral and written avalanche activity records, and/or snow supply and climate data. Google Earth™ or other GIS-based digital terrain models are helpful tools to gain a general impression of terrain during the initial stages, or for advanced analysis when required. In most cases, a preliminary desktop investigation is conducted in preparation for field investigations.

Terrain Photograph Interpretation

Terrain photograph interpretation ranges from quick referencing for backcountry travel or operational avalanche control, to detailed scaling for translation to maps (Weir, 2002; Akiyama and Ikeda, 2013). Common types of terrain photographs are oblique photographs and vertical photographs (e.g. aerial photographs or "air photos"). In addition, high resolution satellite imagery (e.g. imagery available through Google Earth™) is often sufficient for avalanche terrain identification and freely available for many areas in Canada. The date the photograph was taken is often an important consideration for interpretation. Time series of terrain photographs can be used to observe changes in terrain and vegetation over time due to avalanches and other terrain modifying processes.

Oblique photographs are low-level photographs taken from an opposite side of a valley or from an aircraft, and provide an excellent perspective of avalanche terrain (Figures 4.2, 4.3 and 4.9). Oblique photographs are useful as illustrations in reports, for graphically documenting avalanche occurrences, and as reference photographs for planning travel through avalanche terrain or operational avalanche control. Structure from motion (SfM) photogrammetry is an emerging technique for modeling three-dimensional surfaces using overlapping oblique photographs (Gauthier et al., 2015).

Vertical aerial photograph interpretation is often used to identify specific surface features (e.g. forest cover) and conditions by recognizing the displayed patterns. Stereo pairs of vertical aerial photographs allow three-dimensional interpretation of the terrain. When possible, ortho-photographs (i.e. orthographically rectified vertical aerial photographs that minimize distortion from topographic relief, lens distortion and camera tilt) are used, since the uniformity of scale allows for photogrammetric applications (e.g. overlaying the imagery directly onto maps or taking measurements directly on photographs).

Other useful references for terrain photograph interpretation:
Avery (1968); Gibson (1998); Keeser (1976); Molland and Janes (1984)

Topographic Map Analysis

Topographic map analysis allows for measurements of slope angle, widths and lengths of avalanche paths, elevations and aspects. Map scale determines accuracy. Preferred map scale based on the assessment scale is provided in Table 4.2. Small-scale maps in the range of 1:20,000 to 1:250,000 indicate general characteristics (e.g. aspect and elevation) in and around avalanche paths under study. Large-scale maps in the range of 1:1,000 to 1:10,000 identify detailed characteristics within avalanche starting zones, tracks and runout zones (e.g. slope angle and slope shape). Topographic maps with high resolution satellite imagery showing forests can be very useful in establishing boundaries of large and small avalanche paths and estimating input parameters for numerical runout models. However, standard government issue topographic maps often use low resolution basemap data (e.g. forest cover) with limited application for avalanche terrain identification.

GIS Analysis

GIS analysis includes either segregating or overlaying digital data layers (e.g. base maps, ortho-photographs and specialized terrain queries) to illustrate different parameters (Figure 4.1) or apply classification algorithms (Delparte, 2007). For example, when identifying avalanche starting zones, it may be useful to study layers that include slope angle, aspect, elevation and vegetation, or some combination of these layers. When using GIS, ensure that the projection and map datum is consistent across all layers. It is also important to understand the limitations of surface analysis due to resolution and data acquisition methods. When available, high-resolution (i.e. ~1 m cell) digital elevation data (e.g. from LiDAR or SfM photogrammetry) provides the most precise rendering of terrain for detailed analysis (e.g. particla flow modeling to determine flow directions in subtle terrain).

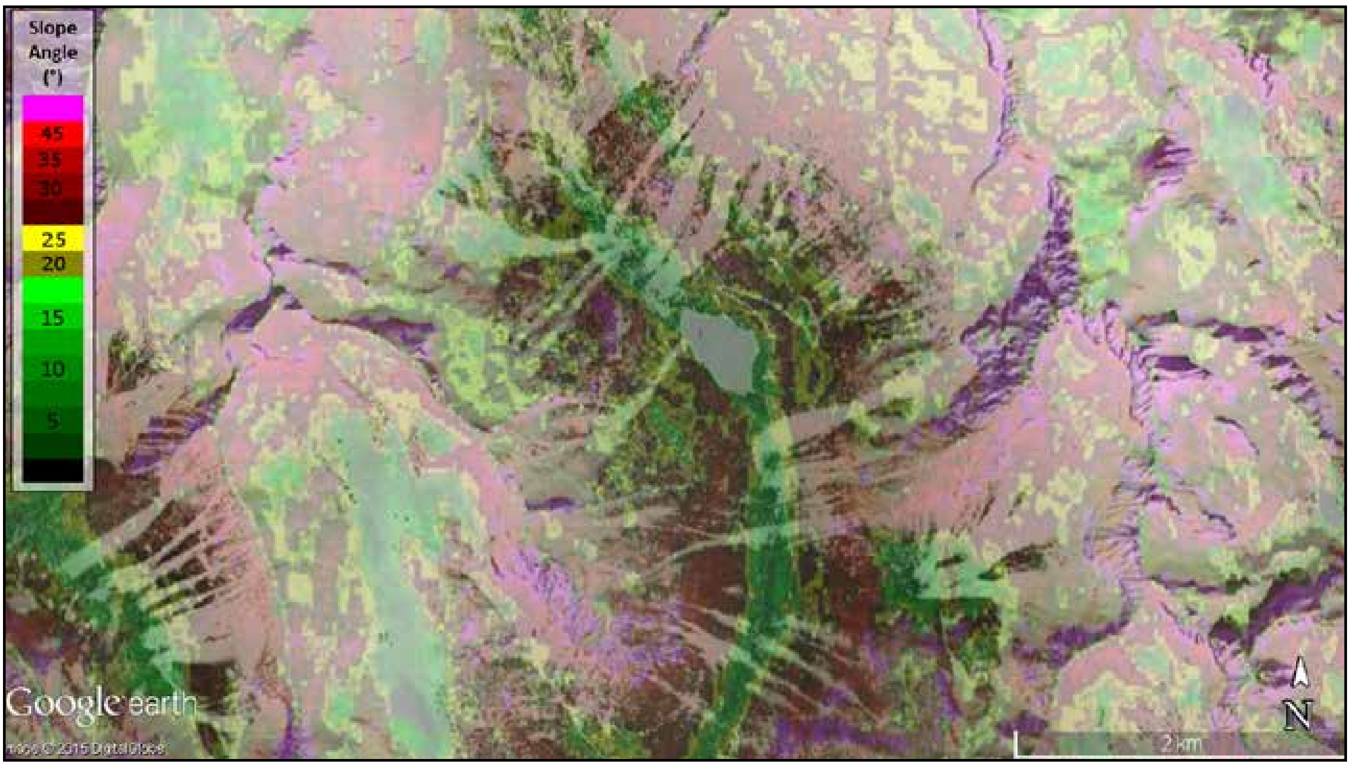


Figure 4.1: *Example GIS display showing a semi-transparent colour-coded slope angle layer overlaying high resolution satellite imagery. The darker shades of red and purple represent steeper slopes while yellow and green represent lower-angled slopes. Forest cover, including avalanche tracks and runout zones, can be clearly seen in the underlying imagery. Image © 2015 DigitalGlobe.*

Field

Avalanche terrain identification often requires verification and supplementary observations from the field since not all avalanche paths, particularly those in forests or in steep northerly quadrants, can be accurately identified on photographs or maps. Furthermore, field observations often provide the information needed for conclusions about the frequency of previous avalanches. For detailed interpretations, it is essential to visit the terrain in question, observe it closely, and form an impression of the severity of the terrain (e.g. overall steepness, forest cover, concentration of avalanche paths and runout zone characteristics) and the subtleties of each avalanche path.

Ground-based Survey

Ground-based survey of avalanche terrain for planning purposes is often completed when the ground is snow-free in the summer or fall, which allows for detailed investigation of vegetation and surficial materials in the runout zone (required for estimating return periods to various locations), and eliminates the concern for avalanche risk that may be present during winter or spring field study. But ground surveys can also occur when avalanche risk is present during winter operations. Slope angle and shape, ground cover, clues from dendrochronology, and measured dimensions of the avalanche terrain are typical recorded parameters. Although summer and fall field visits are preferred, observations of paths on snow-covered ground aids in understanding the snowpack distribution across the terrain in study. In addition, late winter or spring observations, after large avalanches have occurred, help to visualize patterns of avalanche flow.

Aerial Reconnaissance

Aerial views allow expert observers to quickly interpret terrain from several angles. Often patterns and clues emerge from aerial reconnaissance that otherwise would not be evident from a ground-based survey. Helicopters are often the most desirable aircraft for aerial reconnaissance, due to their ability to fly slow and hover; airplanes may also be used as a lower-cost alternative. Although not considered a replacement for aerial reconnaissance from aircraft, drones are increasingly being used to supplement ground observations, especially during the planning stage.

Level of Effort

The level of effort put into an avalanche hazard/risk assessment, and the corresponding extent of investigation required, depends on the objectives and stage of assessment (i.e. planning or operational), along with size of the study area or assessment scale (Chapter 2), complexity of the terrain, and element(s) at risk, including exposure-time characteristics. The level of effort can be determined by the preferred map scale using Terrain Survey Level of Effort (TSLE) scale (Table 4.2) (after BCMoFLNRO, 1999). The four-level TSLE scale represents the extent of field surveying from A (most field surveys) to D (least field surveys) recommended for accurate avalanche terrain identification at the preferred map scale.

Table 4.2: *Terrain Survey Levels of Effort (TSLE) recommend the extent to which terrain identification and mapping should be checked from the field (after BCMoFLNRO, 1999). Based on a preferred map scale, the typical assessment scale (Section 2.5), percent (%) of avalanche terrain field-surveyed, method of field-surveying, and rate of field progress is listed.*

TSLE	Preferred map scale	Typical assessment scale	% of avalanche terrain field-surveyed	Method of surveying	Rate of field progress per day (ha)
A	1:1,000 to 1:10,000	Terrain feature- to slope-scale	50 – 100	Ground surveys by foot traverses.	20 – 100
B	1:20,000 to 1:50,000	Slope- to path-scale	20 – 50	Ground surveys by foot traverses, supported by vehicle and/or flying.	500 – 1,200
C	1:20,000 to 1:50,000	Path- to mountain-scale	1 – 20	Vehicle and flying with selected ground observations, supported by desktop investigations.	1,500 – 5,000
D	1:20,000 to 1:50,000	Path- to mountain-scale	0	No field surveys. Desktop investigations only.	n/a

4.1.2 Topography

Topography (terrain configuration) is the most important consideration when identifying avalanche terrain. Topography is studied using both desktop and field methods. While long avalanche paths (e.g. Figure 4.2) are more easily recognized, short avalanche paths (e.g. Figure 4.3) are more often overlooked. However, in Canada, from 1950 to 2000, 55 % of avalanche fatalities in or near residential or public buildings occurred at the base of slopes < 150 m high.

Avalanche hazard depends on many topographical characteristics of the starting zone (Chapter 2) (Figure 4.2), including slope angle, size and shape of the starting zone, orientation to wind and sun, and the presence, size and character of a fetch zone (i.e. source for wind-transported snow). The slope angle of the starting zone is the leading topographical factor that affects avalanche hazard. Large avalanches most often start on slopes with an angle of 25° - 40°. Avalanches on steeper slopes tend to be smaller but more likely to trigger or frequent.

Large avalanches usually decelerate on slopes of < 15°, which is generally the steepest slope angle found at the top of runout zones (Chapter 2) (Figure 4.2). However, this depends on topological characteristics such as ground roughness and vegetation. Furthermore, avalanches with sufficient momentum can run onto the valley floor and sometimes ascend steeper slopes on the opposite side of the valley.

Tracks (Chapter 2) (Figure 4.2) usually have a slope angle of 15° - 25° and contain narrow gullies that channel avalanche flow. However, they can also be indistinct and difficult to define with no clear division between the starting zone and runout zone.

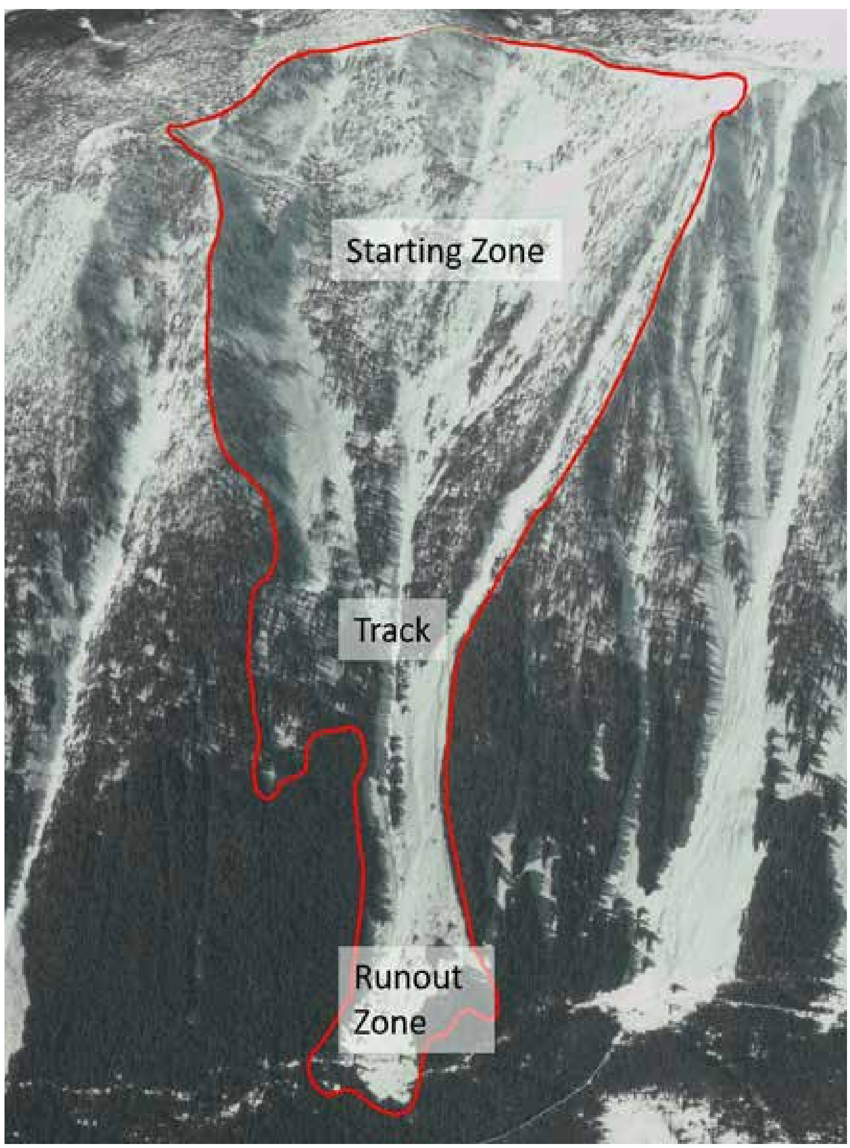


Figure 4.2: *Oblique photograph of an avalanche path with distinct lateral boundaries (i.e. trim lines) The three main parts of an avalanche path (i.e. starting zone, track and runout zone) are labeled. The perimeter of the avalanche path (red line) is commonly marked in an avalanche atlas (Chapter 11). Image © 2015 DigitalGlobe.*

Figure 4.3: *Oblique photograph of an avalanche slope with trees. The spacing of trees on this slope allows avalanches to start and run. Although there are no distinct lateral boundaries (i.e. trim lines) to these avalanche paths, the full width of this slope is capable of producing destructive avalanches. B. Jamieson photo.*

4.1.3 Vegetation and Surficial Materials

Vegetation is an important indication of the location and extent of avalanche terrain. The motion of avalanches often damages vegetation (e.g. trees and bushes) leaving clues (sometimes for decades) about frequency, magnitude and runout extent. Surficial materials may be transported from slopes above and can provide some of the oldest clues available. However, forest fire, harvesting, disease, as well as tree and ground cover clearing for development can obscure the vegetative and surficial material evidence of previous avalanches.

Vegetation is studied using both desktop and field methods, while the study of surficial materials often requires field methods. Large avalanches often leave a boundary between damaged or younger vegetation and older undamaged vegetation. These boundaries, known as trim lines, can be obvious (Figure 4.2) or subtle (Figure 4.3). Dendrochronological studies (Figure 4.4) can yield important information about the frequency, magnitude and runout extent of avalanches that provides input into hazard assessments (Luckman, 2010). Radiocarbon dating (Jakob, 2010) of surficial materials (e.g. woody debris or peat) may be used to date historic avalanches and approximate runout extents with very long return periods (e.g. > 100 years) (Boucher et al., 1999).

Avalanche hazard depends on the type and density of vegetation. Weir (2002) estimates that a tree density of > 1,000 stems/ha is necessary to prevent avalanches from releasing by way of mechanisms such as anchoring (McClung, 2001). However, destructive avalanches can release in a forest opening as small as 10 m x 10 m (Gubler and Rychetnik, 1991). Standing dead forests should be considered as bare ground.

Other useful references for dendrochronology:
Burrows and Burrows (1976); Weir (2002); Luckman (2010)

Figure 4.4: *Dendrochronological studies being conducted to determine vegetative clues, such as tree age and damage. Analysis of these data are often necessary to evaluate avalanche hazard for planning. B. Gould photo.*

4.1.4 Avalanche Activity Observations and Records

Direct observations or oral or written records of avalanche activity can be valuable for avalanche terrain identification during both the planning and operational stages. Social media can also be used to cast a wide net when searching for information on potential avalanche locations. Depending on the quality, reliability, timing and resolution of the observation or record, terrain identification can range from confirmation of avalanche terrain to specific topography associated with different avalanche characters.

4.1.5 Numerical Runout Models

Numerical runout modeling is used during the planning stage and often incorporated into secondary desktop study, after preliminary desktop work and field survey, in situations where:

- Vegetation and surficial materials and oral and written records are insufficient for determining runout extent (e.g. in remote alpine terrain).
- The determination of runout extent requires a high level of precision.
- Impact pressures are needed for design.
- Determination of runout extent with infrequent return periods (e.g. 300 years) is required.

This includes *topographical-statistical models* and *physical-dynamic models*. Often, many models are used to estimate runout extent and/or impact pressures for the same avalanche path in order to address uncertainty.

Topographical-statistical Models

Information on runout distances within the same mountain range and similar snow climate may be used to statistically estimate the runout distance for a particular path using topographical-statistical models. There are two commonly used models: the Alpha-Beta model (Lied and Bakkehöi, 1980); and the Runout Ratio model (McClung and Mears, 1991). Both models use the Beta (β) point, which is where the slope angle of the path first decreases to a certain angle (usually 10°) when descending from the starting zone. Measurements needed for both models as shown in Figure 4.5.

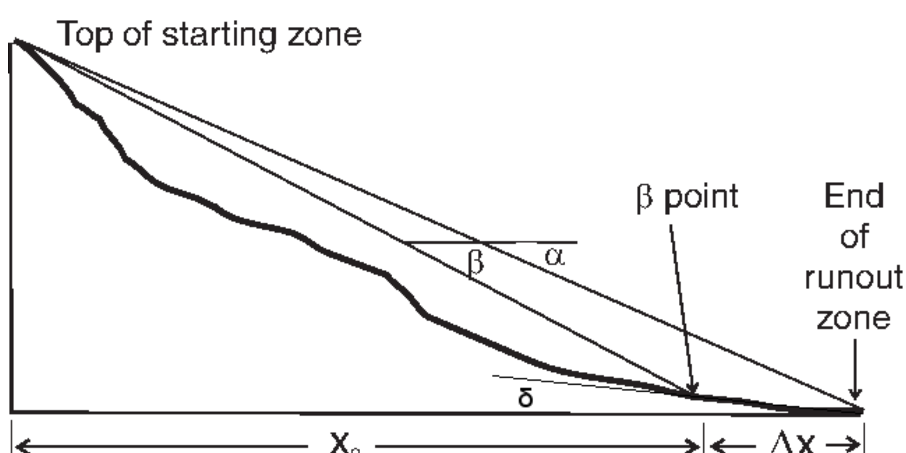


Figure 4.5: *Profile of a hypothetical avalanche path that shows measurements used for topographical-statistical models. The path profile extends from the very top of the staring zone to the extreme end of the runout zone. The β (beta) point is the position at which the slope angle first reaches a certain angle (usually 10°) when descending from the starting zone. The angle β is measured from the β point to the top of the starting zone, while the angle α (alpha) is measured from the end of the runout zone to the top of the starting zone. δ (delta) is the average slope angle of the runout zone.*

Physical-dynamic Models

Physical-dynamic models use physical laws (e.g. conservation of momentum) to predict avalanche velocity and trajectory down the often simplified topography of an avalanche path. Some models (e.g. Bartelt et al., 2011) represent the physical processes well but involve many parameters, which may have not yet been measured. Others simplify the physical processes and involve only a few parameters (e.g. release area, release depth and two friction coefficients). These practical models (e.g. Perla et al., 1980, 1984; Salm et al., 1990; Christen et al., 2010) are used in two distinct ways. In a path with a known runout distance, the parameters can be adjusted so the runout distance is accurately modeled, in which case, the velocity and impact pressure along the path are well estimated. Alternatively, if the friction coefficients are taken from runout distances in similar nearby paths, the models will estimate runout distances, as well as velocity and impact pressure, but with uncertainty (Jamieson et al., 2008).

Other useful references for numerical runout models:
Mears (1992); Rudolf-Miklau et al. (2014); Jamieson and Sinickas (2015)

4.1.6 Snow Supply and Climate Characteristics

A study of snow supply and other climate characteristics is normally performed in conjunction with avalanche terrain identification. During preliminary desktop analysis, this can help to confirm minimum snowpack and weather threshold exceedance for avalanche potential (i.e. threshold snowpack depths to bury ground roughness, plus sufficient additional snow load for an avalanche to occur). If any physical-dynamic modeling is undertaken, snow supply and other climate characteristics (e.g. wind patterns and temperatures) can provide an indication of design slab depths. Climate characteristics can also provide clues into the typical avalanche character and frequency, which can be useful for avalanche terrain identification.

An initial understanding of the snow supply and climate characteristics is achieved through the study of historic patterns of precipitation, temperature and wind. Different snow climate types (i.e. maritime, transitional and continental) have been related to avalanche hazard characteristics. Adding avalanche information to the climate description was introduced by Haegeli and McClung (2007) in an aim to describe interannual variability.

Other useful references for avalanche terrain identification:
Fitzharris and Schaerer (1980); Schaerer and Fitzharris (1984);
Claus et al. (1984); Fitzharris (1987)

4.2 Avalanche Terrain Classification

Terrain classification systems are intended to categorize avalanche terrain into areas with common attributes. These attributes may be topographical (e.g. slope angle and/or forest density) (Figure 4.6), related to avalanche exposure (e.g. degree of interaction of the element at risk with starting zones) or they can include some elements of avalanche hazard (e.g. frequency-magnitude relationships). The two main types of classification systems used in Canada include *impact-based* classification and *terrain exposure* classification.

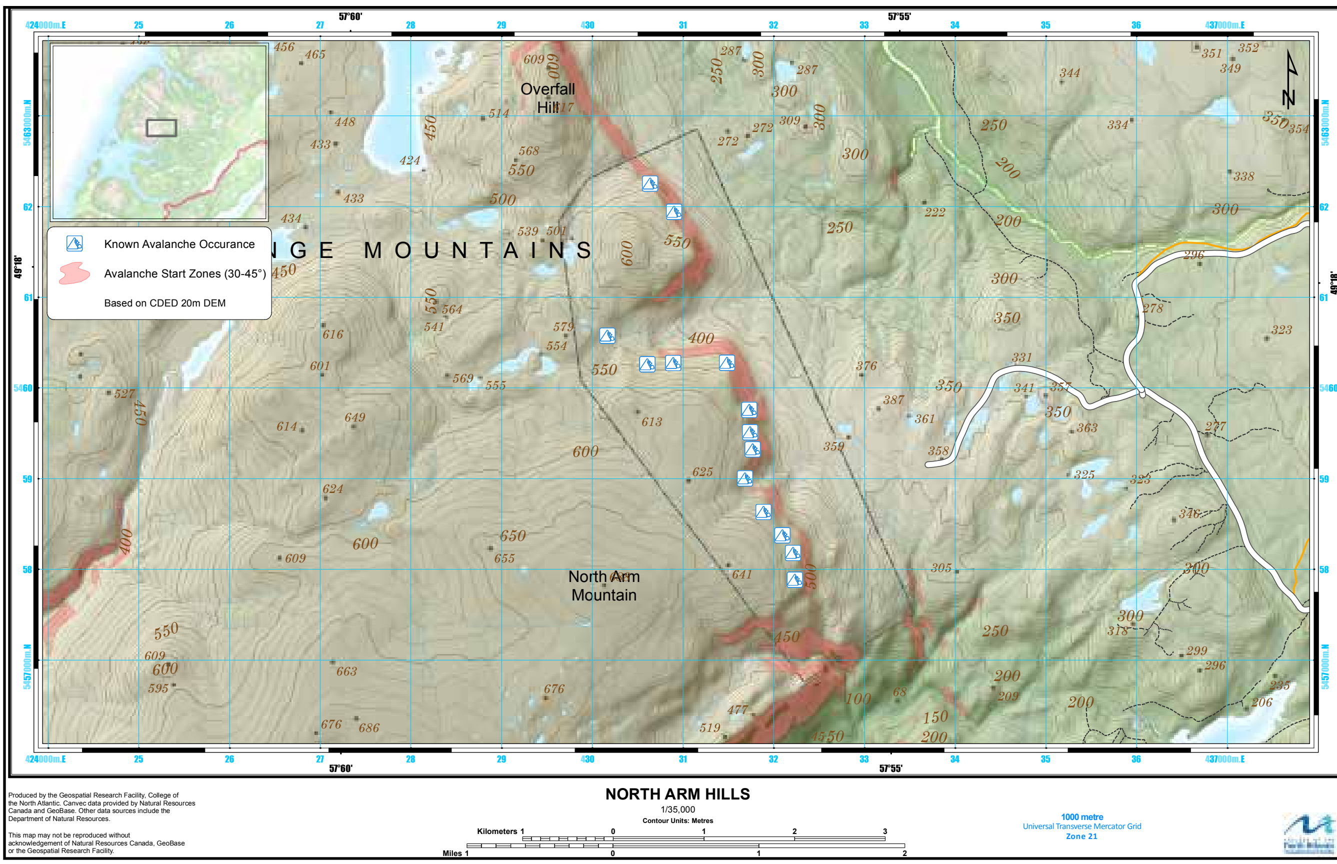


Figure 4.6: *Terrain classification map of the North Arm Hills winter backcountry recreation area in Newfoundland. The terrain is classified by slope angle, with slopes between 30°* and 45° shaded in red. Locations of observed avalanches are also shown. Courtesy of R. Wheeler.

4.2.1 Impact-based Classification

Impact-based classification results from a detailed assessment of hazard or risk that considers avalanche magnitude in terms of the impact of avalanches to people, facilities or the environment. This type of terrain classification is most common for fixed (unmoving) facilities during the planning stage of risk assessment.

A hazard zone model for occupied structures is shown in Appendix 1 (McClung, 2005). This is an impact-based classification system that leads to a hazard map (Figure 4.7), which has associated zoning recommendations for development of occupied structures in Canada (Section 8.2.2). Hazard zones result from an analysis of impact pressure and return period within the avalanche path.

Some European publications including IRASMOS (2009) refer to impact-based classification as *intensity classification*, in reference to magnitude, impact, consequence or destructive potential. Intensity classification sometimes results in the development of intensity maps, which are commonly used for illustrating intensity or impact levels from several hazards.

