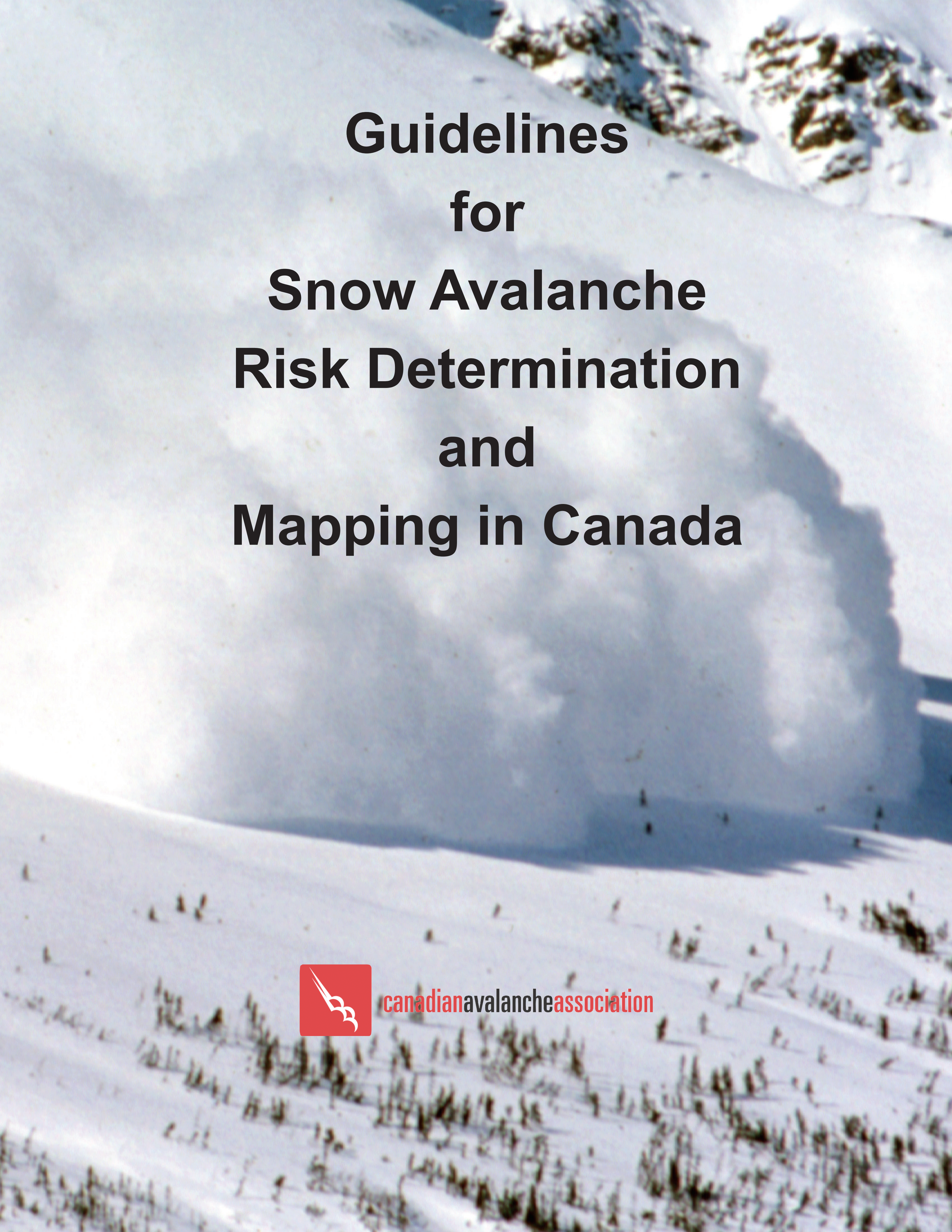

# Guidelines for Snow Avalanche Risk Determination and Mapping in Canada

canadianavalancheassociation

# Guidelines
# for
# Snow Avalanche Risk Determination
# and
# Mapping in Canada

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# Table of Contents

# 1. Introduction

This document, Guidelines for Snow Avalanche Risk Determination and Mapping in Canada, describes concepts for determining avalanche risks and contains proposed guidelines for avalanche mapping and acceptable risks. This is the technical supplement to its companion publication, Land Managers Guide to Snow Avalanche Hazard in Canada (Canadian Avalanche Association, 2002). Ideally, these guidelines will be adopted as minimum standards throughout Canada, resulting in more consistent decision-making and greater safety.

Support from the National Search and Rescue Secretariat (NSS) under sponsorship from Parks Canada has made publication of this handbook possible. This publication is part of an NSS accident prevention initiative. The Canadian Avalanche Association (CAA) administered the Avalanche Hazard Mapping (AHM) project and is the publisher of this handbook. The CAA is a non-profit organization dedicated to promoting avalanche safety and representing avalanche professionals, affiliates and associated companies in Canada.

### 1.1 Snow avalanches and limitations of mapping

Snow avalanches are the most common mountain slope hazard that threatens people, facilities and the environment in Canada. Other mountain slope hazards including rockfall, debris torrents and landslides are not discussed in this document.

Risk analysis and mapping of snow avalanche hazards require the application of scientific principles gained through education and professional experience, conditioned by the knowledge of limitations and implied uncertainty of methods employed. Snow avalanche work also involves an appreciation for the destructive effects of avalanches, an understanding gained through professional experience in avalanche terrain.

Snow avalanche risk determination and mapping depends on terrain analysis, estimates of avalanche frequency, snow supply, destructive potential and avalanche runout distance. The uncertainty of these factors, which may include order of magnitude estimates of avalanche frequency or destructive potential, requires that the avalanche specialist clearly states the underlying assumptions in the analyses and the approximate nature of results. The number of significant digits in numerical results presented in accompanying reports should reflect the accuracy of the underlying assumptions.

Appendix A describes typical methods employed in avalanche hazard mapping at the time of publication of this document. In general, a combination of methods may be applied to achieve a complete and accurate map. The scientific understanding of snow avalanches is rapidly evolving and it is the responsibility of the avalanche specialist to remain informed of accepted procedures and of the appropriateness of a particular method for a given assessment. New methods and refinements of existing methods should be expected.

# 2. Risk basis for avalanche decision-making and mapping for land-use planning

Decisions and mapping for snow avalanches in Canada are risk-based. This means an average avalanche return period (or frequency) and some measure of consequences are considered. Two common measures of destructive potential that can be incorporated in the consequence portion of risk are: 1) predicted impact pressures; and 2) destructive potential (based on the five-part Canadian system for classifying avalanche size, Appendix B).

Probable exposure (probability of exposure in time or space) is required in certain applications such as transportation routes. This document provides guidelines on limits of acceptable risk for common Canadian applications, including plans for: land-use zoning, forest harvesting and other activities in steep, snowy terrain; roads and rail lines; facilities in ski areas; and placement or protection of fixed structures (e.g. power line towers).

### 2.1 Types of snow avalanche mapping

There are three types of snow avalanche mapping applications in Canada:

1) **Locator maps** that identify potential avalanche terrain.
2) **Avalanche atlas maps** that provide illustrations of potential avalanche terrain for a series of locations in an avalanche area.
3) **Risk maps** that are used in numerous capacities including land-use planning for fixed facilities (occupied and unoccupied buildings or structures), linear risk mapping for highways, roads or railways, and maps for forestry applications.

#### 2.1.1 Locator maps

These maps identify potential avalanche terrain for the preliminary assessment of transportation and energy corridors, resource projects or recreation areas (Appendix C1). The scale of mapping is usually 1:20,000 to 1:50,000. A more detailed map is used when required. Vertical air photos (or satellite imagery) and topographic mapping are often combined with field visits to prepare the map. The locator map is typically included in a report that describes estimated magnitude and frequency of avalanche effects on the project in question.

#### 2.1.2 Avalanche atlas

An avalanche atlas is a catalogue of avalanche paths or potential avalanche terrain in an avalanche area (e.g. Appendix C2). It provides topographic and photographic illustrations of avalanche terrain, and a data sheet that describes terrain attributes. Photographic illustrations may be vertical or oblique, and the map scale is usually in the range of 1:20,000 to 1:50,000. Typical atlas applications include: highway, road and rail avalanche lines (polygons outline the estimated extent of avalanche paths); commercial backcountry operations (potential travel routes and key locations); and ski areas (starting zones, avalanche control routes and affected ski runs). Typical content of an avalanche atlas for transportation corridors are also described in McClung and Schaerer (1993).

#### 2.1.3 Risk maps

Risk determination and risk maps include a formal assessment of risk (avalanche frequency, damage and exposure) that considers the threat of avalanches to people, facilities or the environment.