4.2.2 Terrain Exposure Classification

Terrain exposure classification categorizes avalanche terrain according to severity with respect to the exposure of an element at risk. Commonly known as terrain ratings, these classifications are determined by independent analysis of individual terrain parameters, then systematically combining them to produce a discrete rating.

This type of terrain classification is often used in backcountry travel where the element at risk (e.g. a person) is mobile. These tools provide backcountry users with information on the severity of the avalanche terrain, which is a key element in risk assessment and mitigation for backcountry travel. The Avalanche Terrain Exposure Scale (ATES) (Statham et al, 2006) (Appendix 1) is one example that includes three models: technical, public communication and zoning. Terrain exposure classifications are generally applied as a single overall classification for a defined area or route (e.g. Statham et al., 2006), or as multiple classified zones within a defined area or along a particular route (e.g. Campbell and Gould, 2014).

4.3 Avalanche Maps

Avalanche maps presents the findings of the terrain identification to create a spatial reference point for hazard/risk assessment. Maps range in level of detail and precision depending on the intended application. Digital representation for ease of operational use is also becoming more common with the application of GIS; however, this section approaches mapping as it would be applied for reporting or presentation purposes (Chapter 11).

4.3.1 Scale

The resolution and precision requirements for maps depend on the scale of the situation (Chapters 1 and 9). Large-scale maps (i.e. 1:5,000 to 1:20,000) require higher TSLE (Table 4.2), thus are commonly assumed to be more reliable and appropriate to support decisions about specific avalanche paths. More general small-scale maps (i.e. 1:20,000 to 1:100,000) are commonly used to indicate locations of avalanche terrain for preliminary risk assessment or route planning.

4.3.2 Types of Maps

Locator Map

Locator maps (Appendix 2, Map 1) give a general impression of where avalanche terrain is located and are considered a reconnaissance type of map for preliminary assessments. Avalanche paths are identified by an arrow that indicates the avalanche flow centerline and direction, and normally extends from the top of the starting zone to the approximate maximum runout. The scale is usually 1:20,000 to 1:50,000, and a TSLE of C or D is often sufficient depending on the availability of accurate base maps and higher resolution imagery. Locator maps are commonly used to support planning and operational risk assessment and mitigation for transportation and energy corridors, natural resource projects and recreation areas.

Although useful for providing baseline information as to where avalanche hazards exist, locator maps do not provide areal extent (width and length) of the hazard, or sufficient detail for locating facilities in and around the avalanche path. In addition, since locator maps generally excludes small avalanche paths (i.e. ≤ Size 2 maximum potential) and short avalanche slopes involving terrain traps, insufficient detail is provided to support risk management at the terrain feature- to slope-scale (Gould and Campbell, 2014).

Avalanche Path Map

Avalanche path maps (Appendix 2, Map 2) show the areal extent of specific avalanche paths, normally with a polygon drawn around the boundaries of the starting zone, track and runout zone. In some cases, boundaries of avalanche paths downslope of the element(s) at risk are not indicated (e.g. only the boundaries above a transportation corridor are drawn, even if the avalanche path extends below). The scale is usually 1:20,000; however, large-scale maps (i.e. 1:5,000) and increased TSLE may be necessary if greater precision is required.

Avalanche path maps provide the basis for any detailed planning that involves avalanche terrain. For example, planning operational avalanche control for a highway or location planning for a worksite that is threatened by an avalanche path. Avalanche path maps are the preferred map type for an avalanche atlas (Chapter 11).

Hazard, Risk and Terrain Class Maps

Hazard, risk and terrain class maps are a detailed representation of avalanche hazard, risk or terrain class often used for risk control based on procedure and policy, planning transportation corridors and pedestrian areas, as well as hazard zoning for occupied structures (Section 8.2.2). They display hazard, risk or terrain class in one of two formats:

- Linear (e.g. transportation corridor or transmission line (Appendix 2, Map 3) or ski run (Figure 4.9)).
- Polygonal (e.g. occupied structures (Figure 4.7) or backcountry area (Appendix 2, Map 4)).

Hazard, risk or terrain class maps scales are typically in the range of 1:5,000 to 1:50,000, depending on the application, and in order to facilitate operational use, hazard, risk and terrain class maps are often provided in digital format (e.g. PDF or KMZ).

The TSLE used for hazard, risk, or terrain class mapping can range from A to D, depending on:

- Desired map scale.
- Level of detail required for the classification system.
- Intended stage (planning or operations) for map use.
- Exposure characteristics for the element(s) at risk.
- Weight prescribed to the hazard levels or terrain classes for risk control based on procedure and policy.
- Risk tolerance.

Regardless of TSLE used for mapping, expert judgment is typically required for accurate hazard, risk or terrain class maps.

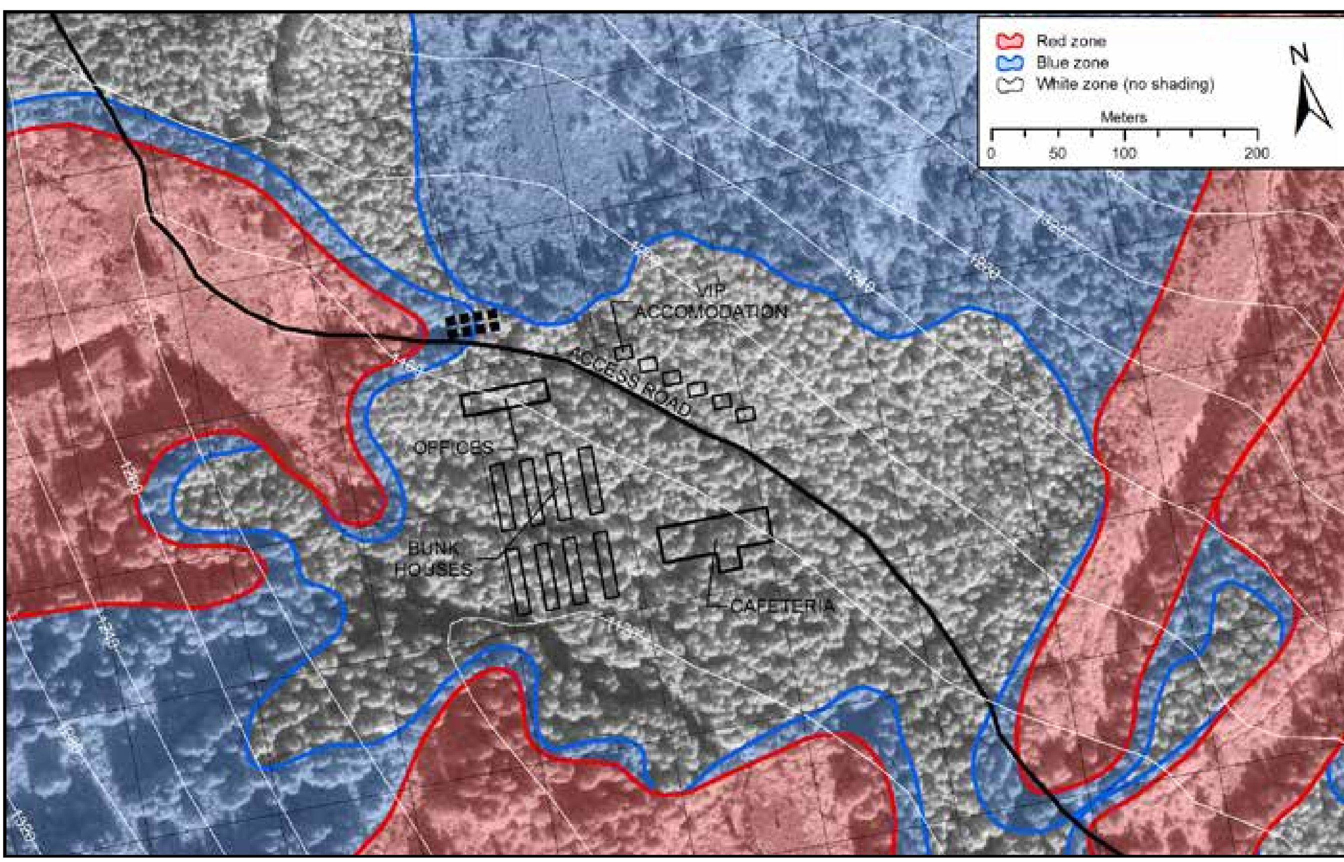


Figure 4.7: *Example hazard map for occupied structures. This map shows colour-coded zones classified according to an impact-based classification system such as the Canadian system for occupied structures (Appendix 1). In this case, the red zone indicates high hazard, the blue zone is moderate hazard, while no shading (white zone) indicates low hazard. Important infrastructure and facilities are also shown. Basemap from Natural Resources Canada and ArcGIS® Online.*

Other Associated Map and Photograph Applications

Run maps (Figure 4.8) are essential tools used in both commercial and self-directed backcountry recreational activities for route planning and terrain selection in the field. Common runs and routes are illustrated as lines or polygons and other important features are noted (e.g. ski lifts, weather stations, helicopter landing zones, snowcat trails, rescue caches and fueling locations). Topographic basemaps are typically used and scale is usually 1:50,000 or 1:20,000.

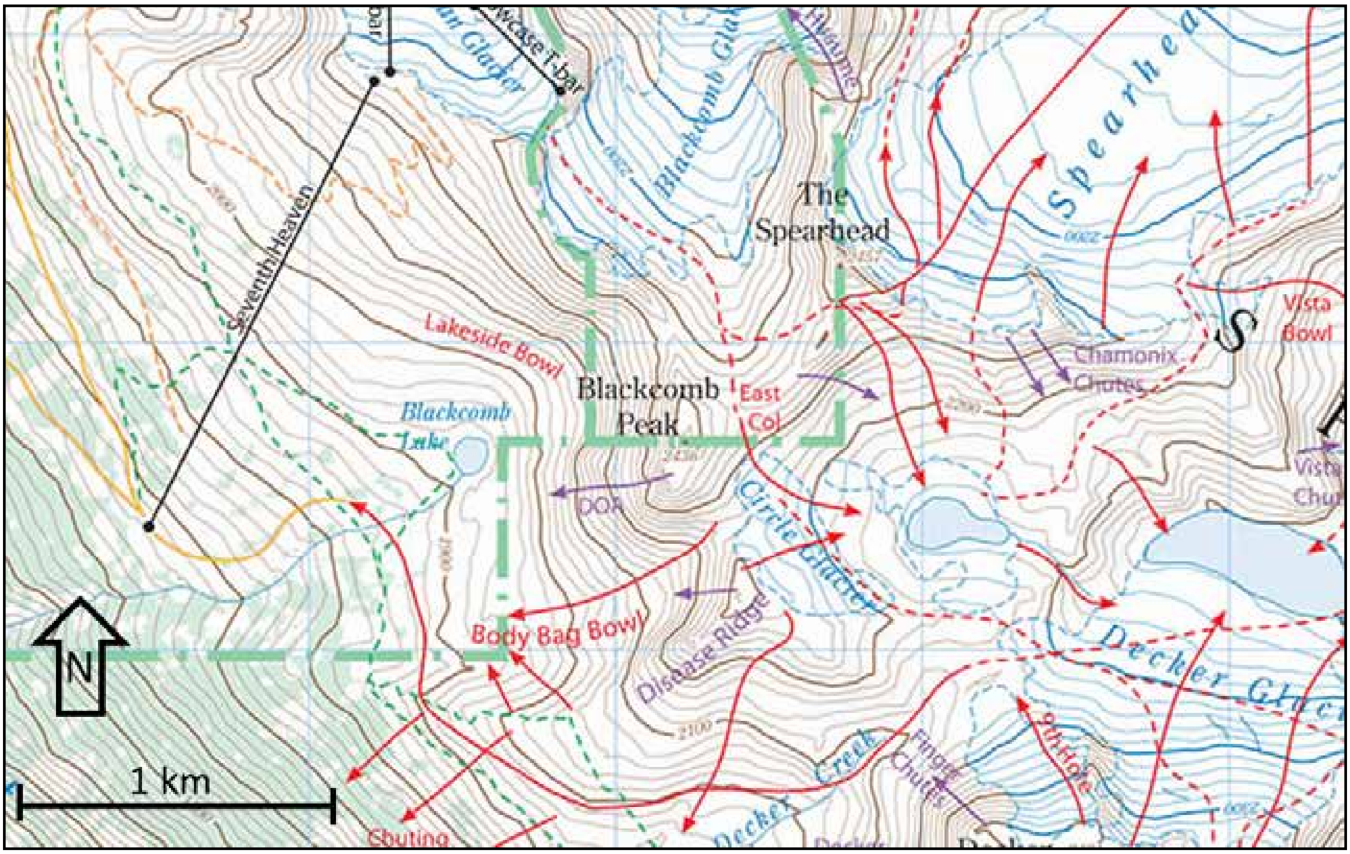


Figure 4.8: *Example run map for a self-directed backcountry recreation area. Common runs are shown as solid red and purple lines, while up-tracks and other routes are shown as dashed lines. Chairlifts (solid black lines) and park boundaries (thick dashed green line) are also shown. Courtesy of J. Baldwin.*

Similar to run maps, run photographs (Figure 4.9) are an important resource for detailed avalanche-risk discussions and decisions. These are high quality oblique photographs of a specific run or riding area that are sometimes overlain with lines or polygons to denote runs as well as other points of interest and land marks. A collection of run photographs are maintained in a run atlas.

Run maps and photographs sometimes incorporate terrain class, locator or avalanche path mapping to highlight avalanche terrain, particularly in high-use areas where exposure to avalanche hazard is the greatest. However, due to the large number and size of public backcountry recreation areas and commercial tenures, comprehensive mapping is impractical and uncommon. Instead, run maps and photographs are used as resources to help facilitate detailed avalanche-risk discussions and decision making for slope-scale operational risk management.

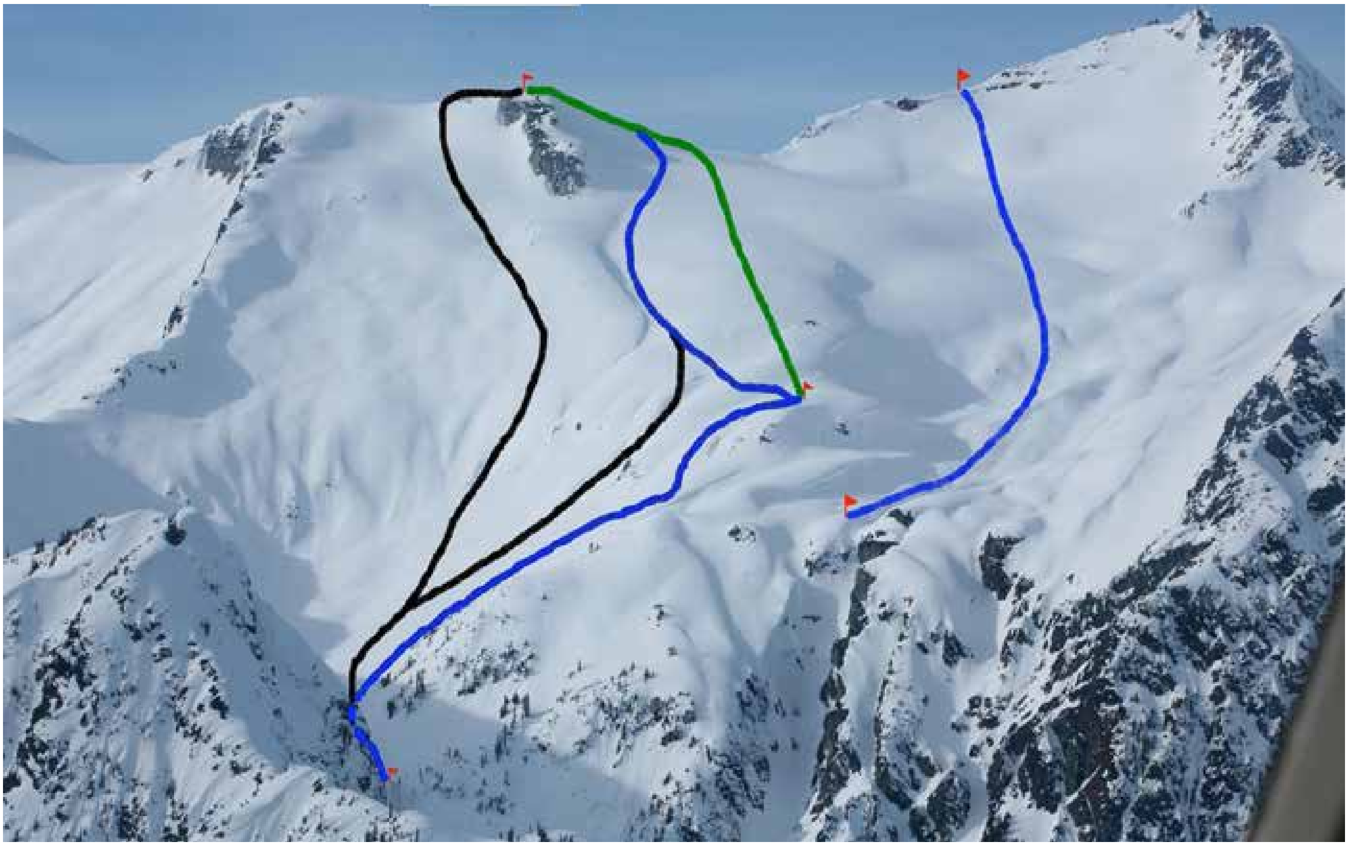
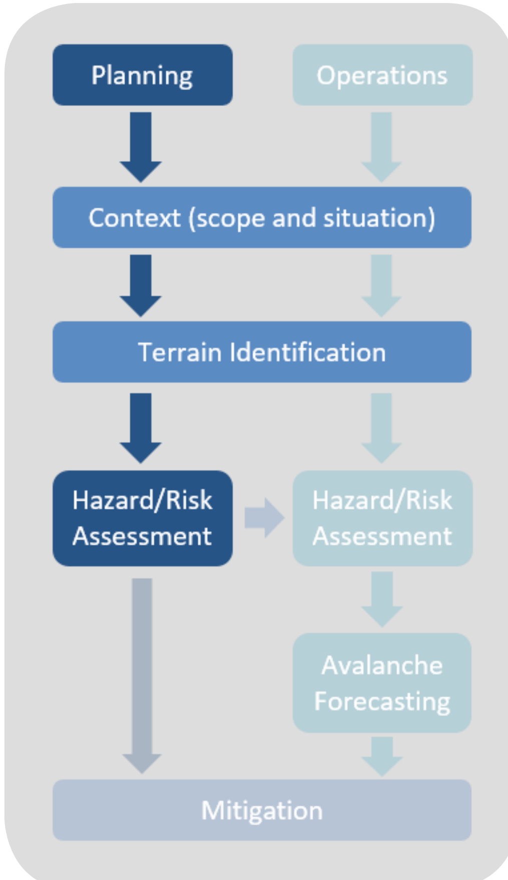


Figure 4.9: *Oblique photograph showing common runs used in a helicopter-skiing operation. The runs are marked with colour-coded lines corresponding to terrain exposure classes. Established helicopter landing zones (red flags) are also marked. Courtesy of Northern Escape Heli-skiing.*

Large fast dry slab avalanche with a significant powder component. This avalanche was artificially triggered using helicopter explosive control and ran a considerable distance up the far side of the valley before turning and running down the valley. D. Wilson photo.



Chapter 5 Outline

5 Avalanche Planning

Avalanche planning involves the study of avalanche hazard, risk, and/or mitigation for specific objectives. This is separate from avalanche operations (Chapter 6) in that the focus of the specific objectives are long term (possibly permanent), and result in maps, plans and reports (Chapter 11).

This chapter outlines a sequence of steps that could be followed when conducting an avalanche hazard/risk assessment from a planning perspective. The assessment could lead to the design of long-term engineered mitigation measures or the development of operational measures to address avalanche hazards in the short term, or a combination of these two approaches. There are several ways to consider avalanche planning; however, this chapter focuses on the risk management process outlined in Chapter 1.

5.1 Initial Steps

The sequence of a planning-stage hazard/risk assessment follows the avalanche risk management process outlined in Section 1.5.2 that includes the initial steps of establishing context (scope and situation) and terrain identification.

5.1.1 Scope of the Planning Assessment

Determining the scope of an avalanche planning assessment includes the clear articulation of the objectives. Some examples of objectives are:

- Complete an avalanche hazard assessment, including avalanche path maps for a proposed transmission line.
- Complete a qualitative risk assessment for a snowcat-skiing operation that includes people (skiers) and snowcat trails.
- Develop an avalanche safety plan for a mining operation that includes an access road and several temporary worksites.
- Design long-term protection measures for a ski-area expansion.
- Complete a quantitative risk assessment for a proposed highway chain-up area.
- Compare mitigation options along a highway segment using the Avalanche Hazard Index (Schaerer, 1989; Conger and Taylor, 1998).

Risk criteria are the terms of reference against which the significance of a risk is evaluated (ISO, 2009). Internal and/or external factors may prescribe the risk criteria or risk treatment options. They may be taken from standards, laws, policies, or other requirements. Risk criteria may also be derived from an organization or individual's readiness to accept the residual risk after mitigation in order to achieve their objectives (i.e. their tolerance of the residual risk).

Risk criteria guidelines outlined in the tables in Chapter 9 should be considered in the scope and agreed upon by stakeholders. There should also be recognition of the factors (internal and external) relevant to the activities or levels of the organization where the risk management process is applied.

5.1.2 Situation for Planning

Determining the situation for the avalanche planning project begins with defining the element(s) at risk (Section 5.3.1). Elements at risk are identified by answering the question "What or who is vulnerable to a potential avalanche?"

Determining the physical (spatial) extent of avalanche terrain or geographic area for the hazard/risk assessment is required to estimate the level of effort needed, and to gather the appropriate resources. Then identifying whether the element(s) at risk is potentially affected by avalanches helps to filter scenario choices (Section 5.3.1). The situation informs the detail and expertise likely required for the hazard/risk assessment. This also helps determine whether long-term mitigation is required, or whether a short-term operational approach may be more appropriate, or a combination of the two.

5.1.3 Terrain Identification for Planning

Avalanche terrain identification that occurs in the planning stage is intended to delineate the extent of avalanche hazard and is a component of both hazard and risk identification. All methods of terrain identification, classification and mapping described in Chapter 4 have application in avalanche planning projects. Some projects will utilize nearly all the methods while others will use only those applicable to the scale and objective of the avalanche planning activity.

For example, regional-scale planning (e.g. defining avalanche forecast regions) may simply involve desktop identification of mountainous terrain with sufficient snow cover for avalanches. However, for planning at the path scale, detailed field-based terrain surveys and desktop analysis may be used to determine precise avalanche path boundaries, estimate frequency-magnitude relationships and model impact pressures.

5.2 Hazard Assessment for Planning

A planning stage avalanche hazard assessment is a series of activities to:

1. Identify and describe the potential for a harmful avalanche.
2. Analyze the environmental conditions that contribute to the hazard.
3. Estimate the likelihood and magnitude of the threat.

These activities follow in general steps of identification, analysis and evaluation.

5.2.1 Hazard Identification for Planning

Avalanche hazard identification may be as simple as recognizing the potential for avalanches. However, when there is uncertainty as to whether avalanche hazard exists for the area in question, more detailed steps that involve the study of terrain, vegetation and snow supply are required. Detailed records from established avalanche operations or long-time residents, employees, etc. may be used to clarify the timing and character of historical avalanches. Further accuracy in frequency and magnitude estimations may be achieved through interviews, especially if people were injured or property was damaged. Additional information may also be written in newspapers, historical records, books or diaries, or captured in images or on video. Numerical runout modeling is incorporated when a high level of accuracy is required. Detailed studies, as well as maps used to record and/or display the results are outlined in Chapter 4.

5.2.2 Hazard Analysis for Planning

The avalanche hazard-analysis step in the planning stage describes the potential avalanche hazard and estimates the probabilities and the dimensions of the area that could be physically impacted. It consists of an *event* analysis and a *frequency-magnitude* analysis.

Avalanche hazard analysis for planning purposes is primarily a desktop exercise in modelling that makes use of available data on climate, terrain and avalanche history. Field surveys, as described in Chapter 4, are important to verify preliminary desktop estimates.

Avalanche Events

An *avalanche event* is set of avalanche outcomes with common characteristics (e.g. avalanches that run beyond a certain point in the runout zone). An avalanche event is used to describe patterns in avalanche activity (e.g. runout extent of the one in 30 year avalanche event), which is one of the most important factors in avalanche hazard assessment. During the planning stage, either formal operational avalanche observation records or informal archival records (e.g. those written in newspapers, historical records, books or diaries, gleaned through interviews, or captured by photographs) may be very useful in determining patterns in avalanche activity. In the case of archival records, residents of the area may recall past avalanches, especially if people were injured or property was damaged. These sources of avalanche activity are used to determine frequency, often in combination with vegetation and terrain-photograph analysis. In cases where such information is unavailable, the hazard analysis must rely on the vegetation or climate data for the assumption of previous avalanche events.

Frequency and Magnitude

Determining the frequency and magnitude of avalanche events is a key component of hazard analysis. Avalanche frequency within a specific path (Chapter 2) is the expected (average) number of avalanches per unit time reaching or exceeding a location. It decreases with distance downslope in the track and runout zone. Avalanche frequency is the reciprocal of avalanche return period and typically expressed in units of avalanches per year as a ratio that ranges from 1:1 (one avalanche per year) up to 1:300 (one avalanche in 300 years). It may also be represented as a probability value or a likelihood statement where each winter, the probability of an avalanche with a certain frequency is constant. However, since it varies with snow conditions, the probability of avalanches with a certain frequency is not constant throughout the winter.

In general, it is expected that as the average frequency decreases down slope into the track and runout zone, the average magnitude increases. For example, a road location near the toe of an avalanche path will be affected by avalanches on a less frequent basis, but the avalanches that reach the road will be larger. Both low frequency large avalanches and high frequency small avalanches may affect a road that is higher up in the same avalanche path. Avalanche magnitude is typically represented by using avalanche size (Chapter 2) or impact pressure (Table 5.1).

Table 5.1: *Avalanche impact pressures and corresponding examples of potential damage (Perla and Martinelli, 1976; Mears, 1992).*

Impact pressure (kPa)	Potential damages
1	Breaks windows
5	Pushes in doors
30	Destroys wood-frame structures
100	Uproots mature spruce
1000	Moves reinforced concrete structures

5.2.3 Hazard Evaluation for Planning

Hazard evaluation for planning involves comparing the results of the analysis to hazard evaluation criteria (e.g. avalanche terrain classification (Section 4.2) (Appendix 1)).

5.3 Risk Assessment for Planning

A risk assessment provides evidence-based information and analyses to support making informed decisions on how to treat particular risks and how to select between mitigation options (after ISO, 2009). The risk assessment builds on the hazard assessment through these additional efforts:

1. Find, recognize, describe and comprehend the element at risk.
2. Analyze its exposure and vulnerability to the hazard for a given scenario.
3. Determine the level of risk.
4. Compare the results to a given criteria to determine whether the risk meets the identified risk tolerance.

5.3.1 Risk Identification for Planning

The risk identification step connects the hazard assessment to the element at risk through risk scenarios. The hazard assessment provides a location, a description of the frequency of occurrence and probability of magnitude for potential avalanche hazard. This potential event is combined with an element at risk.

Element at Risk

At the planning stage, it is important to determine whether the element at risk is mobile or stationary, and how it fits within the broad groups outlined in Section 9.2.1.

Risk Scenario

A risk scenario is a description of a hypothetical sequence of events that occur during the exposure of the element at risk to the hazard. A scenario is easily arrived at by answering the question “What could go wrong (or right)?” (e.g. an avalanche impacts the road). The goal in describing a scenario is to capture, in a practical sense, a set of all the important initial conditions (e.g. snowfall exceeds extreme value predictions) (Garrick, 2008). In addition, the scenario should include the event-initiating circumstance (e.g. major storm) and progress through to one of the final states (e.g. reduction of hazard or loss to the element at risk). In formal risk assessments, establishing scenarios begins with defining the “successful” or “as planned” scenario (e.g. long term mitigation measures stop the 100-year avalanche event from reaching the road) (Kaplan et al, 2001). This allows for additional scenarios to be constructed as deviations from the ideal.

5.3.2 Risk Analysis for Planning

Risk analysis for planning is an examination of the consequence of an event; an analysis of the outcome or range of outcomes. This analysis is a series of actions to understand the potential risk, as well as the uncertainties associated with the risk scenario. In the end, it determines a level of risk through analysis of avalanche hazard, plus exposure and vulnerability of the element at risk, and existing mitigation.

Avalanche risk analysis is completed using either quantitative methods, qualitative methods, or a combination of both. Methods are quantitative in as much as they assign numerical probability values to the identified uncertainties (Vick, 2002). Quantitative procedures typically work from the bottom up, detailing component probabilities, then combining their interaction as a system. Probabilities are interpreted through two approaches, sometimes alone and sometimes combined: the relative frequency approach and the subjective approach. Numerical assignment is the step in the subjective approach to convert likelihood to a numerical probability.

Qualitative procedures are frameworks that provide a structure to start at the top with a broad view and work down. Using the ISO 31000 risk management guidelines is an example of a qualitative procedure. Following the conceptual model of avalanche hazard (Section 6.2.3) is another. Numerous other examples exist (e.g. CAN/CSA-IEC/ISO 31010-10 Risk management – Risk assessment techniques).

> Other useful references for avalanche risk analysis methods: IRASMOS (2009); ISO (2009); CSA (2010); Vick (2002); and others listed in subsequent sections

Exposure

Exposure is the temporal or spatial extent of avalanche hazard to a specific element at risk. It is normally described in terms of time period and position(s) of the element in an avalanche path. Fixed (static) facilities or infrastructure (e.g. buildings and ski-lift towers) are permanent and always located at a defined location within an avalanche path, whereas mobile objects (e.g. people in vehicles or on foot) are not.

Exposure is often expressed as a probability of an avalanche of sufficient size to reach the element at risk. For static elements at risk entirely within avalanche paths, probable exposure is 100 %. For mobile elements at risk, probable exposure is < 100 % and depends on the effective time that the element at risk is exposed to potential avalanche hazard as well as the position within the avalanche path.

Vulnerability

Vulnerability is the fraction of loss given that the element at risk is hit by or caught in an avalanche with a specified type or magnitude. When people are affected by avalanches, vulnerability is the probability of death (after IUGS, 1997). Vulnerability is a function of the resistance of the element at risk to avalanche. It is often expressed in terms of probability of loss of value or life, where 100 % is complete loss (or death), and zero percent is no loss. Since magnitude (e.g. destructive potential or impact pressure) varies with avalanche size, there is a level of vulnerability associated with each size of avalanche for a given element at risk.

Existing Mitigation

There may be risk mitigation measures (e.g. access restriction) already in place that may have an effect on the level of risk due to the potential avalanche hazard. An analysis of the adequacy and effectiveness of these completes the risk analysis step (ISO, 2009).

5.3.3 Risk Evaluation for Planning

Avalanche risk evaluation is the process of comparing the results of risk analysis with evaluation criteria to determine whether the risk and/or its magnitude is acceptable or tolerable (ISO, 2009) (see *risk tolerance* and *risk acceptance* in Section 2.4). When risk tolerance is not provided by regulations, standards or the organization conducting the risk planning, it is often appropriate to develop a risk evaluation system that measures and ranks each risk scenario to help prioritize them. One strategy is to use the "as low as reasonably practical" (ALARP) criteria as outlined in Figure 5.1. Under ALARP, high risks for potential harm must be reduced to a sliding scale where costs and benefits can be directly compared (CSA, 1997; Weir, 2002). Risks are "as low as reasonably practical" when the mitigation efforts result in a tolerable level of risk that cannot be reduced further without resources and costs being disproportionate to benefit gained or where the solution is impractical to implement.

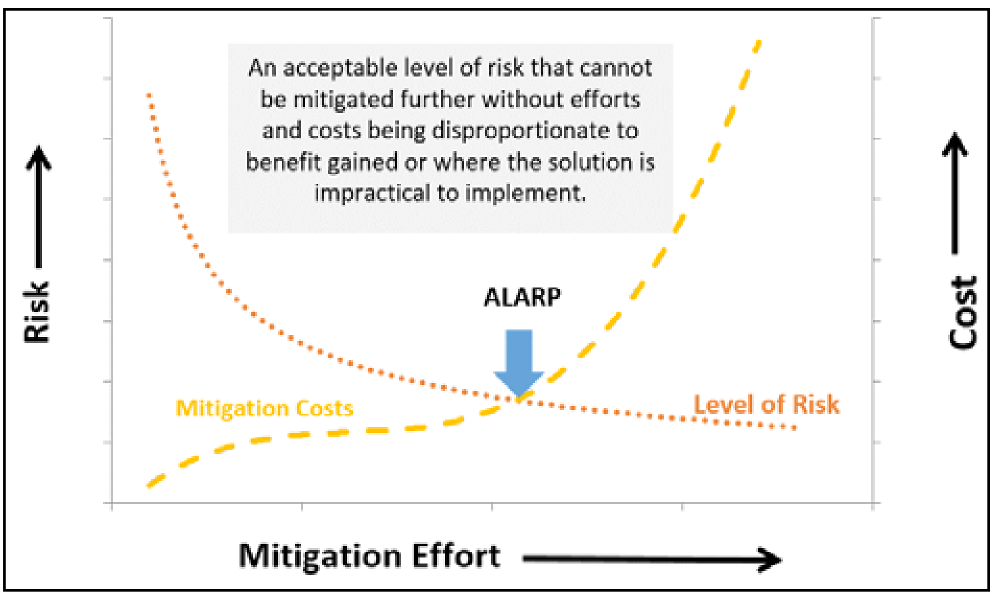


Figure 5.1: *Example of "as low as reasonably practical" (ALARP) risk evaluation strategy. As shown in the figure, risk is mitigated to a level as low as reasonably practical when the residual risk is acceptable and any additional risk reduction comes at a disproportionate mitigation cost or effort, or is impractical to implement.*

The method chosen for the risk evaluation step is directly related to, and must be appropriate for, the situation for which the avalanche risk assessment is being undertaken. Along with the uncertainties due to missing historical information, the assumptions for the modeling of processes are to a large degree based on expert experience and are therefore subjective and uncertain. Selection of an evaluation method should address the level and nature of uncertainties inherent to the scope, stage and situation identified in the context.

Though methods are typically described as either quantitative or qualitative, all methods include a subjective component that should be acknowledged in the results. Comparative methods and uncertainty analysis are common components to both quantitative and qualitative methods. Examples of commonly used quantitative methods include a cost-benefit analysis (Wilhelm, 1998 ; Fuchs et al, 2007; Rheinberger et al., 2009), the Avalanche Hazard Index (AHI) (Schaerer, 1989; Conger and Taylor, 1998), and Probability of Death for Individuals (PDI) (Hendrikx and Owens, 2007).

At a fundamental level, the risk evaluation works through the questions:

1. What is tolerable?
2. How safe is safe enough (i.e. what is acceptable)?
3. What needs to be done?

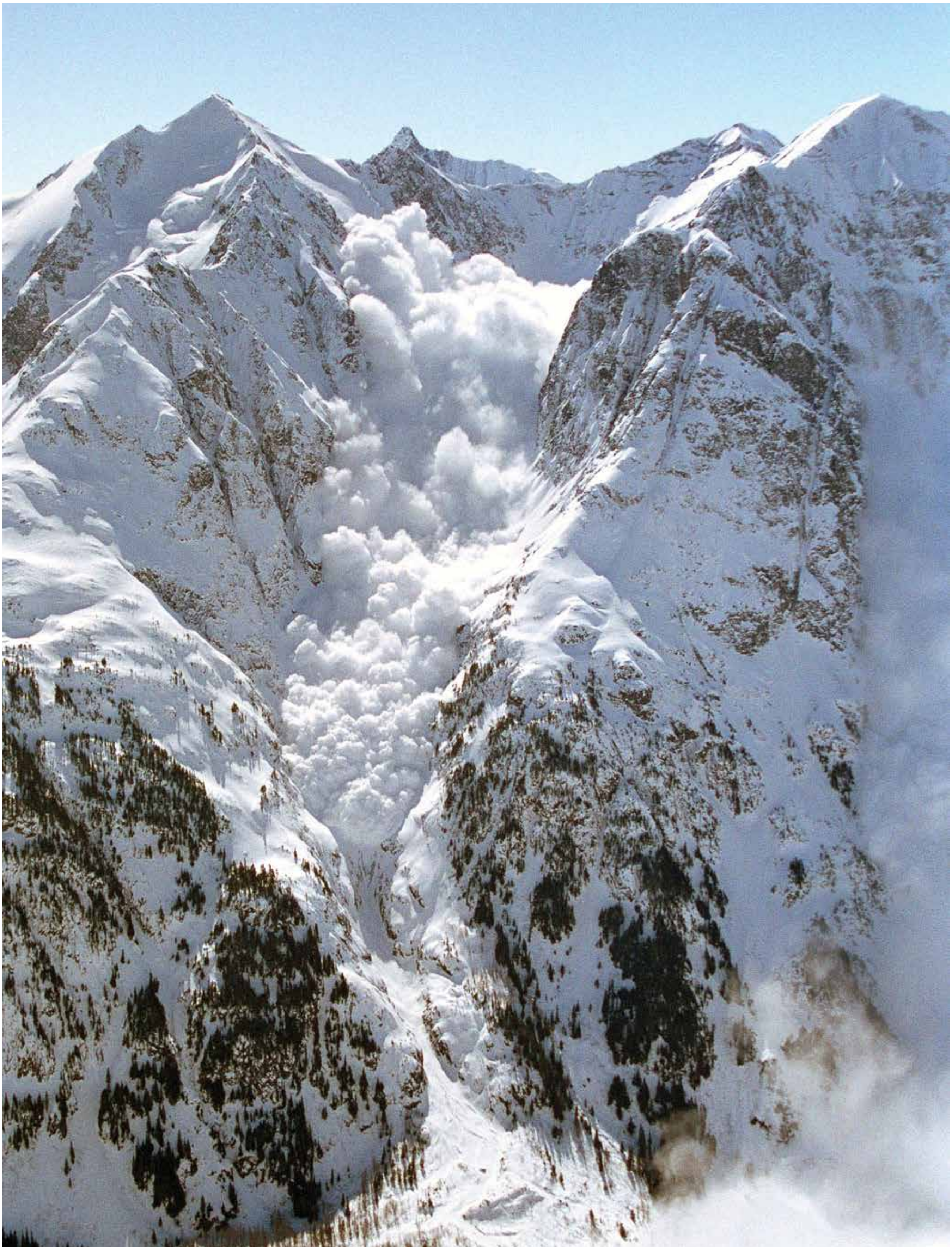
The determination of what is tolerable in establishing the context provides the prerequisite. What is acceptable is the basis for the decisions of:

- Whether an activity should be commenced.
- Whether a risk requires treatment.
- Treatment prioritization.
- Which of a number of options should be chosen.

5.4 Risk Treatment

Risk treatment describes the range of measures available for mitigating the avalanche hazard or otherwise reducing the risk from avalanches. Mitigation is accomplished through measures that result in changes of estimated hazard (frequency and magnitude), exposure and/or vulnerability. This is covered in Chapter 8.

D. Scott photo.



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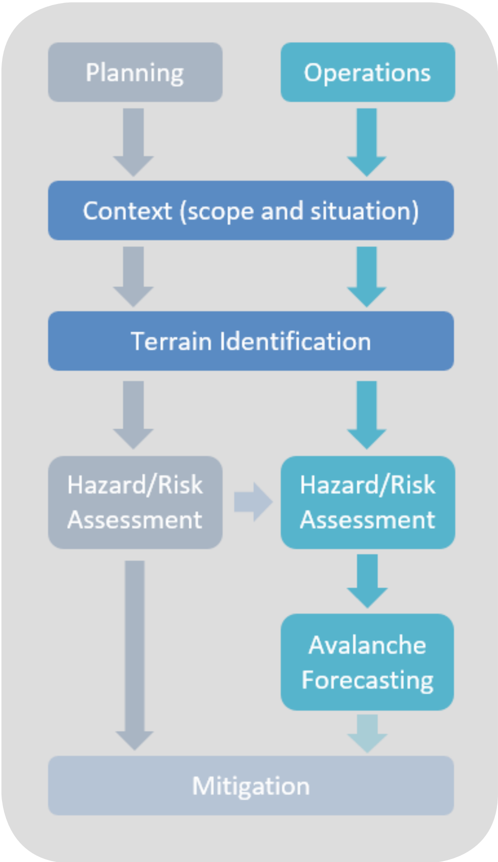


Chapter 6 Outline

6 Avalanche Operations

Avalanche operations refers to activities that include avalanche forecasting tasks and the direction and implementation of short-term mitigation measures in order to achieve specific organizational objectives. Hazard/risk assessment associated with avalanche operations occurs at various levels, from office-based forecasters that rely on field data from a variety of sources (e.g. government highway department regional forecast programs and public avalanche warning services) to individual guides and forecasters at work in the field (e.g. ski hill or helicopter-skiing operation). In some applications, operational avalanche risk assessment may follow an established form or checklist. In other applications it may be reflected in general practice procedures set forth in specialized training and education. In many instances, this process is manifested as a state of situational awareness (i.e. one of constant consideration of the questions that summarize each step).

The steps followed in operational avalanche risk assessment do not fundamentally differ from those of risk assessment in the planning stage. This chapter describes the current best practices using the same steps as the avalanche risk management process outlined in Section 1.5.2.

The distinction from a planning avalanche risk assessment is important. Operational avalanche risk assessment is a real-time activity often in the immediate proximity of the avalanche hazard, though selected steps may be undertaken at a time before assessment and mitigation activities are conducted. In addition, although both short- and long-term mitigation measures may be outlined during the planning stage, avalanche operations normally only involve the application of short-term measures.

This chapter presents a framework that operational and day-to-day avalanche risk assessment utilizes in areas such as transportation, commercial recreation, seasonal field work, search and rescue, and field instruction. Operational risk assessment is typically associated with winter activities; however, it is undertaken anytime there is sufficient snow on terrain with avalanche path characteristics.

6.1 Initial Steps

Similar to the planning stage, it is essential to establish the context when completing an operational avalanche risk assessment. Formulating the scope and determining the situation are examples of possible precursor steps. The next step, though not always apparent when observing operational activities, is terrain identification.

6.1.1 Scope of the Operational Assessment

Defining the scope of the assessment (and resulting mitigation, if required) includes the clear articulation of the operational objectives. Risk tolerance (Section 2.4) must be determined and agreed upon by all stakeholders prior to beginning activities. The recognition of factors (internal and external) relevant to the organization or activities is also necessary to define the scope. Examples of scope of risk assessment for avalanche operations include:

- Complete a morning hazard evaluation for a helicopter-skiing operation and assess daily risk with the guiding team on a run by run basis.
- Conduct explosives control on a slope adjacent to a ski run in order to test instability and determine whether to open the area.
- Analyze regional snowpack data in order to determine if threshold snowpack depths have been reached for a remote site.
- The completion of a site-specific snowpack test to build upon an earlier desktop analysis in order to determine whether to ski a slope.

6.1.2 Operational Situation

Outlining the situation for an operational avalanche hazard/risk assessment begins with identifying the element(s) at risk and determining the physical (spatial) extent of terrain or geographic area where mitigation will occur. This may be specifically described in a risk-control plan (Chapter 8) or may be recognized and acknowledged as part of daily practice procedures.

The element at risk is determined by the operational setting and objectives. Within this parameter, elements at risk can be identified through answering the question "What or who is vulnerable to a potential avalanche?" More information on different types of elements at risk is provided in Section 9.2.1.

6.1.3 Operational Terrain Identification

Operational avalanche terrain identification is an on-going recognition of the extent of the geographic area where avalanche hazard may exist, even when based on prior mapping and terrain analysis, and can occur at numerous spatial and temporal scales. Preliminary desktop methods include photo, map and avalanche atlas (Chapter 11) review and basic GIS analysis to visualize topography, as well as review of reports from other avalanche operations to determine specific terrain characteristics. Subsequent aerial reconnaissance and/or ground-based observations may occur in conjunction with ongoing operational hazard/risk assessment as a component of both hazard and risk identification. For example, direct observations of current or recent avalanche activity can be used to determine specific terrain characteristics associated with different avalanche characters.

6.2 Operational Hazard Assessment

An operational avalanche hazard assessment is a series of activities undertaken to:

1. Recognize the potential for a harmful avalanche.
2. Describe the avalanche problem.
3. Monitor and analyze the environmental conditions that contribute to the hazard.
4. Estimate the likelihood and magnitude of a harmful avalanche.

These activities fall within the general steps of identification, analysis and evaluation.

6.2.1 Operational Hazard Identification

Avalanche hazard identification for operations includes recognition of avalanche terrain and observation of minimum snowpack and weather threshold exceedance for avalanche potential. These topics are covered in Chapter 4.

6.2.2 Operational Hazard Analysis

Avalanche hazard analysis involves the systematic observation, monitoring and investigation of avalanche activity, and snowpack and weather conditions. In addition to emphasizing relevant measurement values, analysis considers the strength and associated uncertainties of the gathered evidence. The careful observation and systematic recording of these factors supports the feedback-driven nature of operational avalanche hazard analysis.

Avalanche Activity

One of the most important factors in analysis is discovery through patterns of avalanche activity. Avalanches observed in real time form a critical input into an operational avalanche hazard analysis (CAA, 2014b).

Snowpack

Hazardous avalanches typically require a threshold snow depth of 30 to 60 cm beyond the amount required to smooth ground roughness or irregularities. Upon nearing this threshold, regular observation and recording of snowpack structure, weaknesses and avalanche character is necessary (Figure 6.1). Since it is not feasible to assess every slope, extrapolation of this information across the spatial scale of the situation is essential. Temporal change of this information necessitates monitoring on an appropriate interval to minimize uncertainty. Understanding the distribution of snow structure and characteristics of weak layers across the terrain is an ongoing requirement in avalanche operations (CAA, 2014b).

Figure 6.1: *A manual snow profile being conducted to observe snowpack structure and identify and assess weaknesses. Analysis of these data are often necessary to evaluate operational avalanche hazard. B. Gould photo.*

Weather

Weather factors have a direct influence on the snowpack, which in turn directly influence the avalanche hazard. Typical observations include sky cover and solar radiation, precipitation type and intensity, air temperature ranges, relative humidity, recent snowfall and total snowpack depth, wind direction and speed, and blowing snow (CAA, 2014b). Spatial redundancy of observations helps to reduce uncertainty.

6.2.3 Operational Hazard Evaluation

Operational hazard evaluation consists of comparing the results of the analysis against benchmarks such as an ordinal set of descriptors. For example, hazard evaluation might result in a rating of:

- Minimal (i.e. practical absence of hazard).
- Low (i.e. low frequency exposure to consequential size under extreme conditions).
- Moderate (i.e. low frequency exposure to consequential size under normal conditions).
- High (i.e. high frequency exposure to consequential size).

The North American Public Avalanche Danger Scale (Table 6.1) is another example of operational hazard evaluation. Its primary objective is to accompany a public avalanche bulletin and provide a relative measure of avalanche danger that corresponds to a set of definitions for each of the five danger levels (Statham et al., 2010). This hazard scale is intended for a mobile element at risk, vulnerable to ≥ Size 2 avalanches, that is traveling through avalanche starting zones. It would need to be adjusted if it were to be used in other situations (e.g. fixed facility or highway with exposure to runout zones only). Operational hazard evaluation is an ongoing process that occurs in real-time and typically leads to forecasts within time scales of 12 to 72 hours.

Table 6.1: *North American Public Avalanche Danger Scale (Statham et al., 2010).*

Danger level	Travel advice	Likelihood of avalanches	Avalanche size and distribution
5 - Extreme	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 – High	Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 - Considerable	Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 - Moderate	Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 - Low	Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

6

Avalanche Problem

Operational hazard evaluation integrates weather, snowpack and avalanche analysis with local terrain factors and weather forecasts. The avalanche hazard evaluation determines the character, elevation and aspect, likelihood, and size of potential avalanche events based on the analysis. This construct of the *avalanche problem* describes the avalanche hazard and regularly includes the degree of confidence and representation of uncertainties associated with the estimation.

Other useful references for avalanche problems:
Lazar et al. (2012 and 2015); Atkins (2004)

Conceptual Model of Avalanche Hazard

The conceptual model of avalanche hazard (Statham et al., in prep) is a series of independent concepts and components that when linked together in a stepwise fashion, provide an organizing framework for the process of avalanche hazard assessment (Figure 6.2). Starting from an initial state (operational objectives, scale) the model proceeds through a succession of analytical steps (avalanche character, location, likelihood of triggering, avalanche size) before concluding with a measure of avalanche hazard.

Avalanche character describes different types of avalanche regimes, each of which presents a general, repeatable pattern of potential or observed avalanche activity that suggests a distinct approach to risk treatment (Statham et al., in prep). An avalanche character (e.g. wind slab, storm slab, persistent slab, deep persistent slab, wet slab, loose wet, loose dry, cornice fall and glide avalanche) is attributed to specific locations by aspect, elevation, vegetation bands, operating zones or terrain features. Likelihood of triggering is a function of the spatial density and distribution of the instability and the sensitivity to triggers of various sizes by natural or artificial means. Destructive size is typically represented by the avalanche size classification system (Chapter 2).

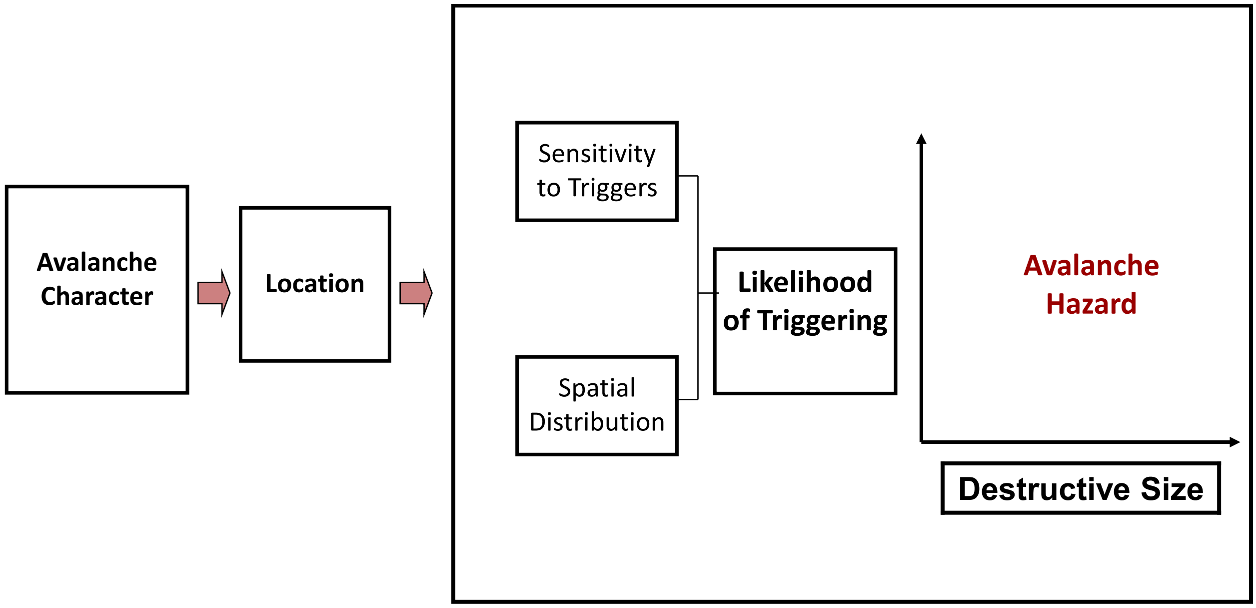


Figure 6.2: *The conceptual model of avalanche hazard (Statham et al., in prep) is used to construct the avalanche problem. For each avalanche character at a specific location, avalanche hazard is determined through evaluating the relationship between likelihood of triggering (a function of the sensitivity to triggers and spatial distribution of a weakness) and the expected avalanche size. Avalanche hazard is often represented as a range of values for both likelihood of triggering and destructive size, representing variability and uncertainty (Section 3.5.1).*

6.3 Avalanche Forecasting

Avalanche forecasting is the prediction, over a specified scale of terrain, of current and/or future (e.g. with the range of a weather forecast) avalanche hazard/risk based on the expected likelihood of triggering, avalanche size and runout extent.

The creation of an avalanche forecast is a unique step in the overall risk management process. It is unique in that it may be the end product of an operational assessment or a perquisite activity in applying direct, short-term mitigation measures. If a forecast is an end product, it is typically in the form of an avalanche warning or bulletin that describes the forecast level of avalanche hazard.

6.4 Operational Risk Assessment

A risk assessment provides evidence-based information and analyses to support informed decisions on how to treat particular risks and how to select between mitigation options (after ISO, 2009).

Similar to a formal risk calculation that may be done in a planning risk assessment, an operational risk assessment is grounded in standardized methods along with the expertise and competence of the individuals performing the assessment. The steps followed are essentially the same as for a planning risk assessment; however, they differ in that a planning risk assessment results in a final (or milestone) report, and an operational risk assessment is a continuous and iterative process that occurs on an ongoing basis, and may or may not be recorded in a variety of formats (e.g. notebooks, forms and/or databases).

An operational avalanche risk assessment builds on the hazard assessment results with these additional efforts:

1. Find, recognize, describe and comprehend the element at risk.
2. Analyze its exposure and vulnerability to the hazard.
3. Determine the level of risk.
4. Compare the results to a given criteria to determine whether the risk meets the identified risk tolerance.

These activities fall in the general steps of identification, analysis and evaluation. An example of a commonly used operational avalanche risk assessment method is the CAA’s morning (a.m.) and afternoon (p.m.) Hazard and Risk Worksheets.

Example of evidence gathering to support operational hazard analysis. M. Boissonneault photo.

6.4.1 Operational Risk Identification

The risk identification step connects the hazard assessment to the element at risk through use of risk scenarios. The hazard assessment result provides a location, an estimation of the likelihood of occurrence, and probability of magnitude for the potential avalanche hazard. This potential event is combined with an element at risk.

Element at Risk

In operational risk assessment, the element at risk is typically people, but may include other elements as determined by the operational setting and specific objectives. For example, an avalanche risk manager for a highway might consider people as the primary element at risk, and vehicles and commerce secondary. Elements at risk considered during the operational stage are listed in Section 9.2.1.

Risk Scenario

In an operational setting, scenarios are typically mental visualizations of the planned activities and objectives that may occur in the area subject to the hazard. This step involves answering the question "Given the avalanche forecast and the locally observed conditions, what can happen?" This question serves both as an identifier of scenarios and supports the constant consideration aspect of maintaining situational awareness.

Visualizing scenarios allows consideration of various outcomes based on changes to the hazard or application of mitigation measures. Envisioning multiple scenarios assists the subjective judgment of event likelihood, consequences and level of uncertainty.

6.4.2 Operational Risk Analysis

Risk analysis is a series of actions undertaken to comprehend the uncertainties associated with the visualized scenarios. Risk analysis occurs at specific points (e.g. preparing for or entering avalanche terrain). It is also a repetitive consideration in maintaining situational awareness. Answering the following questions guides this step:

1. How likely is it that a specific scenario will happen?
2. If it does happen, what are the consequences?
3. What uncertainties can be reduced?