Examples are:

(a) Risk determination for unoccupied structures (e.g. electric transmission lines, energy pipelines and ski lift towers). Risk is described in terms of expected impact pressures for appropriate return periods. Map scale varies from 1:5,000 to 1:50,000 with project type.

(b) Zone maps (Appendix C3) for occupied structures (e.g. residential structures, subdivisions and industrial sites). On these maps risk zones are identified in Red (high risk), Blue (moderate risk and some uses with restrictions) and White (low risk; beyond the reach of destructive avalanches with return periods of 300 years or less). Map scale is usually from 1:5,000 to 1:10,000 and hazard zones may also be outlined on detailed subdivision plans.

(c) Linear risk mapping for transportation routes. This involves formal risk calculation for roads, highways or railways, and accounts for avalanche frequency, traffic volume, waiting traffic, expected damage and path length exposed. It allows for comparison between avalanche paths in an avalanche area and between avalanche areas themselves. Risk assessment methods for highways include the Avalanche Hazard Index (Schaerer, 1989) and linear risk assessment as proposed by McClung and Navin (unpublished). The Avalanche Hazard Index has been applied to the evaluation of risk for most highways affected by avalanches in the United States and Canada.

(d) Forest harvest risk mapping addresses two concerns: possible avalanche initiation in future harvested terrain; and existing avalanche paths that intersect future harvested terrain. Risk matrices are used to define acceptable risk in terms of expected avalanche size (Canadian Avalanche Size Classification, McClung and Schaerer, 1981) and expected frequency depending on what is at risk (e.g. forest cover, transportation routes or other resources or facilities). It is normal mapping practice to outline areas where protective forest cover or other modifications of forest harvest plans are needed (Appendix C4). The map is contained in a report with an outline of mitigation strategies. Map scale is typically 1:20,000. A more detailed map is used when required.

# 3. Definitions

In this section, definitions are provided for the important terms used to describe risk evaluation and mapping. These definitions are consistent with CAN/CSA-Q850-7 Risk Management: Guideline for Decision Makers (Canadian Standards Association, 1997).

### 3.1 Risk:

The probability or chance of death or losses. Losses may include adverse effects on health, property, the environment, or other things of value. It is assumed that all elements of risk may be represented in terms of probability. Estimated risk may be compared to a level of acceptable risk. In avalanche mapping, risk potentially contains three components: return period (frequency); probable consequences; and probable exposure. These components may be potentially related to model calculations or historical data and, depending on the application, they may be expressed quantitatively or qualitatively.

#### 3.1.1 Return period:

The expected average time between events reaching or exceeding a given location. Return period (T) normally has units in years (per event) in avalanche work but mathematically it is the reciprocal of the annual exceedance probability.

**Frequency** is the expected (average) number of events per unit time reaching or exceeding a location. Frequency has units of events per year (events/a) and is normally defined as the annual probability of events (1/T for T>>1). For high frequencies (small values of T), the encounter probability for a Poisson process (described below) should be used as the frequency component in risk calculations. Frequency is determined from empirical evidence in the field, avalanche occurrence records or a probability density function that describes events reaching and exceeding a position.

#### 3.1.2 Probable consequences:

The conditional probability of an attribute representing destructive potential to facilities, people or some elements of the environment (e.g. forest cover) and avalanche occurrence. These attributes represent a set of mutually exclusive measures of destructive potential. For example, the five-part Canadian classification for avalanche sizes is based on destructive potential. For a given facility (B), probable consequences given an avalanche (A) of size ($S_i$ for i = 1…5) at a location could be represented as proportional to: $P_B(S_i \mid A)$. See Appendix D for probability definitions and symbols. In order to convert this to a meaningful estimate of expected damage, the vulnerability of the item at risk would have to be considered (see vulnerability definition below).

Using frequency and probable consequences, with an attribute $X_i$ representing, for example, the partial destruction of a wood frame structure (facility B), risk could be represented as the probabilistic intersection of avalanche occurrence A and attribute $X_i$: $P_B(A \cap X_i) = P(A)P_B(X_i \mid A)$ where P(A) represents the avalanche frequency at a location (e.g. calculated as the exceedance probability from a probability density function) and $P_B(X_i \mid A)$ represents probability of consequence (or attribute $X_i$) given avalanche occurrence at the site.