In operations, focus is on the analysis of exposure, consequence and existing controls.

Exposure

Exposure is the extent to which the element(s) at risk is (are) subject to potential avalanche hazards. It is a function of the time period and position the element is present within an avalanche path. Controlling or managing exposure has a vital effect on the uncertainties associated with potential avalanche hazard.

Consequence

In avalanche operations, consequence is the outcome of an avalanche occurrence. For fixed elements at risk, it is a function of vulnerability of the element at risk (Section 5.3.2) and the avalanche size. For mobile elements at risk, exposure can also affect consequence (e.g. for people in an avalanche path, the number of people exposed and their position within the path affects the consequence). Consequence can be positive or negative, or a range of outcomes that can be expressed qualitatively or quantitatively. Since vulnerability is typically constant, the potential for positive or negative consequences is largely attributed to exposure and avalanche size. Hence, a focus on consequence rather than only vulnerability is typical for operational avalanche risk analysis.

Existing Mitigation

Risk treatments already in place are considered for their effect on the probability, exposure, consequence or any related uncertainties as part of the risk analysis.

6.4.3 Operational Risk Evaluation

Avalanche risk evaluation compares the results of risk analysis with risk criteria to determine whether the risk or its magnitude is acceptable or tolerable (see *risk tolerance* and *risk acceptance* in Section 2.4). The amount of uncertainty associated with the likelihood of the hazardous event or the potential consequence is also considered in risk evaluation. In an operational setting, risk evaluation is often conducted in tandem with risk analysis where both are part of the same step in the risk assessment process.

At a fundamental level, risk evaluation works through the questions:

1. What is tolerable?
2. How safe is safe enough (i.e. what is acceptable)?
3. What needs to be done?

What is tolerable is a prerequisite drawn from establishing the context. What is acceptable is the basis for the decisions of:

- Whether an activity should be commenced.
- Whether a risk requires treatment.
- Treatment prioritization.
- Which of a number of options should be chosen.

Implicit in the question of “how safe is safe enough” is the critical continuous feedback that occurs in operational avalanche risk assessment. This feedback comes in the evaluation of whether the chosen method of mitigation is effective and has altered the risk level to within what is acceptable. For example, the continued analysis and re-evaluation of hazard following explosive avalanche triggering efforts to determine if the avalanche forecast has changed substantially from the previous one. This reflects a return trip through the assessment steps prior to deciding to remove the mitigation measure of temporary closure and evacuation.

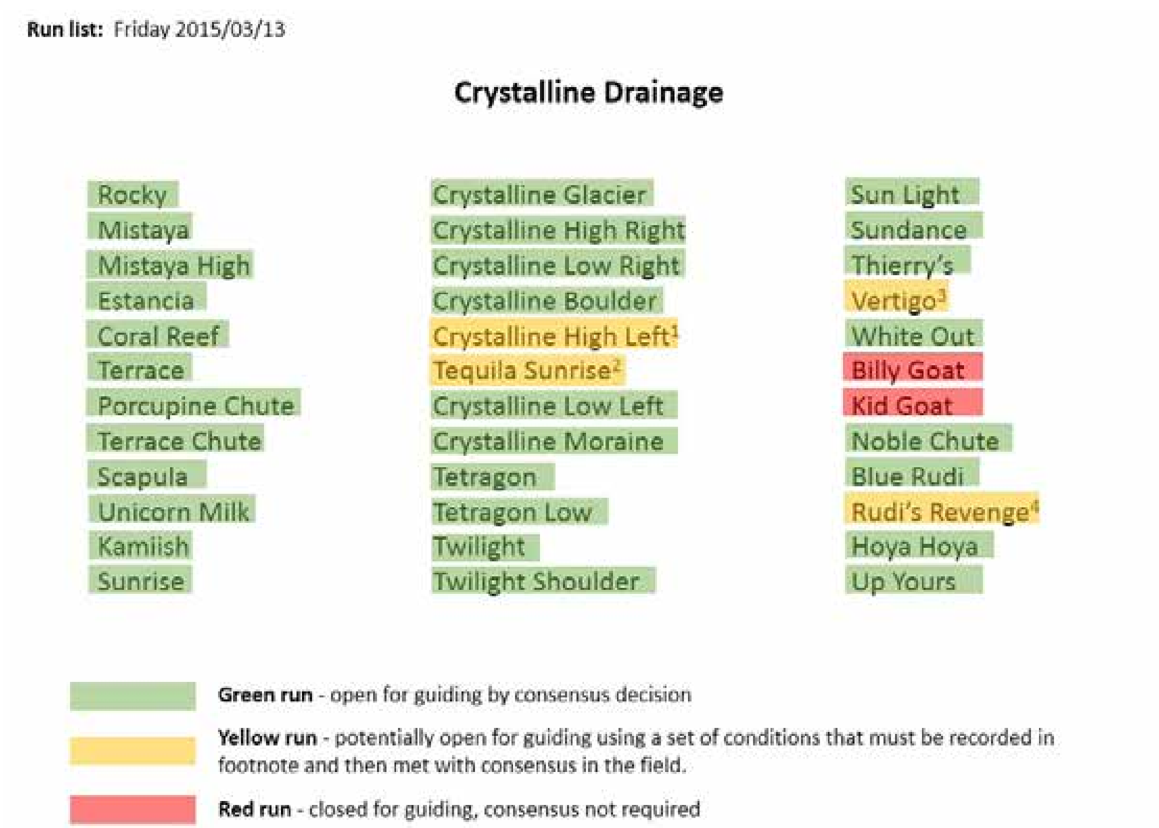
Typical strategies for operational risk evaluation use the operational risk band (ORB) concept. The ORB is described as the area between an upper and lower limit of acceptable risk. Decisions outside the upper limit (e.g. allowing too much uncertainty or exposure to harm) can lead to incidents. Decisions outside the lower limit represent excessive conservatism and likely missed opportunity or unnecessary failure of meeting objectives. Excessive costs (death or economic loss) characterize errors of decisions outside either limit (McClung and Schaerer, 2006).

Terrain Coding

A common strategy for operational risk evaluation relies on detailed terrain identification, classification and mapping maintained as an inventory of ski runs (i.e. run list) and/or operational zones (i.e. terrain list). This list is used to systematically evaluate risk on a run-by-run (or zone-by-zone) basis to determine where the risk associated with that particular run (or zone) fits within the ORB.

Typically accomplished in the morning in an office setting, terrain coding follows a very specific analysis of avalanche risk considering forecasted avalanche hazard and all possible exposure points in the terrain. This process often involves team decision making with map and photograph review, as well as reference to avalanche occurrence and slope use history records.

Each run or zone is subsequently coded as either open if it fits within the ORB, or closed if it doesn't, typically using green or red colors respectively to illustrate this (Figure 6.3). If there are identified knowledge gaps, some operations will conditionally open a run or zone pending a set of prescribed conditions. In this case, the color yellow is used and a predetermined process is used to open that run (e.g. face-to-face meeting with the avalanche forecaster). For example, a run can be conditionally open if the large cornice above the landing in absent. If the cornice is in fact determined to be absent after field investigations then the run can be opened after a face-to-face meeting with the avalanche forecaster, but if the cornice continues to threaten the landing zone then the run must remain closed.



Run list: Friday 2015/03/13

Crystalline Drainage

Rocky	Crystalline Glacier	Sun Light
Mistaya	Crystalline High Right	Sundance
Mistaya High	Crystalline Low Right	Thierry's
Estancia	Crystalline Boulder	Vertigo[3]
Coral Reef	Crystalline High Left[1]	White Out
Terrace	Tequila Sunrise[2]	Billy Goat
Porcupine Chute	Crystalline Low Left	Kid Goat
Terrace Chute	Crystalline Moraine	Noble Chute
Scapula	Tetragon	Blue Rudi
Unicorn Milk	Tetragon Low	Rudi's Revenge[4]
Kamiish	Twilight	Hoya Hoya
Sunrise	Twilight Shoulder	Up Yours

Green run - open for guiding by consensus decision

Yellow run - potentially open for guiding using a set of conditions that must be recorded in footnote and then met with consensus in the field.

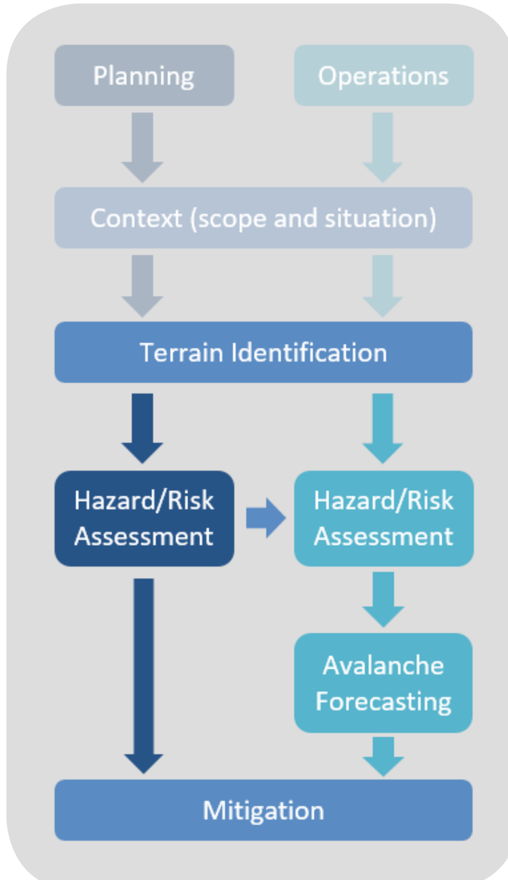
Red run - closed for guiding, consensus not required

Figure 6.3: *An example of a run list for a helicopter skiing operation. Courtesy of Canadian Mountain Holidays.*

6.5 Risk Treatment

Risk treatment describes the range of measures available for mitigating the avalanche hazard or otherwise reducing the risk from avalanches. Mitigation is accomplished through measures that result in changes of estimated hazard (likelihood of triggering and avalanche size), exposure and/or consequence. This is covered in Chapter 8. Most short-term mitigation measures are implemented at an operational level.

M. Austin photo.



Chapter 7 Outline

7 Assessment / Decision Aids

Avalanche experts and safety services use a wide range of support tools to increase the quality and efficiency of risk management. These tools are used throughout the planning and operational stages of avalanche risk management to enhance objectivity and consistency.

Assessment/decision aids are particular support tools that explicitly help decision makers combine multiple observations to produce a assessment and/or decision in regards to risk mitigation. These aids can be used to encapsulate advanced avalanche knowledge or operational risk management expertise and make it broadly accessible. Straight operational guidance (e.g. travel recommendations related to an avalanche hazard rating) is not considered a decision aid in the context of this chapter as it does not combine multiple factors.

This chapter provides a brief overview of assessment/decision aids commonly used in avalanche risk management, and offers guidance about the design and operational use of these support tools.

7.1 Common Assessment / Decision Aids

The use of assessment/decision aids is widespread in avalanche risk management. This section describes the general characteristics of assessment/decision aids, explains their operational use and provides links to additional background material.

7.1.1 Assessment Tables

Assessment tables are typically used in avalanche risk management for the definition of fundamental rating scales. In an assessment table, the rating scale is listed on one axis, and the relevant contributing factors are presented on the other. The cells of the table contain rules that associate the presence of a specific value of a contributing factor with a particular rating level. Some assessment tables distinguish between key rules that automatically result in a specific rating level and more relaxed rules that are considered in a general manner in combination with other rules. This table structure offers a simple but effective format that captures assessment expertise; it incorporates a large number of input parameters and presents it in transparent and easy-to-follow logical rules.

Examples of assessment tables include the technical model of the Avalanche Terrain Exposure Scale (ATES) (Statham et al., 2006) (Appendix 1) and the North American Public Avalanche Danger Scale (Statham et al., 2010) (Section 6.2.3).

7.1.2 Numerical Runout Models

Numerical runout models (Section 4.1.5) are used in the planning stage of avalanche risk management to assess the exposure of a location to avalanche hazard. These models are either based on a statistical relationship between the runout distance and topographical factors (i.e. topographical-statistical models), or they mathematically simulate the physical processes involved when the dynamic avalanche flow interacts with the local topography (i.e. physical-dynamic models).

Software packages for numerical runout models are commercially available, and their application requires relatively little effort. However, all of these models contain parameters that might need adjustment to adequately represent local conditions. Therefore, it is important to locally or regionally validate the model performance before its application in a particular case.

7.1.3 Risk Matrices

In Canadian avalanche risk management, a form of risk matrix is commonly used for backcountry travel activities as an aid to decide the appropriate level of training required to travel safely in specific areas of avalanche terrain under certain conditions. A risk matrix for this application typically combines an avalanche hazard rating and a terrain exposure class in a table or chart format. The values presented in the cells of the matrix represent the relative risk levels (often colour coded) and the corresponding recommended level of training and/or experience is listed. Sets of risk matrices can be used to integrate additional input parameters (e.g. avalanche safety training level or vulnerability).

Note that risk matrices used in backcountry travel activities are slightly different from a more common form of risk matrices used to assess the risk to stationary elements-at-risk (e.g. Porter and Morgenstern, 2013). In these types of applications, the exposure is constant (i.e. 1) and the axis of risk matrices represent the pure probability and consequences of expected events. The elements-at-risk in backcountry travel activities are mobile and risk can therefore be managed by adjusting exposure to the hazard. In this case, the consequence component of risk is split between the hazard axis (via avalanche size in the conceptual model of avalanche hazard (Section 6.2.3)) and the terrain axis (e.g., terrain traps).

The Avaluator™ Trip Planner (Haegeli, 2010) is a simple example of a risk-matrix decision aid for backcountry travel activities. It allows users to combine a current avalanche danger rating for a given area (provided by an avalanche warning service) with the published and static ATES rating (Appendix 1). Users are able to assess whether they have the required experience and knowledge to manage avalanche risk under given conditions.

The Avaluator™ Trip Planner is intended for self-directed backcountry recreationists that are responsible for their own risk management, and travel in a variety of terrain under a wide range of avalanche conditions. As such, it is designed for use in all types of terrain and under all avalanche conditions. The resulting recommendation is limited to the minimum level of training and experience required to travel safely in the chosen terrain under the given conditions. However, in industrial applications, risk matrices are typically more prescriptive since they are explicitly used to mitigate organizational risk. As a result, industrial risk matrices are often specifically designed to take into account the goals and structure of the operation and specific avalanche characteristics for the location. Figure 7.1 is an example of a risk matrix developed by Parks Canada. It defines the required levels of training by group leaders to travel in specific types of avalanche terrain classified by the ATES (Appendix 1).

	ATES Simple (Class 1) Terrain		**ATES Challenging (Class 2) Terrain**			**ATES Complex (Class 3) Terrain**		
Level of Training	**Low / Moderate Avalanche Danger**	**Considerable / High / Extreme Avalanche Danger**	**Low / Moderate Avalanche Danger**	**Considerable Avalanche Danger**	**High / Extreme Avalanche Danger**	**Low / Moderate Avalanche Danger**	**Considerable Avalanche Danger**	**High / Extreme Avalanche Danger**
CAA Professional Member	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed	Requires Forecaster Consult
CAA L1 and a Resumé	Allowed	Allowed	Allowed	Requires Forecaster Consult	Requires Forecaster Consult	Requires Forecaster Consult	Requires Forecaster Consult	Not Allowed
AST 2 or CAA Level 1	Allowed	Requires Forecaster Consult	Requires Forecaster Consult	Not Allowed	Not Allowed	Requires Forecaster Consult	Not Allowed	Not Allowed
AST 1	Allowed	Requires Forecaster Consult	Requires Forecaster Consult	Not Allowed	Not Allowed	Not Allowed	Not Allowed	Not Allowed

Figure 7.1: *Example of a risk matrix used in an industrial application. This matrix is used for risk control based on policy and procedure to determine whether a field team, whose leader has a certain level of training, is allowed to travel in avalanche terrain with varying degrees of exposure, under different avalanche danger levels. Levels of recreational avalanche skills training (AST) and professional (CAA) avalanche training and membership are listed on the vertical axis, while avalanche terrain exposure (ATES) classes and danger levels are listed on the horizontal axis. The matrix is used to determine whether the field trip is allowed or not allowed, or whether the decision is made by an in-house avalanche forecaster. Courtesy of Parks Canada.*

7.1.4 Checklist Sums

Checklist sum assessment/decision aids are an enhancement of general checklists that are widely used in a variety of risk fields (e.g. aviation) to ensure correct execution of steps associated with a task. While general checklists specify a sequence of steps, a checklist sum assessment is a series of yes-or-no questions where the total number of yes answers is added up to an overall score. This score is either used as a numerical measure for the severity of the conditions at hand, or converted into a discrete assessment by comparing it to a specified score threshold. In more advanced checklist sum assessments, questions are associated with individual multipliers to give them different weights that reflect their importance for the assessment.

Examples of checklist sum assessment aids are the yellow-flags approach for assessing manual snow profiles (Jamieson and Schweizer, 2005) (Figure 7.2), and the avalanche and terrain assessment questions of the Avaluator™ Slope Evaluation tool (Haegeli, 2010). Similar checklist sum assessment aids can be developed to allow staff with limited avalanche expertise to monitor conditions and initiate basic mitigation procedures at operations that have minimal exposure to avalanche hazard.

Property	**Critical range (Columbia Mountains)**
Layer properties	
Average grain size	> 1 mm
Hardness*	< 1F (3*)
Grain type	Persistent (SH, FC or DH)
Interface properties	
Difference in grain size	> 0.5 mm
Difference in hardness	> 1*
Depth of interface	20 to 85 cm

* Hand hardness F, 4F, 1F, P, K is assigned values of 1, 2, 3, 4, 5, respectively. Fractional values are allowed. For example, 4F+ and 1F- are 2.3 and 2.7, respectively.

Figure 7.2: *Yellow-flag criteria for identifying potential failure layers (Jamieson and Schweizer, 2005). Three snowpack layer properties and three interface (between two layers) properties are listed with critical values or ranges of values to assign a "yellow flag" (i.e. check) to that layer or interface. Interfaces with more associated yellow flags (both assigned to the interface as well as the adjacent layer with the most yellow flags) were found to be less stable in the Columbia Mountains.*

7.1.5 Decision Trees

In literature on decision-research, the term *decision tree* typically refers to a type of decision aid that is rooted in operations research and uses a tree-like graph or model to compare consequences of possible options and identify the strategy that most effectively reaches the objective at hand. This approach might be used at the planning stage of risk management to evaluate the consequences of different mitigation strategies and to choose the most economical solution (Bründl et al., 2009).

In operational avalanche forecasting, decision trees most often refer to decision aids that use a tree-like flow chart to classify a situation into mutually exclusive categories based on multiple input parameters. These types of decision trees are typically derived directly from a representative dataset, using a classification tree analysis (Breiman et al., 1998), a data-mining technique that can be used for a variety of purposes. Examples of decision trees that have been developed for avalanche forecasting include the estimation of avalanche hazard from simulated snow profiles (Bellaire and Jamieson, 2013) (Figure 7.3), and the identification of days with significant avalanche activity along highway corridors (Hendrikx et al., 2014).

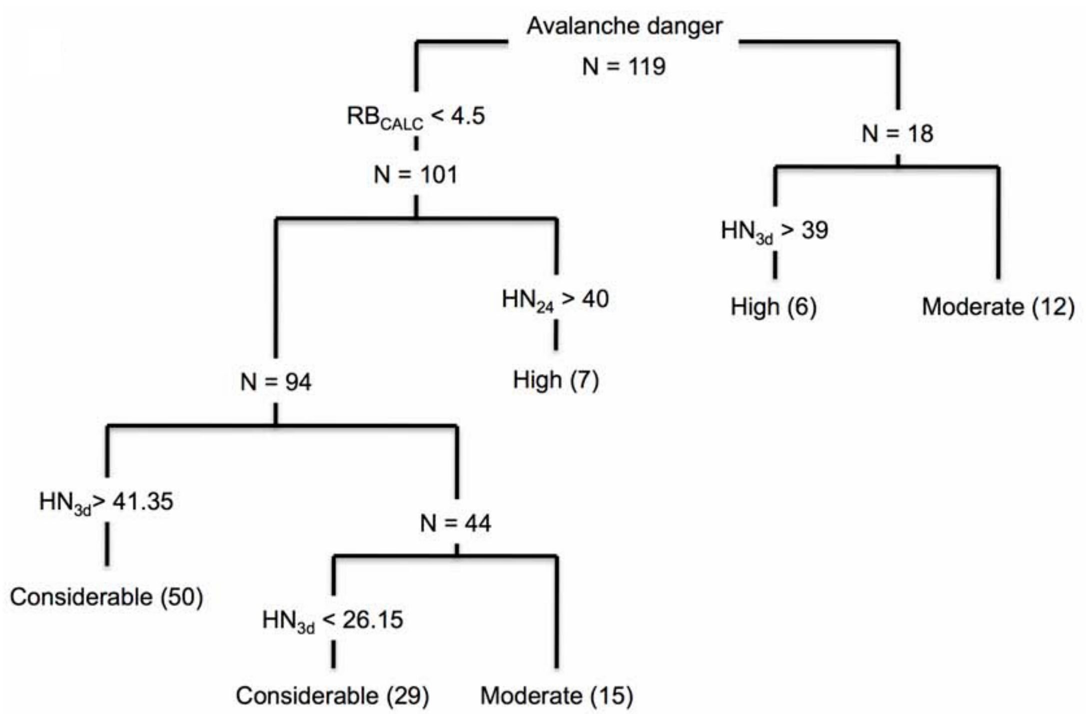


Figure 7.3: *This decision tree is used to rate avalanche hazard in the alpine. It is based on simulated snow profiles that use a Rutschblock score (RB_{CALC}), and 24-hour (HN_{24}) and three-day (HN_{3d}) new-snow amounts. Threshold values for the new-snow amounts are given in centimetres. RB_{CALC} is an index from one to seven (Bellaire and Jamieson, 2013).*

In comparison to other statistically based decision aids, decision trees are easier to understand and interpret, which makes the approach more suitable for manual (not computer-based) decision aids. Decision trees can be developed for general assessments (i.e. snow-profile assessments) and specific operational applications (i.e. avalanche forecasting for a transportation corridor). However, the development of a meaningful operational decision tree requires a substantial local dataset and advanced statistical expertise. Hence, decision trees have primarily been developed by academic research teams.

7.1.6 Nearest Neighbour Systems

The nearest neighbour algorithm is a data-mining technique that was introduced in avalanche forecasting programs by Buser (1983). The method allows avalanche forecasters to efficiently access historic avalanche activity records on previous days similar to the day in question. Nearest neighbour systems are implemented as computer applications where users enter the weather conditions of the day in question, and the algorithm returns a ranked list with a predefined number of days that are most similar to the one at hand. While the percentage of days with avalanche activity can be used as an indicator of the likelihood of avalanching on the day in question, Purves et al. (2003) highlights that forecasters found the list of avalanche paths that ran on similar days to be most useful. In Canada, Cordy et al. (2009) applied the method to the highway avalanche safety programs at BC's Bear Pass and Kootenay Pass.

Whereas the nearest neighbour algorithm is relatively simple and the method can be applied at a range of scales (e.g. for an individual path or entire region), a meaningful application critically depends on a substantial historic weather and avalanche activity record. The method is therefore particularly suitable for avalanche safety programs along transportation corridors, long-term worksites or ski areas where it is possible to maintain reasonably complete avalanche activity records. Any thresholds used to convert the percentage of historic days with avalanche activity into an actual prediction of local avalanche activity needs to be verified within that area.

7.1.7 Statistical Forecast Models

In addition to classification trees and nearest neighbour systems, numerous statistical analysis methods have been used to develop models for operational avalanche forecasting. Possible approaches include discriminant analysis (Floyer and McClung, 2003), ordinal logistic regression analysis (Haegeli et al., 2012), neural networks and other machine-learning algorithms.

The development of these models requires advanced statistical expertise.

7.1.8 Snowpack Evolution Models

Snowpack evolution models, also referred to as snow cover evolution models or snow cover models, are used to simulate the formation and evolution of the seasonal snowpack. They work in accordance to the current scientific understanding of the underlying physical processes and as a function of observed or predicted meteorological conditions. Examples are the Swiss SNOWPACK model (Bartelt and Lehning, 2002) (Figure 7.4), and the French Crocus model (Brun et al., 1989).

In Canada, the use of snowpack evolution models is currently an active area of research. Efforts are currently underway to combine the SNOWPACK model with Canadian weather prediction model outputs to produce snowpack information in otherwise data-sparse regions (Bellaire and Jamieson, 2013). This type of application requires considerable local verification of input parameters and model output before operational use of the system is feasible.

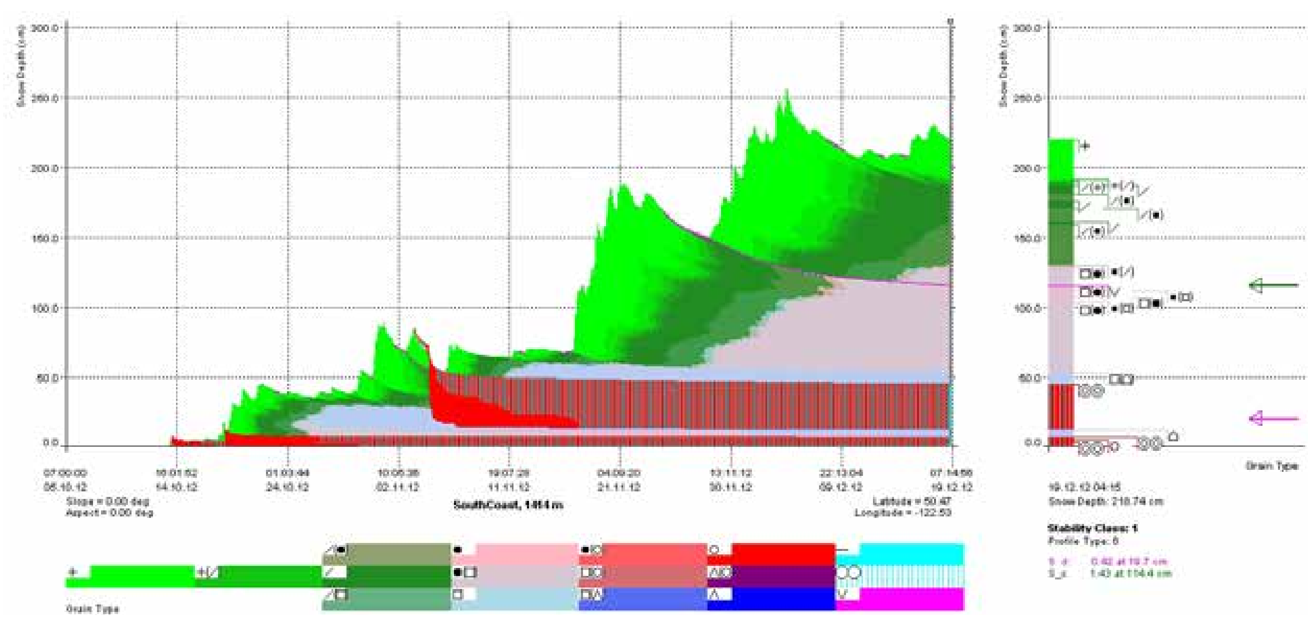


Figure 7.4: *Output from the Swiss SNOWPACK model (Bartelt and Lehning, 2002) showing a modeled vertical snowpack structure profile from early October (no snow) to mid-December. Colours and symbols represent different snow grain types.*

7.2 Design and Implementation Considerations

While there is only a small number of assessment/decision aids designed for broad use by a general audience (e.g. the Avaluator™), most are aimed at specific operational tasks completed by a well-defined user. To be effective, these types of assessment/decision aids need to be explicitly designed for the intended purpose. An in-depth understanding of the foundation of a decision aid is crucial for understanding its strength and weaknesses for a particular operational application.

This section provides information on assessment/decision aid design, and how operational suitability and effectiveness for specific avalanche safety applications is qualitatively evaluated.

7.2.1 Quality of Knowledge Base

The quality of knowledge base is the most important factor that affects the performance of assessment/decision aids. While current scientific understanding of relevant physical processes or in-depth statistical analyses of relevant long-term datasets are preferred due to their objectiveness, these types of knowledge sources are not always available. In these circumstances, community consensus and individual or combined expert opinions are also acceptable types of knowledge bases.

The knowledge base used for the development of an assessment/decision aid must be representative of the aid's objective. For example, a decision aid used for opening or closing a particular road must be based on a local dataset or locally verified expert knowledge that captures the range of expected conditions. Assessment/decision aids that attempt to assess conditions outside of the knowledge base are unable to provide reliable guidance.

It is important that the knowledge base of an assessment/decision aid remains relevant. For example, the knowledge base of a nearest neighbour system is continuously updated while in use, while assessment aids derived from classification-tree analyses may require updates at regular intervals to remain current. Expert opinion-based assessment/decision aids may also need to be updated if circumstances change at a fundamental level (e.g. due to climate change). However, decision aids, like the Avauator Trip Planner, that focus on the basic principles of avalanche risk management may retain their validity since the consequences of environmental changes can be incorporated via the expert-based input parameters.

7.2.2 Character and Number of Input Parameters

Input parameters for assessment/decision aids must be appropriate for the skill level of the intended user. These parameters can either be simple yes-or-no questions (e.g. Have you seen signs of recent slab avalanche activity?) or detailed observations that require technical expertise (e.g. assessing the hardness difference between two snowpack layers). They can also be objective observations (e.g. a temperature measurement) or involve expert judgment (e.g. an assessment of the likelihood of triggering). The number of input parameters should be as few as possible yet adequately capture the factors relevant for the task.

7.2.3 Complexity and Transparency of Assessment Method

The methods used by an assessment/decision aid to combine input parameters and produce a result (output) may range in complexity and transparency. Assessment/decision aids implemented as software applications are often based on advanced statistical methods and remain somewhat of a black box for users. Simpler approaches (e.g. a series of if-then rules, hazard or risk matrices, checklist sums or decision trees) are more transparent for users and have the potential to be applied without technical assistance. Higher transparency generates more trust in the user, which results in improved and more widespread application. The key is to design the assessment/decision aid as simply as possible.

7.2.4 Character of Assessment / Decision Output

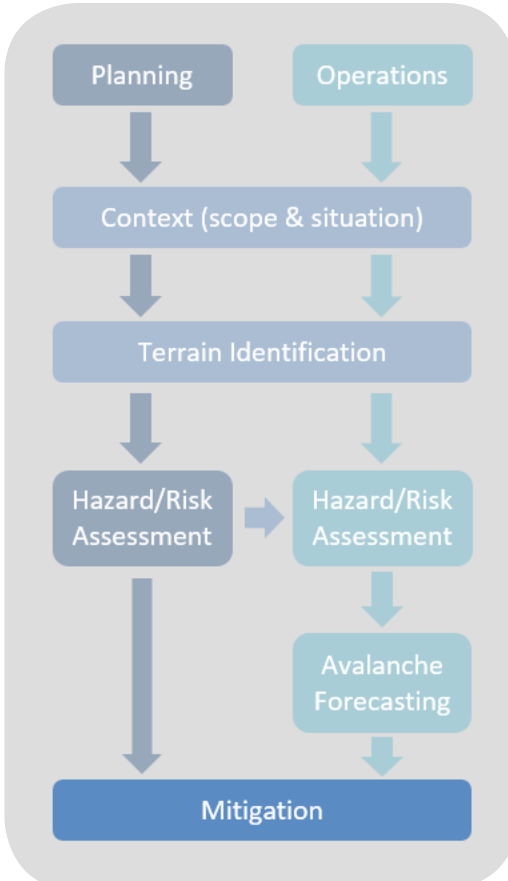
In design, it is critical to have a clear understanding of how the output of the assessment/decision aid is used. Determine if its assessment/decision recommendation is used as one of many information sources in an expert-driven assessment/decision process (e.g. use of a nearest neighbour system in an avalanche forecasting program), or if the output triggers operational protocols (e.g. risk matrix for risk control based on procedure and policy). Output can either be an explicit assessment and/or decision (e.g. hazard level, or go or no-go decisions) or it can provide supportive guidance (e.g. the North American Public Avalanche Danger Scale or the Avaluator™). The appropriate type of output for a given application depends on whether the user is responsible for risk management. For example, the Avaluator™ was designed for recreationists that are ultimately responsible for their own decisions. As a consequence, the Avaluator™ only provides recommendations about the level of expertise and formal avalanche training required to adequately manage avalanche risk under given conditions, and does not offer explicit go or no-go decisions. Risk matrices designed for workplace applications are typically used to exert management-level controls on staff activities and therefore need to be more prescriptive.

The lower the avalanche expertise of the user and the more prescriptive the decision guidance, the more precise and conservative the output of the assessment/decision aid needs to be. Similar to input parameters, output of an assessment/decision aid must be appropriate to the skill level of the user.

7.2.5 Implementation Cost

The implementation of a course of action recommended by a decision aid can be associated with considerable cost. For example, in a highway avalanche safety operation, cost is associated with two potential scenarios: an avalanche hitting an open road; and closing the road for explosive control that only triggers small avalanches and neither substantially unloads the starting zone nor threatens the road (Blattenberger and Fowles, 1995). Cost-benefit analyses can be used to evaluate the expense of various recommendations and assist in the local calibration of the decision aid to produce operationally practical options.

A. Leyland photo.



Chapter 8 Outline

8 Mitigation

Avalanche risk mitigation, also referred to as "avalanche protection" or "risk control", may involve single or multiple layers of systems or techniques to reduce or eliminate avalanche risk. Both long-term and short-term measures may be used, and specific measures may involve direct or indirect intervention with the avalanche hazard (Section 1.5.2). The type(s), level and sophistication of mitigation are based on several factors, though decisions often involve some form of cost-benefit evaluation.

Often an integrated approach to mitigation is used and is incorporated at various stages and scales. For example, the avalanche risk to roads is reduced by:

1. Location planning (e.g. reducing the length of a road exposed to avalanches during the design phase).
2. Static defenses (e.g. snow sheds, diversion dikes and retarding mounds).
3. Warning signs (to reduce the number of vehicles stopping in avalanche paths).
4. Short-term measures (e.g. forecasting, artificial triggering and road closures) to reduce the likelihood of avalanches reaching open roads.

As another example, avalanche risk to a ski lift could be reduced by:

1. Locating the towers and terminal stations where avalanche frequency and/or impact pressures are low.
2. Reinforcing the lift structures to withstand expected impact pressures.
3. Compaction of the snowpack and artificial triggering of the slopes above the exposed towers.

Typical mitigation options for avalanche terrain land-use in Canada are provided in Chapter 9.

8.1 Types of Mitigation

There is some discrepancy amongst the international avalanche community with regards to categories of mitigation. In some references, different types of avalanche mitigation are considered active or passive and may be temporary or permanent. Furthermore, in other geohazard disciplines mitigation measures are classified according to the components of risk they operate on (e.g. hazard, exposure or vulnerability). For example, rock fall mitigation categories include avoidance, removal, stabilization and protection, all of which can be tied to a specific component of risk.

In order to maintain the distinction between planning and operations, this document categorizes measures according to the strategy for intervening in the avalanche process (direct versus indirect) and the duration in which the intervention occurs (short term versus long term) (after Wilhelm et al., 2000; and Schweizer, 2004). Long-term measures are applied during the planning stage, while short-term measures are applied during the operational stage. Furthermore, short-term indirect measures are specified during the planning stage. Figure 8.1 shows the overlap of strategy and duration with example mitigation measures.

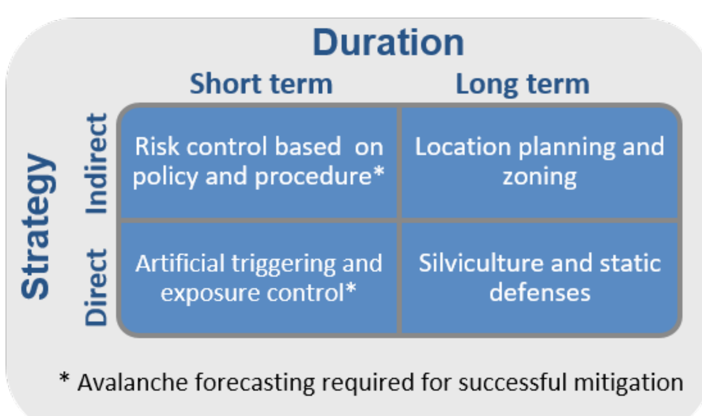


Figure 8.1: *Avalanche mitigation measures categorized by the strategy for intervening with the avalanche hazard and duration in which the intervention occurs. Example mitigation measures (Chapter 8) that employ each strategy for each duration are listed in the four quadrants.*

Definitions for duration and intervention descriptors are as follows:

Long term: Effective over the period of several years.

Short term: Effective for hours to a winter, depending on the context.

Direct: Involves direct intervention of the avalanche hazard (i.e. snowpack, terrain and/or avalanches).

Indirect: Involves adjustment of exposure and/or vulnerability of the element at risk.

In this chapter, mitigation is organized into long- and short-term measures. Avalanche terrain classification and maps, described in Chapter 4, are a key component of mitigation that may be considered for both short-term and long-term measures. These are described in a separate section (Section 8.4).

8.2 Long-term Measures

Long-term direct measures physically inhibit, constrain or channel avalanche formation and flow in some way. While long-term indirect measures locate element(s) at risk in appropriate areas (i.e. zoning and location planning). Most long-term measures involve some level of engineering analysis and/or evaluation. The following four subsections describe these measures.

8.2.1 Location Planning

Location planning, within the context of land-use planning, is an indirect measure that involves positioning facilities where avalanche risk is reduced or eliminated by means of reduced exposure or hazard. It should be the first consideration for protection. In some cases, avalanche paths can be avoided completely.

8.2.2 Zoning for Occupied Structures

Land-use planners often incorporate avalanche hazard maps (e.g. Figure 4.7) into zoning for occupied structures. Hazard mapping for occupied structures includes the impact-based classification system, hazard zones for occupied structures, described in Appendix 1. Considering land values in mountain communities are often expensive due to geographical restrictions, a high level of accuracy is required.

Recommended activities in Canada according to zone colour (Appendix 1) are:

1. White zone (low hazard) – Construction of occupied structures is normally permitted.
2. Red zone (high hazard) – Construction of occupied structures should not be permitted.
3. Blue zone (moderate hazard) – Construction of occupied structures may be permitted with specified conditions.

Considerations for development of occupied structures in a blue zone include:

- Number of occupants. For example, the level of risk associated with locating a structure designed for > 100 occupants it typically not tolerable, regardless or mitigation measures taken. Whereas a structure designed for < 10 occupants might be considered for development in a blue zone.
- Timing of occupancy. For example, public structures such as residences, hotels, lodges and restaurants that could be occupied at all times with limited control over access, should not be considered for the blue zone. Whereas private structures, such as industrial plants, storage facilities, field offices and warehouses, that can be unoccupied for long periods (e.g. days to months) and access can be controlled, might be considered for development in a blue zone.
- Whether the structure is a place of refuge during a storm. For example, backcountry huts or isolated occupied structures where precautionary evacuation and restricted access (Section 8.3.1) is unreasonable and/or requires additional exposure to avalanche hazard should not be considered for development in a blue zone.
- Whether the occupants are aware of, and accept the risk associated with avalanches. For example rented properties, in which the tenant may not be aware of or have accepted the risk, should not be considered for development in a blue zone.
- Whether the structure is critical infrastructure for essential and/or emergency services. For example hospitals, schools and community centres should not be considered for the blue zone.

- Whether access can be effectively restricted to allow for occupancy only during periods deemed to be safe periods as determined by a qualified person.
- Whether an effective precautionary evacuation plan can be implemented that can quickly evacuate the entire structure during high hazard periods. Note that the planned frequency of precautionary evacuations should be less than annual (e.g. in Europe, evacuations are planned to occur no more than once every five to 10 years). If higher frequency evacuation is required to mitigate risk to an acceptable level, then the structure should not be considered for development in a blue zone.

Conditions that may be specified for development of occupied structures in a blue zone include: structures reinforced to withstand avalanche impact; structures protected by long-term runout zone mitigation measures (e.g. diversion dikes or catchment basins); P&P-based risk control and evacuation plans; or a combination of these. Niemczyk (1984) provides a list of typical planning policies and land-use controls for occupied structures exposed to avalanche hazard.

For pre-existing occupied structures found to be located in a blue or red zone, specific conditions may be required by the land manager for continued use or occupancy. These may include conditions mentioned above.

A program of artificial triggering and/or snowpack compaction cannot be relied upon to reduce the frequency or magnitude of maximum avalanche events. Consequently, these measures should not influence the location of hazard zones, nor be considered as a sole measure to allow for occupation of a normally restricted-access structure. However, specific long-term measures (e.g. diversion structures and catchment basins) may be considered if there is no reliance on maintenance to ensure risk reduction (e.g. snow deposit removal after larger avalanches). Other long-term measures would need to be evaluated on a case-by-case basis.

The acceptable risk levels associated with these recommendations are similar to (or more conservative than) those used in European alpine nations, where there is a long history of effective risk reduction for occupied structures.

8.2.3 Starting Zone Measures

Long-term measures in starting zones include:

Snowpack support structures (rigid or nets): Engineered rigid supporting structures (Figure 8.2) or nets (Figure 8.3) arranged to retain snow and prevent large avalanches. Their purpose is to provide support to the snow cover, to limit the size of avalanches by impeding fracture propagation in the snow, and to stop small avalanches before they gain momentum. These starting zone measures are expensive and are normally only justified for areas that are already inhabited, for sites with limited tolerance for precautionary evacuation, and/or when the starting zone is small. They can also be rendered ineffectual by extreme snow cover.

Snow collection fences: Walls or panels arranged to induce irregular wind patterns that force wind-transported snow to accumulate in desired places and break the continuity of slabs. These are useful only when and where wind is a major factor in avalanche formation, and are usually not used as the sole means of avalanche risk mitigation.

Protection Forest

Dense forest in starting zones will reduce the frequency and magnitude of avalanches. For the suppression of avalanche initiation some estimates suggest stand density should be > 1000 stems/ha, once the mean stem diameter at breast height (dbh) exceeds 15 cm (Weir, 2002).

For planned cutblocks, leaving high stumps in the ground can suppress avalanche release, but the associated loss of the forest canopy can increase the frequency of unstable snowpack conditions. As a result, this technique as a mitigation measure must be carefully evaluated. Reforestation of logged, burnt or diseased starting zones may also be integrated with engineered structures to create a more permanent solution if a mature forest is regenerated. The time needed to establish new forests depends on the size of the start zone, but is typically 30 to 100 years for large avalanche paths (Weir, 2002).

Although forest in the track and runout zone may retard and arrest small (< Size 3) avalanches, the capacity of a forest to stop large avalanches is limited.

Forests in the fetch zone up-wind of the starting zone can also inhibit wind-transported snow, similar to snow collection fences.

Figure 8.2: *Example of supporting structures in the starting zones of large avalanche paths in the European Alps. B. Gould photo.*

Figure 8.3: *Example of avalanche netting in the starting zone of a small avalanche path in the 35 Mile avalanche area, located on Highway 16W 56.4 km west of Terrace, BC. S. Brushey photo.*

8.2.4 Track and Runout Zone Measures

Long-term measures in the track or runout zones include:

Tunnels: Tunneling through mountainsides. The avalanche risk mitigation provided by a tunnel is often secondary to other design considerations (e.g. travel distances, grade and degree of curve).

Snow sheds (galleries): Roofs or sheds (generally reinforced concrete) designed to carry the snow over the object to be protected - usually railways and roads with limited tolerance for delays or closures (Figure 8.4).

Retarding mounds, breakers or arresters: Earthen or masonry mounds arranged in such a manner to break up the flowing snow into crosscurrents that internally dissipate its kinetic energy. They are built in the lower part of the runout zone where avalanches are already slowing down (Figure 8.5).

Reinforced concrete walls: Designed to arrest or deflect avalanches (Figure 8.6). Mechanically stabilized earth (MSE) walls are also common.

Diversion dikes or berms: Reinforced concrete or earthen structures designed to divert avalanches. Depending on the design intention (e.g. to mitigate the one in 10-year avalanche), it may be acceptable for maximum avalanche events to overrun these dikes or berms. Similar dikes and berms can also be made by ploughing and piling snow; however, the duration of mitigation is short term.

Catchment basins: Basin or depression in the ground designed to arrest avalanches, generally in runout zones. May range from large-scale earthworks (tens of metres deep) to an enhanced roadside ditch in the order of a metre or two in depth. Depending on the design intention (e.g. to mitigate the one in 10-year avalanche), and/or the ability to maintain the catchment volume in winter (with heavy equipment) it may be expected that large avalanches overrun these basins on occasion.

Catchment bench: Bench cut into slope (generally into the track) in order to slow the avalanche and reduce the amount of deposit flowing past the bench cut. One advantage of a bench catchment versus a basin is that it provides increased ability to remove deposits mid-season using heavy equipment.

Splitting wedges: Reinforced concrete, steel, wood or earthen wedges designed to divert avalanches around either side of a structure (e.g. a transmission line tower) (Figure 8.7).

Catching nets: Similar to starting zone avalanche nets, but designed to shorten the runout zone by arresting small to medium (e.g. Size 2-3) avalanches.

Reinforcement and Design of Structures

Transmission line structures, ski lift towers, occupied structures, etc. that are exposed to avalanches can be reinforced and designed so that planar surfaces are smooth and not perpendicular to the avalanche flow. Eaves on the exposed sides of buildings can be reinforced, reduced in size or eliminated. Less vulnerable spaces (e.g. garages and kitchens) are located facing the avalanche path while bedrooms are located on the opposite side.

8.3 Short-term Measures

Short-term measures are all measures applied either on a seasonal basis or within a timescale related to the fluctuation of snow and weather conditions (i.e. hours to days, or in some circumstances, weeks to months). These measures are normally guided by the framework of an avalanche risk control plan, which incorporates avalanche hazard forecasting and/or structured organizational measures and is regularly audited and revised. Most short-term measures involve some level of avalanche forecasting in order to be effective. Short-term measures are described in the next six sections.

8.3.1 Precautionary Evacuation and Restricted Access

The simplest form of short-term measure is precautionary evacuation and restricted access, as the risk is effectively eliminated while the measure is applied. Since precautionary evacuation and restricted access is a form of exposure control, the measure can be effective for people and any object that is mobile (e.g. a vehicle), but cannot protect fixed property or infrastructure. Although route selection (or route finding) and group management is a form of exposure control used in all backcountry travel (e.g. for recreational, commercial and industrial

***Figure 8.4:** Example of a snow shed with avalanche deposit on top located along the Coquihalla Highway (Hwy 5) east of Hope, BC. BC MoTI photo.*

***Figure 8.5:** Example of retarding mounds in the runout zones of three avalanche paths in the Rohr Ridge area, located on the Duffey Lake Road (Hwy 99) east of Pemberton, BC. B. Gould photo.*

purposes), in the context of this section on precautionary evacuation and restricted access it refers to an organized system that would be managed by avalanche professionals.

Evacuation and access restriction may be defined and communicated in multiple ways, depending on the context and time period of the evacuation. Precautionary evacuation and restricted context examples are provided in Table 8.1 while communication is expanded upon in Section 8.3.5.

Figure 8.6: *Example of a reinforced concrete wall used to protect vehicles on the Coquihalla Highway (Hwy 5) east of Hope, BC. BC MoTI photo.*

Figure 8.7: *Example of a splitting wedge protecting two lattice transmission line structures in runout zones of avalanche paths. BC MoTI photo.*

Table 8.1: Precautionary evacuation and restricted access examples.

Element at risk	Evacuation and time context
Occupied structure	Inhabitant evacuation (temporary or seasonal). Temporary curfew (restricted to inside of structure in order to evacuate immediate outside area) may also be appropriate.
Transportation corridor	Evacuation of vehicles and pedestrians and closure of avalanche areas during elevated hazard. Restrict pedestrian exposure by not allowing stopped vehicles in avalanche areas. Typical designation and time context: • Traffic delay – hours. • Temporary closure – hours to days. • Seasonal closure – winter season. Although evacuation is typically implemented by an avalanche forecaster that is completing ongoing risk assessments, automated systems that rely on slide detector fences in the avalanche track or runout zone may be used (Figure 8.8).
Workers at a fixed outdoor worksite	Evacuation and/or restricted access – short term (temporary) or long term (seasonal).
Workers engaged in backcountry travel	Temporary restricted access to specific terrain depending on hazard rating and level of training (in context of risk control based on procedure and policy).
Ski area	Run or zone closure.
Commercially guided group	Restricted coding (e.g. red) on daily run list, followed by real-time route selection and group management (exposure control) on individual terrain features.

8.3.2 Artificial Triggering

Artificial triggering is intended to reduce the likelihood of triggering large avalanches and/or release unstable snow at controlled times, once the area is evacuated. Triggering measures range from ski cutting and hand charging with explosives to sophisticated remote avalanche control systems (RACS) utilizing either explosives or gas (Table 8.2). The level and sophistication of triggering technique or system is normally based on cost-benefit evaluation and worker safety considerations. Often a combination of systems will be employed for a particular control program (e.g. ski area control routes that utilize ski cutting and hand charging).

Table 8.2: Artificial triggering measures with descriptions.

Triggering measure		Description
Skis or vehicles	Ski cutting (ski testing) or vehicle control	Triggering avalanches by skiing or operating a vehicle (e.g. snowmobile) near or across the top of a starting zone. Often used to determine likelihood of triggering the upper snowpack. Only employed on slopes with minimal potential consequence.
Explosives*	Hand charging	Deployment of explosives from ground position, generally above the starting zone of the avalanche path.
	Helicopter explosive control	Helicopter deployment of explosive charges. Charge size may range from small (500 g) to large (25 kg or greater) (Figure 8.9).
	Case charging	Detonation of large amounts (often 50 to 100 kg) of pre-placed explosives at the base of a relatively short steep slope.
	Avalauncher	Pressurized gas propelled explosive projectiles.
	Artillery	Military specified explosive projectiles.
	Cableway or tram systems	Explosives transported by cable to starting zones. May range from simple hand crank to sophisticated manufactured electronic system.
Explosives* or gas	Remote avalanche control systems (RACS)	Sophisticated systems installed in starting zones and remotely controlled by radio or other communications link. Systems may incorporate cast explosives (tethered or mortar based) or gas mixture that is detonated by a timed ignition sequence (Figures 8.10, 8.11 and 8.12).

**Note: Explosive control requires trained and certified blasters.*

Figure 8.8: *Example of a slide detector fence located above a railway line. Avalanches running into the system from the slopes above will break wires strung between the poles, thus signaling personnel and triggering closures. Canadian Pacific photo.*

8.3.3 Snowpack Compaction

The intent of snowpack compaction is to disrupt layers in the snowpack in order to reduce future instability. It is considered a short-term mitigation measure, though its effect may not be realized for weeks or months after it is employed, and its effectiveness cannot be directly measured. The snowpack can be compacted using intentional boot or ski packing, or as a corollary of public recreational ski or snowmobile traffic. The impact of compaction on hazard reduction, and resulting success of as avalanche risk mitigation measure, depends on the snow and weather conditions that develop subsequent to compaction (generally over weeks to months).

8.3.4 Procedure and Policy

Risk control based on procedure and policy (P&P) involves the use of a structured operating procedure (e.g. risk matrix) to restrict or enable access to hazard areas based on forecasted hazard levels, terrain classification and level of training of the user. These systems are normally employed in an environment where there may be an array of field-based activities occurring at a large scale, and there is potentially a spectrum of staff training levels. They may also be used by a guiding or field team to restrict or enable specific routes (e.g. run list). Details regarding the procedures and policies would normally be described in an avalanche risk control plan.

Terrain classification used within the scope of P&P-based risk control is often determined in advance during the planning stage. Hazard ratings may be provided by a forecasting program within the organization, outside contract services, or from publicly available sources. However, it is important to note that P&P-based risk control should be guided by hazard assessments specific to the element at risk. If non-specific or inappropriate sources are used, it must be understood that there are often more restrictions than with risk control based on hazard and guidance provided by a forecasting program within the organization (or from contract services), due to potential differences in spatial and temporal scale, intended audience and element at risk characteristics.

The risk control procedure (risk reduction parameters and access decisions) are typically provided in a table or matrix format. Figure 7.1 (Chapter 7) is an example of this in an industrial application.

Avalanche safety equipment and training and an emergency response plan are all normal components of P&P-based risk control. For workplaces, these are normally outlined in the organization's avalanche safety plan (ASP), along with maps and other procedures and policies (e.g. risk matrices). An ASP is a risk control plan that is specific to workers. The CAA has produced an ASP template for snowmobile clubs (CAA, 2014a) and a recommended generic table of contents for ASPs (CAA, 2008).

Figure 8.9: *Example of helicopter explosive control. M. Boissonneault photo.*

Figure 8.10: *Example of a remote avalanche control system (RACS). This Gazex® is located along a mine access road in Northwestern BC, The splitting wedge uphill of the exploder is to protect the Gazex® from rockfall. B. Gould photo.*

Figure 8.11: *Example of a remote avalanche control system (RACS). This Wyssen Avalanche Tower is located near Davos, Switerland. B. Gould photo.*

Figure 8.12: *Example of a remote avalanche control system (RACS). This Avalanche Guard® is located along the Trans-Canada Highway (Hwy 1) east of Revelstoke, BC. BC MoTI photo.*

8.3.5 Risk Communication

Risk communication with all stakeholders is an essential component of short-term mitigation. Risk communication is described in the organization's operating procedures or avalanche risk control plan.

For highways, worksites, ski areas and public land, communication may be provided at the site by way of warning signs or in electronic media (e.g. websites, email and social media platforms) as well as radio and traditional methods (e.g. internal memos). Examples are provided in Table 8.3.

Table 8.3: *Risk communication examples.*

Land-use	Warning signs and other communication
Highway	Seasonal road signs that state "no stopping" and "end of avalanche area" at start and end of avalanche areas.
Worksite, highway or ski area	Area closure or danger area sign at site, often with physical gate or barrier. Media announcement or posting, typically with several hours advance notice.
Railway	Avalanche forecasts and operational recommendations provided by way of an internal communication system.
Public land	Signs at trailheads and in backcountry huts. Public forecast bulletins and warnings delivered through various media outlets (e.g. online, print, television and radio).

8.4 Avalanche Terrain Classification and Maps Used for Mitigation

The use of avalanche terrain classification and maps is an indirect mitigation measure that may be considered both short and long term. Maps are an essential tool for P&P-based risk control systems and ongoing operational mitigation needs. Common classification systems and map types are described in Chapter 4. Avalanche terrain classification and maps used for mitigation is described in the next three subsections.

8.4.1 Avalanche Path Map

For established element(s) at risk (e.g. those within ski areas, on highways and at worksites), avalanche path maps are essential for communicating the location and approximate boundaries of avalanche terrain. Used in combination with a complete avalanche atlas (Chapter 11), avalanche path maps document and communicate explicit terrain features and static hazard boundaries in order to facilitate planning in and around avalanche terrain.

8.4.2 Terrain Exposure Classification

Terrain exposure classification is primarily used as a tool for self-directed recreationists to choose trips on a broad scale (i.e. trip planning), and for P&P-based workplace risk control. Using systems such as the Avalanche Terrain Exposure Scale (Appendix 1), terrain exposure classification facilitates broad-scale route finding choices for backcountry travel scenarios by helping people select different levels of avalanche terrain relative to degree of exposure.

Specific exposure classes for routes may be described in text format or displayed on a hazard map. Areal terrain exposure classification and mapping using zoning models (e.g. Campbell and Gould, 2014) may be provided for unstructured or roving-based exposure. The classification can be incorporated into a simple risk matrix for risk control.

8.5 Acceptance of Risk

Avalanche risk may be accepted, often by designing mitigation to protect from a high-frequency event, and accepting risk from a low-frequency event. For example, a ski lift might be located where damage is possible (when the lift is closed to skiers) and the cost of repairs over the life of the lift is acceptable. Such risk tolerance must be consistent with applicable legislation and regulations. In the case of occupied structures, restrictive covenants may be required.

J. Weinel photo.

Chapter 9 Outline

9 Guidelines for Avalanche Terrain Land-use in Canada

This chapter provides guidance for typical hazard/risk assessments for new developments or activities, and for mitigation strategies during both the planning and operational stages of avalanche risk management. If an initial hazard assessment determines that avalanches of a given size or impact pressure affects the element at risk more frequently than the thresholds given in the following tables, a risk assessment must be undertaken and mitigation considered. The chapter begins with a description of the organization and structure of these tables. The subsections reflect types of land-use in avalanche terrain.

9.1 Guideline Structure

Consideration of land-use in avalanche terrain in Canada is segregated by the following activities or industry sectors:

1. Municipal, residential, commercial and industrial areas.
2. Transportation corridors.
3. Ski areas and resorts.
4. Backcountry travel and commercial activities.
5. Worksites, exploration, survey, resource roads, energy corridors and utilities, managed forest land and other resources.

This chapter is organized by these activities and sectors.

Each section includes a description of the element(s) at risk, their vulnerability, and their potential for exposure, along with a table that summarizes both planning and operational risk management guidelines, for a specific activity or industry sector.

The backcountry travel and commercial activities section (Section 9.6) focuses on land use for outdoor recreation, wilderness and adventure tourism. Natural resource, energy and other industry-related backcountry travel and activities (e.g. exploration and surveying) are addressed in Section 9.7.

The tables are organized with column headings for:

- Element at risk.
- Avalanche size or impact pressure.
- Return period (years).
- Risk management guidelines for planning.
- Risk management guidelines for operations.

The following subsections provide an expanded description and the background for each of these table headers.

9.1.1 Element(s) at Risk

One or more element(s) at risk may be involved in each of the activities and sectors. Elements at risk generally fit within the following groups:

- Persons (e.g. occupants, pedestrians, recreationists, workers, motorists, passengers, etc.).
- Structures (e.g. unoccupied, occupied, essential and/or emergency service, etc.).
- Infrastructure (e.g. chairlifts, utilities, transmission, transportation, communication, etc.).
- Vehicles, aircraft or rail stock (on roads, railways, landings, helipads, over snow, etc.).
- Natural resources and environment (e.g. forest cover, fish-bearing streams, etc.).
- Goods (usually in transit) (e.g. manufactured goods, commodities and resources).

Different elements at risk have different vulnerabilities and economic values. This makes some at higher risk to avalanches than others, and some with lower risk tolerance than others. Consideration of whether an element at risk is static or mobile is necessary to determine exposure.

Elements at risk that are indirectly impacted by avalanches include commerce (e.g. delays in transportation of goods due to highway or railway closures) and productivity (e.g. delays due to worksite closures). However, due to the complexity of evaluating and thus providing guidelines for indirect elements at risk, only elements at risk that are directly impacted by avalanches are considered in this chapter. Furthermore, the tables below are not a comprehensive list, and only include elements at risk most commonly considered in avalanche risk management.

There is similarity between assessment and mitigation strategies across the activities and sectors that is based on the commonality of the elements at risk. However, every situation in which things of value are exposed to avalanches is different, and some may not fit within the typical parameters listed; good judgment is essential. Furthermore, some situations may involve overlapping land-use types and multiple elements at risk, creating complexity where all opportunities and threats must be carefully assessed (Figure 9.1). This is especially important when considering the rapid expansion of recreational land use.

Figure 9.1: *Example of multiple overlapping land use types and overlapping elements at risk in the Coquihalla Pass area of BC. Land use types and elements at risk include forestry (timber resources), transportation corridor (people in vehicles) and backcountry recreation (mobile people on foot). BC MoTI photo.*

9.1.2 Frequency and Magnitude Thresholds

In order to know when and how to implement measures that mitigate avalanche risk, thresholds of avalanche size and/or impact pressure, and corresponding return period are provided in the tables below for each element at risk. Typical return-period thresholds of one, 10, 30, 100 and 300 years are used. These values are the borders between periods as shown in Table 9.1.

Table 9.1: *Typical return-period thresholds with corresponding time range (frequency).*

Return period (years)	**1**	**10**	**30**	**100**	**300**
Time range (frequency)	One or more avalanche(s) annually	One or more avalanche(s) every 10 years	One or more avalanche(s) every 30 years	One or more avalanche(s) every 100 years	One or more avalanche(s) every 300 years

If an initial hazard assessment determines that avalanches of a given size or impact pressure affects the element at risk more frequently than the thresholds given in the following tables, a risk assessment must be undertaken and mitigation considered.

The thresholds also represent minimum hazard levels for mitigation planning (e.g. mitigation for an avalanche with a 30-year return period might not be required where the following tables indicate a threshold return period of 10 years). Also, a greater level of effort is required to assess exposed areas as the return period increases, due to the associated increased uncertainty (e.g. a threshold of ≤ 100 years typically leads to a more thorough assessment than a ≤ 30-year threshold).

9.1.3 Planning and Operational Guidelines

These columns in each sector table illustrate both subtle and substantial differences between planning and operational assessments. Assessments are a function of the objectives and type of assessment (i.e. hazard or risk), along with size of the study area or assessment scale (Chapter 2), complexity of the terrain, element(s) at risk (including exposure time characteristics, and availability, quality and reliability of background information and field data.

Scale

This subheading describes the spatial extent that is typically addressed in the planning and operational context. It also provides a typical exposure time length or time range that is addressed during the planning and operational stages.

Identification and Analysis

This subheading describes the fieldwork and desktop steps to identify and describe the potential for a harmful event, and catalogue and analyze the environmental conditions that contribute to the hazard. It includes the suggested terrain survey level of effort (TSLE) (Table 4.2) required during the planning stage, along with what analysis is typically undertaken. For the operational stage, this subheading describes the typical data and evidence to be gained through both fieldwork and other information sources to support the evaluation.

Assessment Techniques and Decision Aids

This subheading describes the general processes to evaluate and estimate the likelihood and magnitude of the threat. Both qualitative and quantitative procedures are referenced (Section 5.3.2). Primary use of one technique or aid over the other is based on the scope, situation and objectives of the assessment. This subheading also provides examples of assessment/decision aids (Chapter 7) commonly used for planning or operational hazard/risk assessment. It is important to remember that limitations associated with available techniques and aids to determine avalanche hazard or risk must be recognized, and typically necessitates the application of expert judgment.

Supporting Map Types

This subheading describes the typical map types (Section 4.3.2) utilized in the assessment relative to the element(s) at risk. Avalanche maps present the findings of the terrain identification to create a spatial reference point for hazard/risk assessment. Resulting maps range in level of detail and precision, and therefore, scale, depending on the application. Typical scales for each map type are given in Section 4.3.2.

Mitigation Options

This subheading describes typical single or multiple layers of systems or techniques to reduce or eliminate risk. Implementation of mitigation measures generally follows the assessment in both the planning and operational stages. Mitigation options are chosen to reduce the risk to a tolerable level based on planning and operational considerations, and must also take into account other factors (e.g. costs, benefits and closure times).

Short-term mitigation measures are often required to supplement long-term measures to achieve the desired risk tolerance. Rarely is operational mitigation undertaken without an initial planning stage.

9.2 Municipal, Residential, Commercial and Industrial Areas

Occupied structures located in proximity to avalanche terrain require careful assessment of the boundaries of extreme runouts. Some residences and public facilities are exposed to avalanche hazard in Canada, including people who are in and around those structures. Though the structures have an economic value, the primary element at risk is people. Exposure of the structure (but not the people) is static (i.e. in a fixed location), while people in and around structures are mobile. Furthermore, the protection afforded by the structure may decrease the vulnerability of any occupants.

Structures are divided between two classes: *occupied* and *unoccupied*. Both classes require a hazard assessment based on the combination of expected impact pressures and return periods of avalanches.

Occupied structures are inhabited during seasonal periods when avalanche potential occurs (typically summarized as "winter"). Occupied structures include industrial, residential, commercial and other structures where people spend portions of the day or night, may gather in or around during a period of avalanche hazard, provide essential services, or otherwise attract people. For structures that are vacant for long periods of time, operational risk management is typically only implemented during periods when the structure is occupied.

Unoccupied structures generally serve as part of an infrastructure (e.g. storage, pump houses and electronics enclosures). They should be included in an initial hazard assessment if there is potential for public or personnel access during avalanche hazard periods, or if the value of the structure and/or its contents warrant an assessment. Pedestrian areas (both public and personnel) may also need to be considered for municipal, residential, commercial and industrial areas.

M. Bender photo.

***Table 9.2:** Typical elements at risk for municipal, residential, commercial and industrial areas with avalanche size and return-period thresholds for avalanche planning (Chapter 5). Also listed for each element at risk is: the typical assessment scale (Chapter 2); exposure time scale; fieldwork including Terrain Survey Level of Effort (TSLE) (Section 4.1.1); assessment techniques and decision aids (Chapter 7), supporting map types (Section 4.3.2); and mitigation options (Chapter 8) for both the planning and operational stages (Chapter 6).*

Typical element at risk	**Typical avalanche size or impact pressure**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.2.1 Occupied structures	≥ 1 ≥ 1 kPa	≤ 300	**Scale**	Path-scale assessment for an exposure time scale of decades.	Daily drainage- to regional-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A. Path profile mapping (including e.g. statistical runout estimation). Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily weather observations and conditions reports. Weekly to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Quantitative procedures (e.g. locally validated numerical runout modeling); impact-based classification.	Assessment tables; avalanche forecasting; decision tree; risk matrix.
			Supporting map types	Hazard zone map; avalanche path map.	Hazard zone map; avalanche atlas[vii].
			Mitigation options	Location planning; reinforcement and design of structures; starting zone snowpack support structures and, track and runout zone long-term measures (e.g. splitting wedges). Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans) where long-term mitigation does not achieve tolerable risk.	Sufficient mitigation is typically achieved at the planning stage. Otherwise, short-term measures (e.g. avalanche forecasting; precautionary evacuation; temporary curfew and restricted access) are considered.

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.2.2 Unoccupied structures and other infrastructure	> 2	≤ 30	**Scale**	Path-scale assessment for an exposure time scale of years to decades.	Drainage- to path-scale assessments during periods of increased hazard or access as determined in planning stage.
			Identification and analysis	TSLE: B. Frequency-magnitude analysis (e.g. vegetation and climate studies, and historical and human records).	Weather, snowpack and avalanche observations during periods of increased hazard or access as determined in planning stage.
			Assessment techniques and decision aids	Qualitative or quantitative procedures; impact-based classification.	Assessment tables; avalanche forecasting.
			Supporting map types	Hazard zone map.	Avalanche atlas.
			Mitigation options	Location planning; reinforcement and design of structures; starting zone snowpack support structures, and track and runout zone long-term measures (e.g. splitting wedges). Specification of short-term operational measures (e.g. developing operational assessment aids).	Avalanche forecasting; artificial triggering.
9.2.3 Recognised pedestrian areas	> 1	≤ 100	**Scale**	Slope- to path-scale assessment for an exposure time scale of hours to days.	Daily drainage- to regional-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A.	Daily weather observations and conditions reports. Weekly to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Quantitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; decision tree; risk matrix.
			Supporting map types	Hazard zone map.	Avalanche atlases for areas with long-term use, or if artificial triggering is planned.
			Mitigation options	Location planning; seasonal closures. Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans).	Avalanche forecasting; warning systems; temporary curfew, evacuation or closure.

9.3 Transportation Corridors

The traveling public, workers and commerce on some transportation routes (road and rail) in Canada are exposed to avalanche hazard. Though vehicles and trains and their cargo have economic value, the primary elements at risk are persons and workers in vehicles or trains as well as economic loss (opportunity costs) due to delays. When mitigating risk to transportation corridors, it is therefore critical to achieve an optimal balance between safety of the traveling public and workers, and excessive closures causing unnecessary economic loss.

Exposure is considered mobile (i.e. moving through the avalanche hazard area during a given period of time). The calculated exposure is related to the peak hourly traffic volume and is a function of the road's vehicle traffic capacity and how the traffic is moving (Conger and Taylor, 1998). The protection afforded persons from being inside a vehicle or train along with the transit speed of the exposure, are important to planning in this land-use sector. Vulnerability is associated with the nature of the avalanche (e.g. powder, slough, light, deep, plunging) (Schaerer, 1989; Rheinberger et al., 2009).

Elements at risk in transportation corridors are divided between three classes based on the amount and time period of exposed traffic, opportunity costs (i.e. the effect on economic activities and services) and whether rail or road is being considered. Roads are either those with low traffic exposure and/or low opportunity costs (e.g. Highway 31A from New Denver to Kaslo in BC) or those with high traffic exposure and/or high opportunity costs (e.g. Trans-Canada Highway). Rail travel is considered separately since the exposure is fully controlled by the system operator.

Rail hazard and assessment strategies are largely the same as roads (Hamre, 2009), although avalanche deposits contaminated by rocks, woody debris and soil are critical on railways where derailment is a key risk consideration. Furthermore, risk to the environment (e.g. pushing an ore truck into a river, or derailment of a train carrying oil or other toxic chemicals) must also be considered when assessing transportation corridors. Public and personnel pedestrian areas may also need to be considered for some transportation corridors.

Doug Wilson photo.

Table 9.3: *Typical elements at risk for transportation corridors with avalanche size and return-period thresholds for avalanche planning (Chapter 5). Also listed for each element at risk is: the typical assessment scale (Chapter 2); exposure time scale; fieldwork including Terrain Survey Level of Effort (TSLE) (Section 4.1.1); assessment techniques and decision aids (Chapter 7), supporting map types (Section 4.3.2); and mitigation options (Chapter 8) for both the planning and operational stages (Chapter 6).*

Typical element at risk	**Typical avalanche size**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.3.1 Roads with low traffic exposure and/or low opportunity costs	≥ 2 ≥ 3	≤ 10 ≤ 30	**Scale**	Drainage-scale followed by path-scale assessment, for an exposure time scale of days to years. Assessment of a group of paths (i.e. avalanche area) is often useful.	Drainage- to path-scale assessments during periods of increased hazard or access as determined in planning stage.
			Identification and analysis	TSLE: B or C. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Weather, snowpack and avalanche observations during periods of increased hazard or access as determined in planning stage.
			Assessment techniques and decision aids	Qualitative or quantitative procedures based on objectives. Terrain exposure classification or impact-based classification.	Assessment tables; avalanche forecasting; decision tree; risk matrix.
			Supporting map types	Locator and linear hazard/risk maps.	Locator and linear hazard map; avalanche atlas[vii].
			Mitigation options	Location planning is the first consideration for mitigation, followed by long-term measures (e.g. protection forest and occasional runout zone measures such as enhanced catchment zones or retarding mounds). Seasonal closures are also a mitigation option considered during planning. Specification of short-term operational measures (e.g. avalanche forecasting and developing operational assessment aids).	Temporary closure (potentially with aid of slide detector fences); occasional artificial triggering. Stopped vehicles and pedestrians are not usually permitted in avalanche areas through use of signs. Risk control based on procedure and policy is often used for workers and emergency service personnel.

Typical element at risk	**Typical avalanche size**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.3.2 Roads with high traffic exposure and/ or high oppor-tunity costs	≥ 2 ≥ 3	≤ 30 ≤ 100	**Scale**	Drainage-scale followed by path-scale assessment, for an exposure time scale of hours to days. Assessment of a group of paths (i.e. avalanche area) is often useful.	Daily drainage- to regional-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A. Path profile mapping (including e.g. statistical runout estimation). Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily weather observations and conditions reports. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures; impact-based classification.	Nearest neighbour system; checklist sum; assessment tables; avalanche forecasting; decision tree; risk matrix.
			Supporting map types	Locator, hazard, and linear risk maps. Avalanche atlas.	Avalanche atlas, frequency-magnitude maps.
			Mitigation options	Location planning is the first consideration for mitigation, followed by long-term measures (e.g. protection forest, and various starting zone and runout zone measures). Long-term installation of remote avalanche control systems as an operational mitigation measure is a common planning consideration. Specification of short-term operational measures (e.g. avalanche forecasting and developing operational assessment aids).	Temporary closure (potentially with aid of slide detector fences); traffic delays during artificial triggering often with sophisticated systems (e.g. remote avalanche control systems (RACS)). Stopped vehicles and pedestrians are not usually permitted in avalanche areas through use of signs. Risk control based on procedure and policy is often used for workers and emergency service personnel.

Typical element at risk	Typical avalanche size	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.3.3 Recognised pedestrian areas	> 1	≤ 100	**Scale**	Drainage-scale followed by path-scale assessment, for an exposure time scale of minutes to hours. Assessment of a group of paths (i.e. avalanche area) is often useful.	Daily drainage- to regional-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A or B. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily weather observations and conditions reports. Weekly to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures based on objectives.	Checklist sum; assessment tables; avalanche forecasting; decision tree; risk matrix.
			Supporting map types	Locator and linear risk maps; avalanche atlas.	Avalanche atlas, frequency-magnitude map.
			Mitigation options	Location planning is the first consideration for mitigation, followed by long-term measures (e.g. protection forest, remote avalanche control systems and various starting zone and runout zone measures). Specification of short-term operational measures (e.g. avalanche forecasting and developing operational assessment aids).	Temporary closure; artificial triggering often with sophisticated systems (e.g. remote avalanche control systems (RACS)). Risk control based on procedure and policy is often used for workers.

9.4 Ski Areas and Resorts

People on or in the vicinity of ski runs, base area of resorts and ski lifts, as well as associated infrastructure and amenities provided by ski resorts, can be subject to avalanche hazard. Exposure of these elements at risk to the avalanche hazard can be either static or mobile. Vulnerability typically relates to the people at risk.

Ski areas with fixed lifts typically operate under a land-use agreement, in which the resort is responsible for managing the avalanche risk within a defined boundary. Defining this boundary is a key part of initial planning as well as expansion planning. Planning assessments are completed prior to development or expansion and as mitigation measures are introduced or revised.

Table 9.4: *Typical elements at risk for ski areas and resorts with avalanche size and return-period thresholds for avalanche planning (Chapter 5). Also listed for each element at risk is: the typical assessment scale (Chapter 2); exposure time scale; fieldwork including Terrain Survey Level of Effort (TSLE) (Section 4.1.1); assessment techniques and decision aids (Chapter 7), supporting map types (Section 4.3.2); and mitigation options (Chapter 8) for both the planning and operational stages (Chapter 6).*

<table>
<tr><th>Typical element at risk</th><th>Typical avalanche size or impact pressure</th><th>Typical return period (years)</th><th></th><th>Typical planning (Chapter 5)</th><th>Typical operations (Chapter 6)</th></tr>
<tr><td rowspan="5">9.4.1 Infrastructure (including lift towers)

9.4.2 Terminal stations</td><td rowspan="5">> 2

≥ 1</td><td rowspan="5">≤ 30

≤ 300</td><td>Scale</td><td>Mountain-scale, followed by path-scale assessment for an exposure time scale of years to decades.
Assessment of a group of paths (i.e. avalanche area) is often useful.</td><td>Daily mountain-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.</td></tr>
<tr><td>Identification and analysis</td><td>TSLE: A.
Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).</td><td>Hourly to daily weather observations and conditions reports.
Daily to weekly snowpack and avalanche observations.</td></tr>
<tr><td>Assessment techniques and decision aids</td><td>Qualitative and quantitative procedures (e.g. locally validated numerical runout modeling and impact-based classification).</td><td>Checklist sum; assessment tables; avalanche forecasting; decision tree.</td></tr>
<tr><td>Supporting map types</td><td>Avalanche path map; hazard zone map.</td><td>Avalanche atlas.</td></tr>
<tr><td>Mitigation options</td><td>Location planning; reinforcement and design of structures; track and runout zone measures (e.g. splitting wedges).
Long-term installation of remote avalanche control systems as an operational mitigation measure is a common planning consideration.
Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans) where long-term mitigation does not achieve tolerable risk.</td><td>Sufficient mitigation is typically achieved at the planning stage.
Otherwise, short-term measures (e.g. avalanche forecasting, precautionary evacuation, and occasional artificial triggering) are considered.</td></tr>
</table>

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.4.3 Occupied structures (including lodges and restaurants)	≥ 1 ≥ 1 kPa	≤ 300	**Scale**	Path-scale assessment for an exposure time scale of years to decades.	Daily mountain-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A. Path profile mapping (including e.g. statistical runout estimation). Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Hourly to daily weather observations and conditions reports. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Quantitative procedures (e.g. locally validated numerical runout modeling and impact-based classification).	Checklist sum; assessment tables; avalanche forecasting; decision tree.
			Supporting map types	Avalanche path map; hazard zone map.	Avalanche atlas; hazard zone map.
			Mitigation options	Location planning; reinforcement and design of structures; and, track and runout zone measures. Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans) where long-term mitigation does not achieve tolerable risk.	Sufficient mitigation is typically achieved at the planning stage. Otherwise, short-term measures (e.g. avalanche forecasting, precautionary evacuation and controlled access) are considered.
9.4.4 Persons[i]	> 1	≤ 30	**Scale**	Mountain-scale followed by path-scale assessment, for an exposure time scale hours to days. Assessment of a group of paths (i.e. avalanche area) is often useful.	Daily mountain-scale assessments, with ongoing path- and slope-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: B.	Hourly to daily weather observations and conditions reports. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures (e.g. terrain exposure classification).	Checklist sum; assessment tables; avalanche forecasting; operational risk band.
			Supporting map types	Avalanche path map; hazard zone map.	Avalanche atlas.
			Mitigation options	Long-term starting zone measures (e.g. snow collection fences) are often considered for their additional benefits as are installation of remote avalanche control systems. Specification of short-term operational measures (e.g. avalanche forecasting and developing operational assessment aids).	Warning systems; snowpack compaction; precautionary evacuation; artificial triggering; procedure and policy for workers.

9.5 Backcountry Travel and Commercial Activities

The backcountry travel sector is where people, equipment and infrastructure are exposed to avalanche hazard that is generally unprotected by long-term measures. This sector includes search and rescue activities, non-profit and club-operated mountain huts and snowmobiling trails, commercial recreational activities (e.g. guiding, lodges and infrastructure for ski touring, helicopter and snowcat skiing, mountain snowmobiling, etc.) and professional avalanche work activities (e.g. avalanche forecasting, instruction, etc.).

Helicopter landing zones and snowcat trails are included because their location can change from season to season. These are zones and trails that are flagged or constructed and maintained for frequent or regular use (e.g. once per week).

Exposure is considered mobile other than the static exposure of occupied structures. Vulnerability is associated with individual persons in all elements at risk.

It is important to note that there are regular instances where in-situ avalanche terrain identification and hazard assessment are part of short-term mitigation measures directly applied at the slope-scale.

Table 9.5: *Typical elements at risk for backcountry travel with avalanche size and return-period thresholds for avalanche planning (Chapter 5). Also listed for each element at risk is: the typical assessment scale (Chapter 2); exposure time scale; fieldwork including Terrain Survey Level of Effort (TSLE) (Section 4.1.1); assessment techniques and decision aids (Chapter 7), supporting map types (Section 4.3.2); and mitigation options (Chapter 8) for both the planning and operational stages (Chapter 6).*

Typical element at risk	**Typical avalanche size or impact pressure**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.5.1 Persons engaged in commercial recreational activities and professional avalanche work	> 1	≤ 30	**Scale**	Region- to path-scale assessment for an exposure time of minutes to days.	Daily drainage- to run-scale assessments and in-situ run-, slope-, and terrain feature-scale reassessments for an exposure time of minutes to hours.
			Identification and analysis	TSLE: C or D.	In-situ terrain identification. Hourly to daily weather and conditions observations. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; checklist sum.
			Supporting map types	Run map; run/terrain photos; Google Earth™; avalanche path map.	Run map; run/terrain photos; terrain exposure ratings or map. Locator map or avalanche atlas[vii].
			Mitigation options	Mitigation is primarily accomplished through short-term operational measures.	Procedure and policy for workers; temporary closure or use restriction (e.g. on a run list); ski/vehicle triggering; explosives triggering.

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.5.2 Other workers[ii]	> 1	≤ 30	**Scale**	Drainage- to run-scale assessment for an exposure time scale of minutes to hours.	Daily drainage-scale assessments, with ongoing slope-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: C or D.	Hourly to daily weather and conditions observations. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; risk matrix.
			Supporting map types	Terrain exposure map; locator map.	Terrain exposure map; locator map. Locator map or avalanche atlas[vii].
			Mitigation options	Mitigation is primarily accomplished through short-term operational measures (e.g. avalanche forecasting and a risk matrix).	Worksite access restrictions; avalanche forecasting; procedure and policy; artificial triggering.
9.5.3 Helicopter landing zones[ix]	≥ 2	≤ 30	**Scale**	Slope- to path-scale assessment for an exposure time scale of minutes to hours.	Daily drainage- to regional-scale assessments with ongoing slope- to path-scale reassessments.
			Identification and analysis	TSLE: C or D.	Daily weather observations and conditions reports. Daily to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures (e.g. hazard analysis).	Assessment tables; avalanche forecasting; checklist sum.
			Supporting map types	Run map; terrain photos; locator map; avalanche path map.	Run map; run/terrain photos; locator map or avalanche atlas[v].
			Mitigation options	Location planning.	Temporary relocation, closure or use restriction (e.g. on a run list); explosive triggering.

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.5.4 Snowcat trails	≥ 2	≤ 30	**Scale**	Slope- to path-scale assessment for an exposure time scale of minutes to hours.	Daily drainage- to regional-scale assessments with ongoing slope- to path-scale reassessments.
			Identification and analysis	TSLE: B. Avalanche hazard identification.	Daily weather observations and conditions reports. Daily to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; checklist sum; risk matrix.
			Supporting map types	Run map and photos; avalanche path map.	Run map and photos; locator map or avalanche atlas[v].
			Mitigation options	Location planning.	Procedure and policy for workers; temporary closure or use restriction (e.g. on a run list); ski/vehicle triggering; and occasional explosives triggering.
9.5.5 Occupied structures (e.g. backcountry huts)	≥ 1 ≥ 1 kPa	≤ 300	**Scale**	Path-scale assessment for an exposure time scale of years to decades.	Daily mountain-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Hourly to daily weather observations and conditions reports. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures. Terrain exposure classification or impact-based classification (may necessitate numerical runout modeling).	Assessment tables; avalanche forecasting; risk matrix; checklist sum.
			Supporting map types	Hazard zone map.	Avalanche path map; locator map.
			Mitigation options	Location planning; reinforcement and design of structures. Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans) where long-term mitigation does not achieve tolerable risk.	Sufficient mitigation is typically achieved at the planning stage. Otherwise, short-term measures (e.g. precautionary evacuation and controlled access) are considered.

9.6 Worksites, Exploration, Survey, Resource Roads, Energy Corridors and Utilities, Managed Forest Land and Other Resources

Outdoor worksites, resource roads, exploration or survey activities, mining access roads and operations may be exposed to avalanche hazard. Though the primary element at risk is people, value may include equipment or temporary facilities (e.g. a diamond-drilling rig). Logging access roads, harvesting operations, standing timber resources and reforestation may also be exposed to avalanche hazard (Weir, 2002). Cross-mountain transmission and local distribution lines may be exposed to avalanche hazard (Stethem et al., 2003). Avalanche threat to pipelines and transmission lines reflect the risk of environmental damage (pipelines) or loss of service in utilities (transmission and pipelines). Though snow avalanches do not usually affect a pipeline buried below the ground surface, they may threaten above-ground infrastructure (e.g. valves) and access routes.

Clear-cut logging can create new avalanche starting zones that may be capable of releasing avalanches sufficiently large to penetrate and destroy mature forest cover below (Figure 1.1 in Chapter 1). In addition to creating new starting zones, the presence of these logging cutblocks can augment the destructive potential of previously existing avalanche paths (Anderson and McClung, 2012). The BC Ministry of Forests has a handbook for management of avalanche-prone forest terrain (Weir, 2002) that includes avalanche risk assessment and mitigation measures to protect forest cover from avalanche hazard. In Alberta, harvesting is restricted to slopes with an angle of < 25° (Jamieson et al., 1996).

Table 9.6: *Typical elements at risk for worksites, exploration, survey, resource roads, energy corridors and utilities, managed forest land and other resources with avalanche size and return-period thresholds for avalanche planning (Chapter 5). Also listed for each element at risk is: the typical assessment scale (Chapter 2); exposure time scale; fieldwork including Terrain Survey Level of Effort (TSLE) (Section 4.1.1); assessment techniques and decision aids (Chapter 7), supporting map types (Section 4.3.2); and mitigation options (Chapter 8) for both the planning and operational stages (Chapter 6).*

Typical element at risk	**Typical avalanche size or impact pressure**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.6.1 Non-avalanche workers at a fixed outdoor worksite[vi] (e.g. forest workers in and around a yarder).	> 1	≤ 30	**Scale**	Slope- to path-scale assessment for an exposure time scale of minutes to hours.	Daily regional-scale assessments, with ongoing slope- to path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: C or D. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily weather observations and conditions reports. Daily to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; risk matrix.
			Supporting map types	Avalanche path map.	Terrain exposure ratings or map; locator map or avalanche atlas[vii].
			Mitigation options	Location planning. Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans).	Worksite access restrictions and precautionary evacuation; avalanche forecasting; procedure and policy.

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.6.2 Non-avalanche workers engaged in backcountry travel[viii] (e.g. exploration and survey crews).	> 1	≤ 30	**Scale**	Drainage-scale assessment for an exposure time scale of minutes to hours.	Daily regional-scale assessments, with ongoing slope-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: C or D.	Daily weather observations and conditions reports. Daily to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative procedures; terrain exposure classification.	Assessment tables; avalanche forecasting; risk matrix.
			Supporting map types	Terrain exposure map; locator map.	Terrain exposure ratings or map; locator map or avalanche atlas[vii].
			Mitigation options	Mitigation is primarily accomplished through short-term operational measures (e.g. avalanche forecasting and a risk matrix).	Backcountry access restrictions; avalanche forecasting; procedure and policy.
9.6.3 Resource roads[ix]	≥ 2	≤ 30	**Scale**	Mountain-scale followed by path-scale assessment for an exposure time scale of minutes to hours. Assessment of a group of paths (i.e. avalanche area) is often useful.	Daily regional-scale assessments, with ongoing mountain-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: C or D. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily weather observations and conditions reports. Daily to monthly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures depending on objectives, exposure, and costs; linear hazard assessment.	Assessment tables; avalanche forecasting; risk matrix.
			Supporting map types	Locator map; linear hazard map.	Locator map; linear hazard map; avalanche atlas[vii].
			Mitigation options	Location planning; seasonal closures.	Road access restrictions; avalanche forecasting; procedure and policy; occasional artificial triggering.

Typical element at risk	Typical avalanche size or impact pressure	Typical return period (years)		Typical planning (Chapter 5)	Typical operations (Chapter 6)
9.6.4 Occupied structures (e.g. storage facilities, powerhouse, field offices, etc.)	≥ 1 ≥ 1 kPa	≤ 300	**Scale**	Path-scale assessment for an exposure time scale of years to decades.	Daily drainage- to regional-scale assessments, with ongoing path-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: C or D. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Hourly to daily weather observations and conditions reports. Daily to weekly snowpack and avalanche observations.
			Assessment techniques and decision aids	Qualitative or quantitative procedures based on objectives; impact-based classification (may require numerical runout modeling).	Assessment tables; avalanche forecasting.
			Supporting map types	Hazard zone map.	Avalanche atlas[vii].
			Mitigation options	Location planning; reinforcement and design of structures; and, track and runout zone measures. Specification of short-term operational measures (e.g. developing operational risk assessment aids and evacuation plans).	Warning systems; precautionary evacuation; restricted access; artificial triggering.
9.6.5 Telecommunications and other infrastructure	> 2	≤ 30	**Scale**	Mountain-scale followed by path-scale assessment for an exposure time scale of minutes to hours. Assessment of a group of paths (i.e. avalanche area) is often useful.	Daily regional-scale assessments, with ongoing mountain- to drainage-scale reassessments during periods of increased hazard.
			Identification and analysis	TSLE: A. Frequency-magnitude analysis (e.g. vegetation and climate studies, historical and human records).	Daily to weekly weather observations and conditions reports. Weekly to monthly snowpack and avalanche observations.
9.6.6 Transmission line	> 2	≤ 100	**Assessment techniques and decision aids**	Locally validated numerical runout modeling; impact-based classification.	Assessment tables; avalanche forecasting.
			Supporting map types	Avalanche path map; hazard zone map.	Avalanche atlas[vii].
9.6.7 Surface pipeline and above-ground infrastructure	> 2	≤ 100	**Mitigation options**	Location planning; reinforcement and design of structures; track and runout zone measures (e.g. splitting wedges).	Sufficient mitigation is typically achieved at the planning stage. Otherwise short-term measures (e.g. avalanche forecasting and artificial triggering) are considered.

Typical element at risk	**Typical avalanche size or impact pressure**	**Typical return period (years)**		**Typical planning (Chapter 5)**	**Typical operations (Chapter 6)**
9.6.8 Forest cover[x]	< 3 ≥ 3	≤ 1 ≤ 10	**Scale**	Mountain-scale for an exposure time scale of decades, followed by path-scale site-specific assessment and mapping.	None.
			Identification and analysis	TSLE: C. Path profile measurement.	
			Assessment techniques and decision aids	Impact-based classification; qualitative risk matrix. This planning assessment is unique since it must consider likely conditions once forest cover is removed (may necessitate numerical runout modeling).	
			Supporting map types	Avalanche path map; hazard zone map.	
			Mitigation options	Timber harvest layout planning[xi] is used to mitigate risk.	

[i] *Includes staff, volunteers and public, on foot, skis/snowboards or snowmobiles.*
[ii] *Includes staff or volunteers not responsible (nor qualified) for making in-situ terrain identification, assessments and re-assessments (e.g. SAR technicians, custodians, cooks, etc.).*
[iii] *Includes legislation and regulations, such as permit areas and custodial group policies.*
[iv] *Includes operator and passengers (avalanche professionals and other workers, including volunteers, and other passengers) as well as equipment (helicopters and snowcats).*
[v] *For areas where artificial triggering is planned, or when no avalanche professional is on site.*
[vi] *One or more non-avalanche workers working at the same location over multiple days.*
[vii] *For areas where artificial triggering is planned.*
[viii] *Includes non-avalanche work activities in a backcountry setting.*
[ix] *Includes vehicles, passengers and content on private access and haul roads, including seasonal snow roads.*
[x] *For example, the forest downslope of a cut block or along an existing avalanche path that could be damaged by an avalanche that includes the area of the cut block.*
[xi] *May include high stumps, and/or block design to reduce the magnitude and return period of avalanches that may start above and within harvested areas (Anderson and McClung, 2012).*

Chapter 10 Outline

10 Other Considerations

The assessment and mitigation of snow avalanche hazards and risks requires the consideration of many potential effects and impacts, some of which may not be initially apparent. This chapter includes a discussion of associated direct or indirect avalanche effects, cumulative effects of avalanches, the effects of snow creep and glide, and other potential issues.

10.1 Associated Avalanche Effects

The associated indirect or direct effects from avalanches must sometimes be considered. For example:

- The effects on visibility and traction (e.g. for drivers on a highway) from the powder cloud related to a dry flowing or powder avalanche.
- Temporary blockage and associated retention of rivers or streams by avalanche deposits.
- The generation of potentially destructive waves from the impact of avalanches on standing water.
- The sympathetic release of avalanches in other nearby avalanche paths, which may or may not be associated with the operation artificially releasing the avalanches.
- Delayed regrowth of forest potentially for decades, due to the entrainment of sub-surface materials (e.g. soil).
- Environmental consequences from an avalanche impact (e.g. the rollover of a truck or rail car that releases harmful compounds into freshwater streams and fish habitat).
- Increased consequences that arise from the direct control of avalanches (e.g. explosive control that releases avalanches which may not occur naturally, that causes damage to infrastructure or harm to the environment).
- The noise of explosions used for artificial triggering that disturbs nearby residents.
- Impacts to third parties:
  - Clearing forests upslope of other landowners (e.g. logging above a highway corridor).
  - Pedestrians on roads (e.g. backcountry skiers or ice climbers who access highway avalanche areas on foot).

10.2 Cumulative Effects

Multiple events may result in unexpected characteristics of avalanches. For example:

- The effect of multiple avalanche deposits in the track or upper runout that redirects flow patterns for subsequent avalanches (Margreth and Gruber, 2001). Effects may include increased lateral spread or significant deviation from normal flow pattern.
- The effect of increased runout distance that occurs from avalanches flowing over previous avalanche deposits in the runout zone (Margreth and Gruber, 2001).
- The effect of increased runout distance and spread from multiple avalanches reaching the track and/or runout zone at the same time (i.e. the additional push on a flowing mass).
- The static loading of cumulative avalanche deposits on a snow shed or other vulnerable structures.

10.3 Snow Creep and Glide

The snowpack is considered a viscous medium, which under the effect of gravity is subject to deformation and movement. Snow creep (i.e. settling of the snowpack) occurs from the slow deformation of the snowpack over time. Snow gliding is the slow downslope movement of the snowpack. Although glide avalanches may result from snow gliding, this chapter describes the static (or almost static) forces that result from snow creep and glide on objects penetrating the snowpack perpendicular to the slope. Movement of the snowpack can range from millimetres to centimetres per day and has been observed as high as one metre per day. As the snowpack moves slowly and continually downslope, it may generate forces onto obstacles (e.g. buildings, towers or engineered structures) located on or directly at the base of inclined terrain. In addition, isolated horizontal components (e.g. the lattice on transmission line towers) may be affected by snow creep irrespective of whether the terrain is inclined or flat.

Methods have been established for the determination of potential snow creep and glide forces (e.g. Margreth, 2007a, 2007b; Larson, 1998), and current practice generally involves analysis using more than one method. Due to limited research of snow creep and glide, there may be significant uncertainty in results. In addition, climate records allowing for estimation of snowpack depth, density and wind effects may be limited for the study area in question.

10.4 Overhead Clearance Considerations

Ski lifts, overhead electrical transmission and utility lines are required to meet certain clearance standards. Deep snowpacks and cumulative avalanche deposits may result in the potential for encroachment, which may lead to ground faults and potential risk to pedestrians.

10.5 Glaciers and Icefall

Over time, the effect of glacial retreat or advance may change the nature of avalanche flow and runout distances. In addition, snow avalanches on glaciers may need to be considered during summer months.

Although their formation and release is different than snow avalanches, icefall (e.g. serac collapse, calving glaciers) are considered a type of avalanche (CAA, 2014b), and should be included in any hazard/risk assessment that involves glaciers.

10.6 Slush Flow

Slush flows are often seen as phenomena related to snow avalanches, although the dynamics can be different. They consists of snow that is soaked with water, move like liquid, and can run onto level terrain (McClung and Schaerer, 2006). They typically start on gentle slopes, often 5° to 25°, where the ground is poorly drained, and the supply of water is abundant due to rain or snowmelt. Although, some slush flow events are also triggered when a snow avalanche from a higher elevation enters water saturated snow further down. They are generally rare in Canada, and tend to occur mostly in the northern and eastern part of the country.

10.7 Other Mass Movements

Snow avalanches may be associated with other mass movements (e.g. landslides, debris flows and rock fall). Although snow avalanche mass sometimes includes subsurface materials (e.g. a wet spring avalanche that entrains ground cover and soil), there may be instances where there is uncertainty as to which component is the governing flow. All practical scenarios should be considered, and a multi-disciplinary approach is often required when there is any question in regards to the type of mass movement under consideration.

Chapter 11 Outline

11 Records and Reports

Records and reports are necessary to communicate the nature of avalanche risk and mitigation. Daily or periodic records are required in an operational program, and they may range from basic field notes to formalized meeting summaries. Reports are required for planning and review of operations, and are often used to present the results of detailed studies. Despite the purpose, all records and reports may come under intense scrutiny in the case of legal action, inquest or other related review. As such, it is important to exercise care when completing all documentation.

11.1 Records

Records are a form of documentation of observations, basic analyses or decisions. Several records are typically required in an operational setting. Some of the common types of records include:

- Snow profiles.
- Field notes, including observations as per observations guidelines and recording standards (e.g. CAA, 2014b).
- Avalanche control blasters' log book.
- Daily avalanche hazard assessment.
- Daily (morning/evening) meeting summaries, including:
  - Weather and snowpack summary.
  - Hazard evaluation.
  - Mitigation, including run list and control plan.
- Submissions to industry information exchange and database (e.g. CAA's InfoEx®).

Format and level of record detail is normally determined by a combination of the specific operation's requirements and established industry practice (e.g. CAA, 2014b). Records should be retained and archived for future review or legal purposes if required.

11.2 Reports

Reports are generally associated with planning and long-term decision making. They are intended to provide guidance for decision making, as well as planning and design for risk mitigation.

Some of the more common types of reports include:

- Avalanche hazard assessment (may be scoping level or detailed).
- Avalanche risk assessment (may be quantitative, semi-quantitative, or qualitative).

- Recommendations for mitigation (often included in a hazard/risk assessment report).
- Design of mitigation.
- Avalanche risk control plan (e.g. avalanche safety plan).
- Avalanche control blasting procedures.
- Comparative assessment of hazard, risk or mitigation options (often completed within the context of a business case study).
- Operational program review.
- Avalanche investigation report.
- Expert forensic opinion report or legal opinion report.

Although less formal, emails, memorandums and other written correspondence may also be used to convey aspects of the types of reports listed above.

There are numerous ways to structure avalanche reports depending on the scope of the hazard/risk assessment. Most reports are expected to include the following sections:

1. Executive summary.
2. Introduction — purpose and objectives.
3. Background — context.
4. Methods — including assumptions.
5. Results.
6. Discussion — including limitations.
7. Confidence and uncertainty in the results.
8. Conclusions, recommendations and future considerations.
9. References and Bibliography.
10. Appendices.

Further detail on these sections, as well as on maps, drawings and avalanche atlases, is described below.

11.2.1 Executive Summary

The executive summary summarizes the report in such a way that readers can rapidly become acquainted with the important aspects of report without having to read it all. It usually contains a brief statement of the problem, background information, concise analysis and main conclusions.

11.2.2 Introduction

The introduction to the report should clearly state the objectives, and if applicable, specify the area or avalanche paths that are included in the study. Examples of objectives based on type of report are as follows:

- Identify avalanche paths, and size and return period of avalanches that affect km 20 to 32 of Alder Road, and determine the risk from those paths based on a traffic volume of 400 vehicles per day (risk assessment report).
- Determine avalanche hazard zones for the proposed Ridge View Subdivision (hazard assessment report).
- Identify the towers of the proposed Boomer Chair Lift that will be affected by avalanches with a return period of ≤ 30 years. Determine impact pressures for avalanches that reach the base station with return periods of 30 and 100 years (hazard assessment report).
- Provide design run-up height for deflection berm for a return period of 30 years (mitigation design report).
- Provide all procedures and policies to protect employees (avalanche safety plan) and infrastructure (avalanche risk control plan) from avalanches at the Motherlode Gold Mine.
- Provide an operational review of a snowcat-skiing operation (operational program review).
- Provide an analysis and opinion of the events leading up to the Tree Valley avalanche accident (expert forensic opinion report).

11.2.3 Background

All required relevant background information should be included (e.g. details regarding the geographical area of study, information regarding the element(s) at risk and specific documentation or information provided by the client or the commissioner of the report).

11.2.4 Methods

Detail regarding methods and assumptions should be provided. If the work involves a detailed analysis of an avalanche path, the report is expected to include:

- List of sources, which may include:
  - Maps.
  - Aerial photographs.
  - Imagery.
  - Digital elevation models.
  - Digital data files (e.g. shapefiles, CAD drawings, spreadsheets and databases).
- Types and dates of field observations.
- Description of the terrain (e.g. topography and vegetation) including maps as well as path summaries (i.e. downslope profiles of the center lines of avalanche paths).
- Estimated snow depth in the avalanche starting zones.
- References to applicable guidelines, jurisdictional legislation, regulations or policies, or previous reports.

Reports should provide sufficient detail in the methods and assumptions to facilitate peer review. If numerical runout modeling is incorporated, references for the models and values used for the parameters should be provided.

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11.2.5 Results

When presenting results, it is normal to specify the destructive effect of avalanches. For example,:

- Avalanches > Size 2 from Paths 27 and 32 may strike Alder Road with an approximate return period of 10 years.
- Avalanches with estimated impact pressures of 50 kPa may strike transmission line structures 14 and 15 with a return period of 100 years.
- Within the blue zone, avalanches with a 30-year return period may have impact pressures up to three kPa (i.e. capable of breaking windows and damaging walls and roofs), and avalanches with a 300-year return period may have impact pressures approaching 30 kPa (i.e. capable of destroying wood-frame structures).
- Avalanches with a return period of > 300 years or impact pressure of less than one kPa may run past the lower boundary of the blue zone and into the white zone.

11.2.6 Discussion

The impact and/or meaning of the assessment should be discussed, and any limitations should be clearly stated. Future considerations that are specific to the particular land use should also be stated. For example, for a hazard zoning report, the boundaries of hazard zones as well as estimated avalanche sizes, impact pressures and return periods may indicate specifications such as:

- A particular area of forest will remain substantially undamaged by fire, disease, logging, etc.
- No change on slope topography due to re-grading or slope mass movements.

Areas of protection forest should also be clearly specified in the report and indicated on maps.

11.2.7 Confidence and Uncertainty

Uncertainty and the resulting confidence in the results must be communicated clearly, and should include elements described in Chapter 3. In some cases, providing a maximum expected value or range of values may be more appropriate than a single value.

11.2.8 Conclusions

Conclusions should summarize important information and should directly link to the objectives described earlier in the report. Often recommendations are included in the conclusions sections in order to provide guidance for next steps.

11.2.9 References and Bibliography

All sources (e.g. articles, books, personal communications, etc.) cited in the report, as well as other useful background sources, should be listed in alphabetical order according to a citation style guide such as APA (American Psychological Association 6th edition).

11.2.10 Appendices

Any material in the body of the report that is reference oriented and leads the reader away from the main topic, or is too cumbersome to present in the main report, should be provided as an appendix. Some of the more common material in appendices includes large tables, calculations and analysis details, as well as maps, drawings and avalanches atlases, which are described below.

11.2.11 Maps and Drawings

Maps and drawings can be included in the main body of a report, or if there are a large number, or large map sheets, they are usually included as an appendix. Maps provided with reports include all avalanche map types described in Chapter 4, as well as any overview maps or other maps pertinent to the report. Drawings may include design drawings (e.g. dimensioning of earthworks or specific avalanche engineering structures), topography sketches, etc.

All maps and drawings generally include the following common elements:

- Scale.
- Legend with definitions of symbols.
- Designer and reviewer (if applicable).
- Date and version of issue.
- Limitations.
- Report reference.

In addition, maps usually include:

- Datum and projection.
- Source of basemap data (e.g. imagery, digital elevation information, and other topographical data).
- Source of layer data (e.g. shapefiles, CAD drawings and survey data).
- Contour interval.
- North arrow.

11.2.12 Avalanche Atlas

An avalanche atlas is a catalogue of avalanche paths for a particular area. An example of an avalanche path datasheet that would be used in an avalanche atlas is provided in Appendix 2. Avalanche atlases are usually provided as an appendix to a report and normally include:

- A description of the geographic region, terrain and vegetation, with an overview map.
- Snow supply and climate information.
- Avalanche path maps and oblique images of the paths (Chapter 4).
- Data sheets with avalanche path dimensions and other terrain attributes, frequency-magnitude relationships, historical occurrences, avalanche characteristics and other pertinent information (Appendix 2).

Atlases are updated on a regular basis as new information becomes available.

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Appendix 1: Example of Avalanche Terrain Classification Systems

Impact-based Terrain Classification: Hazard Zones for Occupied Structures

The system of hazard analysis and terrain classification for occupied structures shown in Figure A1.1 and Table A1.1 was developed by the Canadian Avalanche Association after reviewing similar systems in Switzerland and Austria. It applies to all occupied structures. Figure 4.7 (Chapter 4) is an example hazard map based on this classification system. Recommended zoning restrictions for occupied structures in Canada are listed in Section 8.2.2.

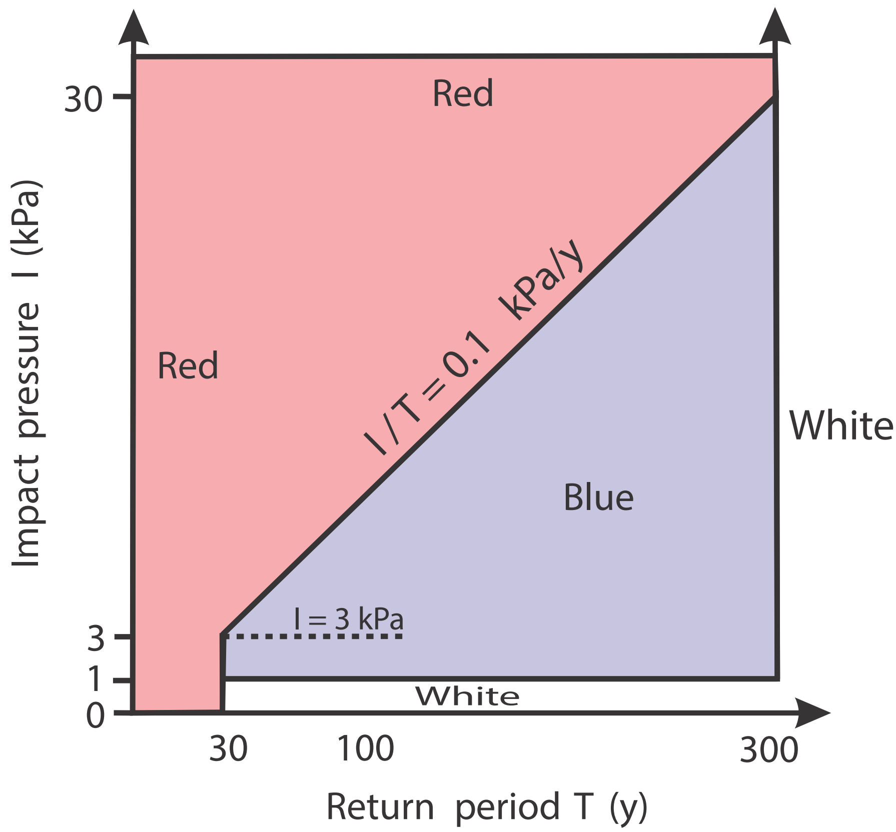


Figure A1.1: *Hazard zones for occupied structures in Canada. Definition for each zone are listed in Table A1.1.*

Table A1.1: *Definitions for the three zones used for occupied structures in Canada as shown Figure A1.1.*

Zone colour	Definition
White	An area with an estimated avalanche return period of > 300 years, or impact pressures < 1 kPa with a return period of > 30 years.
Blue	An area which lies between the red and white zones where the impact pressure divided by the return period is < 0.1 kPa/year for return periods between 30 and 300 years, and impact pressures ≥ 3 kPa. The blue zone also includes areas where impact pressures are between 1 and 3 kPa with return periods of > 30 years.
Red	An area where the return period is < 30 years and/or impact pressures are ≥ 30 kPa, or where the impact pressure divided by the return period is > 0.1 kPa/year for return periods between 30 and 300 years.

Terrain Exposure Classification: Avalanche Terrain Exposure Scale

The Avalanche Terrain Exposure Scale (ATES) was developed in 2004 by Parks Canada (Statham et al., 2006). The Technical Model (Table A1.2) is intended for classifying a specified backcountry route or "trip", while the Communication Model (Table A1.3) is used for communicating terrain ratings in a simple and easy to understand way. The Zoning Model (Table A1.4) was developed by Campbell and Gould, (2014) for classification of an area. It includes an avalanche free, Class 0 category, and more deterministic parameters that can be used for GIS-assisted terrain classification.

Table A1.2: *The Avalanche Terrain Exposure Scale v.1-04 (Statham et al., 2006). Terrain that qualifies under an italicized descriptor automatically defaults into that or a higher terrain class. Non-italicized descriptors carry less weight and will not trigger a default, but must be considered in combination with the other factors.*

	Class 1 - Simple	**Class 2 - Challenging**	**Class 3 - Complex**
Slope angle	Angles generally < 30º	*Mostly low angle, isolated slopes > 35º*	*Variable with large % > 35º*
Slope shape	Uniform.	Some convexities.	Convoluted.
Forest density	Primarily treed with some forest openings.	Mixed trees and open forest.	Large expanses of open terrain. Isolated tree bands.
Terrain traps	Minimal, some creek slopes or cut banks.	Some depressions, gullies and/or overhead avalanche terrain.	*Many depressions, gullies, cliffs, hidden slopes above gullies, cornices.*
Avalanche frequency	1:30 ≥ Size 2	1:1 for < Size 2 *1:3 for ≥ Size 2*	1:1 < Size 3 *1:1 ≥ Size 3*
Starting zone density	Limited open terrain.	Some open terrain. Isolated avalanche paths leading to valley bottom.	Large expanses of open terrain. Multiple avalanche paths leading to valley bottom.
Runout zone characteristics	Solitary, well defined areas, smooth transitions, spread deposits.	Abrupt transitions or depressions with deep deposits.	Multiple converging runout zones, confined deposition area, steep tracks overhead.
Interaction with avalanche paths	Runout zones only.	Single path or paths with separation.	*Numerous and overlapping paths.*
Route options	Numerous, terrain allows multiple choices.	A selection of choices of varying exposure, options to avoid avalanche paths.	*Limited chances to reduce exposure, avoidance not possible.*
Exposure time	None, or limited exposure crossing runouts only.	*Isolated exposure to start zones and tracks.*	*Frequent exposure to start zones and tracks.*
Glaciation	None.	*Generally smooth with isolated bands of crevasses.*	*Broken or steep sections of crevasses, icefalls or serac exposure.*

Table A1.3: *ATES Communication Model (Statham et al., 2006).*

Description	**Class**	**Terrain criteria**
Simple	1	Exposure to low-angle or primarily forested terrain. Some forest openings may involve the runout zones of infrequent avalanches. Many options to reduce or eliminate exposure. No glacier travel.
Challenging	2	Exposure to well defined avalanche paths, starting zones or terrain traps; options exist to reduce or eliminate exposure with careful route finding. Glacier travel is straightforward but crevasse hazards may exist.
Complex	3	Exposure to multiple overlapping avalanche paths or large expanses of steep, open terrain; multiple avalanche starting zones and terrain traps below; minimal options to reduce exposure. Complicated glacier travel with extensive crevasse bands or icefalls.

Table A1.4: *ATES Zoning Model (Campbell and Gould, 2014). Parameters are listed generally in order of importance with the intent of assigning more weight to the top two or three parameters. Although GIS modeling can be used to assist classification, the parameter thresholds are intended to be used as general guidelines to inform expert judgment for classifying avalanche exposure to people.*

		Class 0 (optional)	**Class 1**	**Class 2**	**Class 3**
Slope incline[1] and forest density[2]	**Open**	99 % ≤ 20˚	90 % ≤ 20˚ 99 % ≤ 25˚	90 % ≤ 30˚ 99 % ≤ 45˚	< 20 % ≤ 25˚ 45 % > 35˚
	Mixed	99 % ≤ 25˚	90 % ≤ 25˚ 99 % ≤ 35˚	90 % ≤ 35˚ 99 % ≤ 45˚	
	Forest	99 % ≤ 30˚	99 % ≤ 35˚	99 % ≤ 45˚	
Starting zone density		No start zones.	No start zones with ≥ Size 2 potential. Isolated start zones with < Size 2 potential.	No start zones with > Size 3 potential. Isolated start zones with ≤ Size 3 potential, or several start zones with ≤ Size 2 potential.	Numerous start zones of any size, containing several potential release zones.
Interaction with avalanche paths[3]		No exposure to avalanche paths.	Beyond 10-year runout extent for paths with ≥ Size 2 potential.	Single path or paths with separation. Beyond annual runout extent for paths with > Size 3 potential.	Numerous and overlapping paths of any size. Any position within path.
Terrain traps[4]		No potential for partial burial or any injury.	No potential for complete burial or fatal injury.	Potential for complete burial but not fatal injury.	Potential for complete burial and fatal injury.
Slope shape		Uniform or concave.	Uniform	Convex	Convoluted

[1]Slope inclines are averaged over a fall-line distance of 20-30 m.

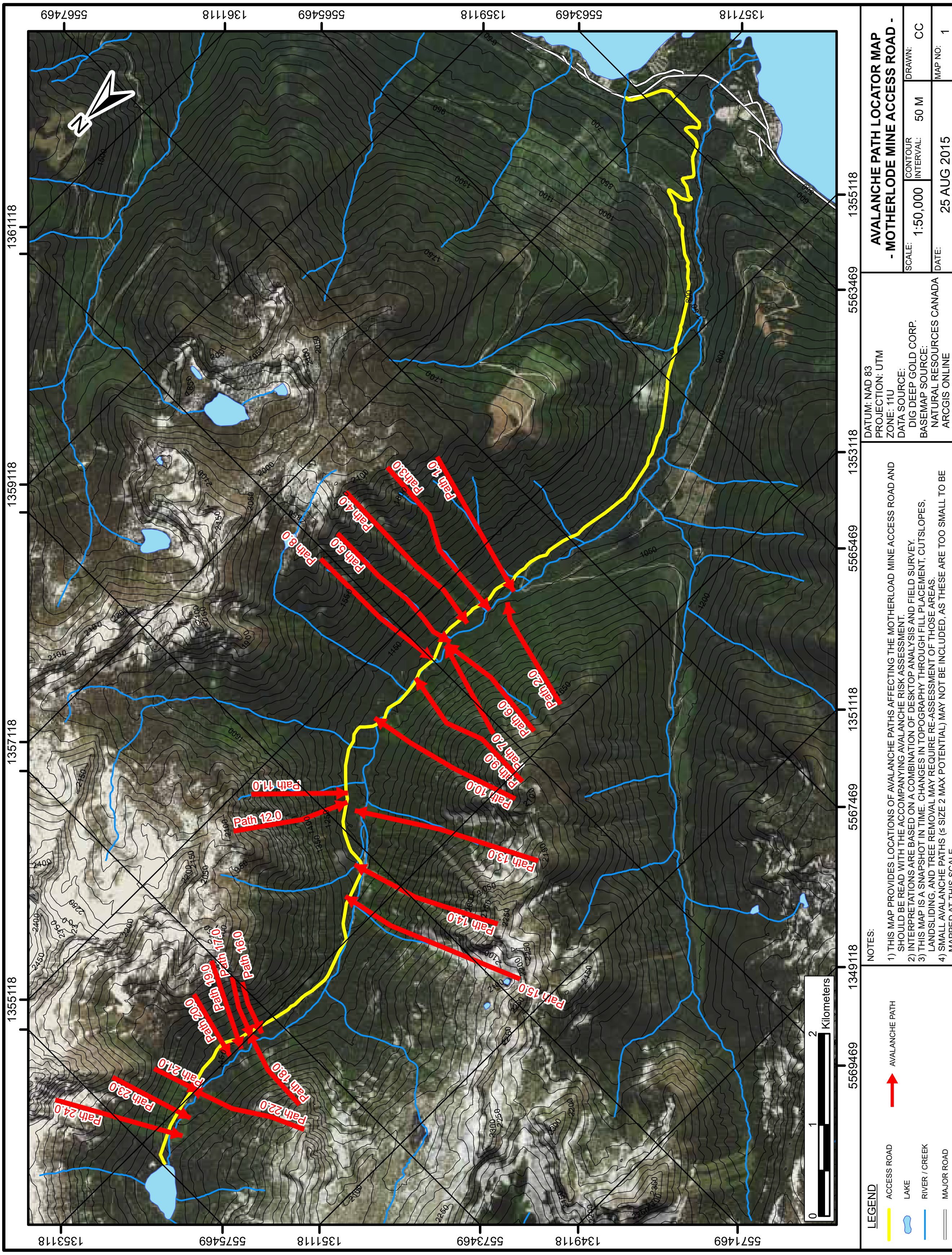
[2]Open: < 100 stems/ha or > 10.0 m tree spacing on average. Mixed: 100-1000 stems/ha or 3.2-10.0 m tree spacing on average. Forest: > 1000 stems/ha or < 3.2 m tree spacing on average.

[3]Position within paths based on the runout extent for avalanches with a specified return period.

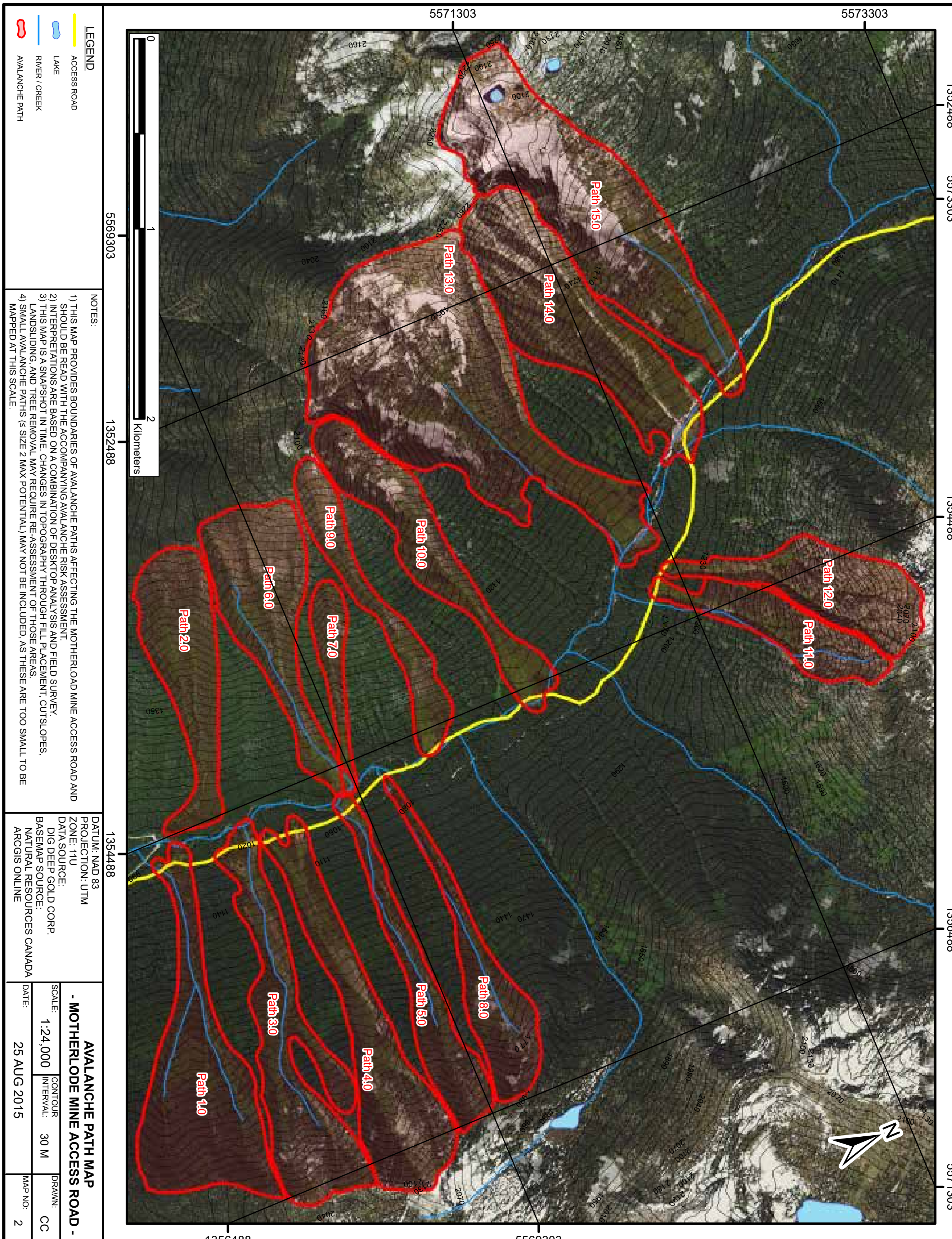
[4]Terrain traps are features in tracks or runouts that increase the consequences of being caught in an avalanche. Thresholds are based on the potential increased consequences they would add to an otherwise harmless avalanche. For this purpose, terrain traps can be thought of as either trauma-type (e.g. cliffs, trees, boulders, etc.) or burial-type (e.g., depressions, abrupt transitions, open water, gullies, ravines, etc.). Degrees of burial used in this model are based on Canadian standard avalanche involvement definitions (CAA, 2014b).

M. Austin photo.

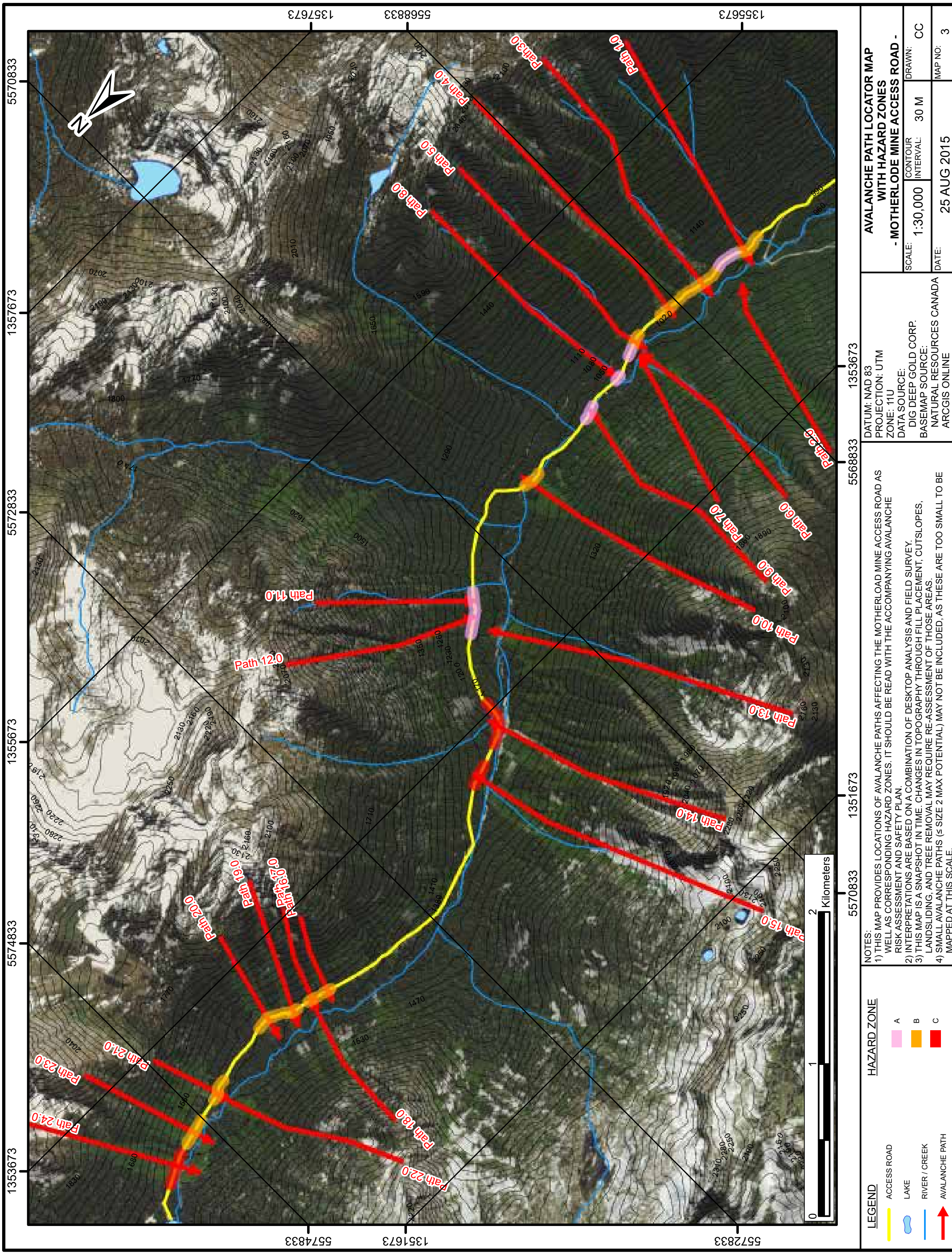
Appendix 2: Example Maps



A2



AVALANCHE PATH MAP
- MOTHERLODE MINE ACCESS ROAD -
SCALE: 1:24,000
CONTOUR INTERVAL: 30 M
DRAWN: CC
DATE: 25 AUG 2015
MAP NO: 2
DATUM: NAD 83
PROJECTION: UTM
ZONE: 11U
DATA SOURCE:
DIG DEEP GOLD CORP.
BASEMAP SOURCE:
NATURAL RESOURCES CANADA
ARCGIS ONLINE
LEGEND
ACCESS ROAD
LAKE
RIVER / CREEK
AVALANCHE PATH
NOTES:
1) THIS MAP PROVIDES BOUNDARIES OF AVALANCHE PATHS AFFECTING THE MOTHERLOAD MINE ACCESS ROAD AND SHOULD BE READ WITH THE ACCOMPANYING AVALANCHE RISK ASSESSMENT.
2) INTERPRETATIONS ARE BASED ON A COMBINATION OF DESKTOP ANALYSIS AND FIELD SURVEY.
3) THIS MAP IS A SNAPSHOT IN TIME. CHANGES IN TOPOGRAPHY THROUGH FILL PLACEMENT, CUTSLOPES, LANDSLIDING, AND TREE REMOVAL MAY REQUIRE RE-ASSESSMENT OF THOSE AREAS.
4) SMALL AVALANCHE PATHS (≤ SIZE 2 MAX POTENTIAL) MAY NOT BE INCLUDED, AS THESE ARE TOO SMALL TO BE MAPPED AT THIS SCALE.
0 1 2 Kilometers
N
Path 1.0
Path 2.0
Path 3.0
Path 4.0
Path 5.0
Path 6.0
Path 7.0
Path 8.0
Path 9.0
Path 10.0
Path 11.0
Path 12.0
Path 13.0
Path 14.0
Path 15.0
5571303
5573303
5569303
1352488
1354488
1356488


AVALANCHE PATH LOCATOR MAP
WITH HAZARD ZONES
- MOTHERLODE MINE ACCESS ROAD -
SCALE: 1:30,000
CONTOUR INTERVAL: 30 M
DRAWN: CC
DATE: 25 AUG 2015
MAP NO: 3
DATUM: NAD 83
PROJECTION: UTM
ZONE: 11U
DATA SOURCE:
DIG DEEP GOLD CORP.
BASEMAP SOURCE:
NATURAL RESOURCES CANADA
ARCGIS ONLINE
NOTES:
1) THIS MAP PROVIDES LOCATIONS OF AVALANCHE PATHS AFFECTING THE MOTHERLOAD MINE ACCESS ROAD AS WELL AS CORRESPONDING HAZARD ZONES. IT SHOULD BE READ WITH THE ACCOMPANYING AVALANCHE RISK ASSESSMENT AND SAFETY PLAN.
2) INTERPRETATIONS ARE BASED ON A COMBINATION OF DESKTOP ANALYSIS AND FIELD SURVEY.
3) THIS MAP IS A SNAPSHOT IN TIME. CHANGES IN TOPOGRAPHY THROUGH FILL PLACEMENT, CUTSLOPES, LANDSLIDING, AND TREE REMOVAL MAY REQUIRE RE-ASSESSMENT OF THOSE AREAS.
4) SMALL AVALANCHE PATHS (≤ SIZE 2 MAX POTENTIAL) MAY NOT BE INCLUDED, AS THESE ARE TOO SMALL TO BE MAPPED AT THIS SCALE.
HAZARD ZONE
A
B
C
LEGEND
ACCESS ROAD
LAKE
RIVER / CREEK
AVALANCHE PATH
Kilometers
0
1
2
N
Path 1.0
Path 2.0
Path 3.0
Path 4.0
Path 5.0
Path 6.0
Path 7.0
Path 8.0
Path 9.0
Path 10.0
Path 11.0
Path 12.0
Path 13.0
Path 14.0
Path 15.0
Path 16.0
Path 17.0
Path 18.0
Path 19.0
Path 20.0
Path 21.0
Path 22.0
Path 23.0
Path 24.0
5570833
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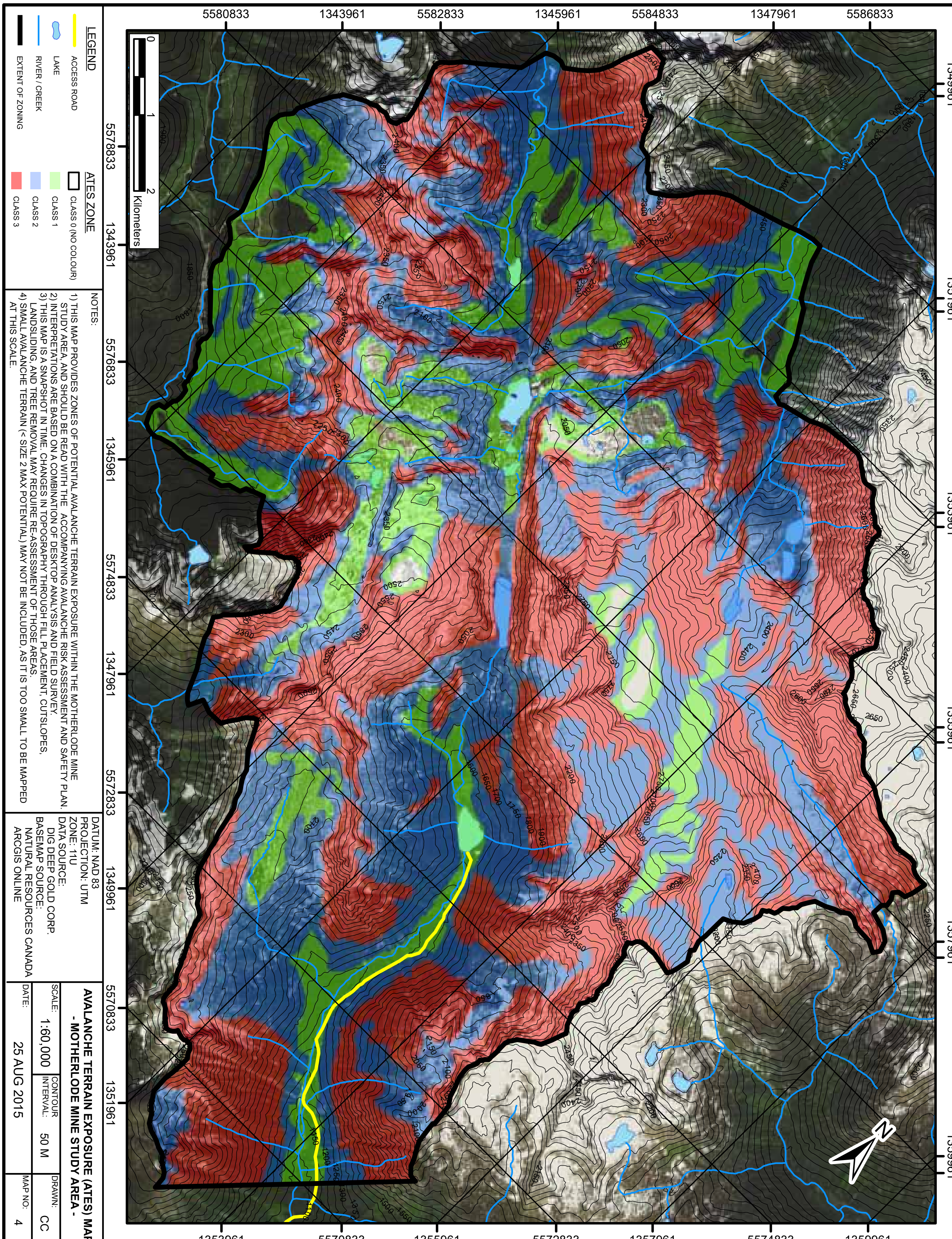
1355673
5572833

A2


LEGEND
ACCESS ROAD
LAKE
RIVER / CREEK
EXTENT OF ZONING
ATES ZONE
CLASS 0 (NO COLOUR)
CLASS 1
CLASS 2
CLASS 3
NOTES:
1) THIS MAP PROVIDES ZONES OF POTENTIAL AVALANCHE TERRAIN EXPOSURE WITHIN THE MOTHERLODE MINE STUDY AREA, AND SHOULD BE READ WITH THE ACCOMPANYING AVALANCHE RISK ASSESSMENT AND SAFETY PLAN.
2) INTERPRETATIONS ARE BASED ON A COMBINATION OF DESKTOP ANALYSIS AND FIELD SURVEY.
3) THIS MAP IS A SNAPSHOT IN TIME. CHANGES IN TOPOGRAPHY THROUGH FILL PLACEMENT, CUTSLOPES, LANDSLIDING, AND TREE REMOVAL MAY REQUIRE RE-ASSESSMENT OF THOSE AREAS.
4) SMALL AVALANCHE TERRAIN (< SIZE 2 MAX POTENTIAL) MAY NOT BE INCLUDED, AS IT IS TOO SMALL TO BE MAPPED AT THIS SCALE.
DATUM: NAD 83
PROJECTION: UTM
ZONE: 11U
DATA SOURCE:
DIG DEEP GOLD CORP.
BASEMAP SOURCE:
NATURAL RESOURCES CANADA
ARCGIS ONLINE
AVALANCHE TERRAIN EXPOSURE (ATES) MAP
- MOTHERLODE MINE STUDY AREA -
SCALE: 1:60,000
CONTOUR INTERVAL: 50 M
DRAWN: CC
DATE: 25 AUG 2015
MAP NO: 4
0 1 2 Kilometers

Dig Deep Gold Corp.
MOTHERLODE MINE ACCESS ROAD – AVALANCHE ATLAS

Path 14.0

Location	W side of Motherlode Mine access road at KM 12.5	**Coordinates**	**Lat**	49°41'5.92"N	**Vertical fall (m)**	1105
			Lon	117°10'3.20"W		

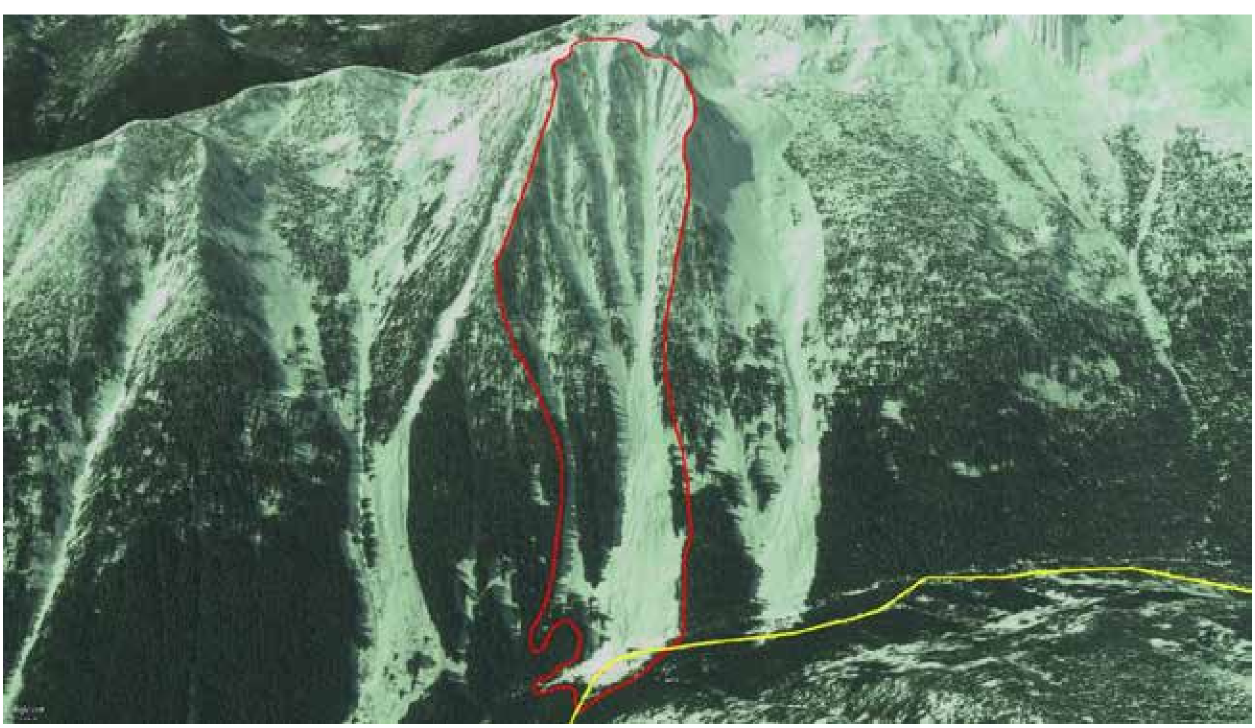
Starting Zone										
Elevation (m)	**Top**	2290	**Avg. Slope Angle (°)**	40	**Aspect**	E	**Width (m)**	510
	Bottom	1800						
Terrain Characteristics	Several distinct starting zones separated by rib features converging into three tracks. Upper starting zone consists of rock bluffs, scree, talus and heather slopes. Lower starting zone consists of 1 m brush, and spaced sub-alpine conifers.							

Track								
Elevation (m)	**Top**	1800	**Avg. Slope Angle (°)**	25	**Width (m)**	330	**Length (m)**	750
	Bottom	1320						
Terrain Characteristics	Three channeled gullies converging into one with 1-2 m vegetation and boulders. Spaced old growth conifers on flanks. Secondary channel and start zone on S side can act as separate path for ≤ Size 2 avalanches.							

Runout Zone						
Elevation (m)	**Top**	1320	**Avg. Slope Angle (°)**	8	**Terrain Trap?**	No
	Bottom	1185				
Terrain Characteristics	Generally planar with seasonal creek down middle. 2-3 m vegetation and alder. Access road in extreme runout.					

Est. Frequency (avalanches:years)	**Size 1**	-	**Size 2**	-	**Size 3**	1:3	**Size 4**	1:10	**Size 5**	-

Historic Avalanche Events	
	Spring 2014: Size 3 overran road with ≤ 2 m deposit depth on road. Spring 2010: Size 4 overran road with ≤ 5 m deposit depth on road. No records prior to 2010.



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