**Vulnerability vector:** Engineers use the term vulnerability, which is contained in "probable consequences". Let $X_i$, one of a set of mutually exclusive attributes, be defined in terms of avalanche size $S_i$ by $X_i = S_i \cap V_i$ where $V_i$ is vulnerability for size $S_i$ defined as the fraction of loss (a number between 0 and 1) delivered by an avalanche of the given size for the object in question. For a given structure B, the risk is then: $P_B (A \cap S_i \cap V_i) = P(A)P(S_i \mid A)P_B(V_i \mid A \cap S_i)$ where the last two components represent the probable consequences in product form: the fraction of avalanches of size $S_i$ times the fraction of loss for an avalanche of size $S_i$ for structure B.

The vulnerability vector for Canadian avalanche sizes, $V_B(S_i)$, is typically related to an object B at risk by assigning values (between 0 and 1) based on experience with the Canadian size classification and the definitions. For example, a Size 2 avalanche interacting with mature forest cover (B) would have $V_B(S_2)$ near zero (nominal damage) whereas $V_B(S_4)$ would be near 1 (total destruction) within the specified avalanche runout zone.

Risk assessments may be easily adopted for estimating costs by multiplying the engineering risk by the total value of a facility, for example. If return periods are estimated in years, risk x value is the **ARC: A**nnual **R**isk **C**ost (e.g. Morgan, 1990).

#### 3.1.3 Probable exposure:

The probability that people, facilities or environmental elements (e.g. forest cover or streams) are exposed to avalanche hazards in time and/or space. For fixed facilities entirely within avalanche paths, probable exposure is one. For people moving (e.g. in evacuations or by vehicles on highways) probable exposure is less than one.

**3.2 Encounter probability:**

The probability of at least one event reaching or exceeding a location characterized by a return period (T) in a finite waiting time (L). Avalanches normally arrive as rare, discrete independent events so that the encounter probability may be calculated by assuming the events arrive according to a binomial probability mass function or a Poisson process (LaChapelle, 1966; McClung, 1999). The finite waiting time may be thought of as broken into n time intervals of length $\Delta t$: $L = n\Delta t$. For fixed facilities, Föhn (1978) calls L the “design period”, and L = 50 years is often the mean service life of buildings. For the binomial distribution, the encounter probability is: $E_p = 1 - (1 - \Delta t/T)^n$ and for the Poisson process, $E_p = 1 - \exp(-L/T)$. In most cases there is little difference between quantitative estimates with these two approaches.

Encounter probability is important for formulating **probable exposure** for applications concerned with moving or waiting traffic on transportation routes and exposure of people outside facilities.

**3.3 Hazard:**

A source of potential harm, or a situation with a potential for causing harm, in terms of human injury; damage to health, property and the environment, and other things of value; or some combination of these. Avalanche hazard implies the coincidence (in space and time) of people, facilities or something of value within the reach of avalanches. Otherwise the hazard is negligible. In avalanche safety operations, the daily hazard to the protected element of the operation can be described in relative terms such as high, moderate and low.

**3.4 Hazard identification:**

The process of recognizing that hazards exist and defining the characteristics of those hazards.

**3.5 Acceptable risk:**

The risk people will accept for a specific situation or site. This depends on factors such as societal and cultural values, the number of people exposed or value of property or environment at risk, whether the risk is voluntary or involuntary (most often the case for mapping applications), to what degree the hazard is known scientifically, or to what degree it is feared by people.

Acceptable risk in avalanche mapping can be stated in terms of destructive potential of events and return periods. Thus, for Canadian mapping guidelines, acceptable risk is mostly represented by a combination of return period (or avalanche frequency) and some attribute related to destructive potential (typically expected avalanche size $S_i$ or expected impact pressure). In some cases, it is possible to calculate the **P**robability of **D**eath to an **I**ndividual (Morgan, 1990) or related measures for comparison to known acceptability. Such calculations are encouraged.

**3.6 Magnitude:**

The destructive potential of avalanches represented in applications either by expected impact pressure or the five-part Canadian system for sizing of avalanches (Appendix B). This system of sizing avalanches can be readily applied in risk estimates as described above since it forms a mutually exclusive set of sizes related to destructive potential. Magnitude may also be expressed approximately by the mass. This is useful where measurements of avalanche deposit size are available, such as on highways. For mapping applications in forestry or on transportation routes, the size system is essential for representing the consequence portion of risk.

Typically, the engineering risk is considered when the Canadian avalanche size classification is used. For the element at risk the analysis depends on the probability of avalanche occurrence, the probable exposure of the element and the probable consequences of an avalanche of a given size.

**3.7 Magnitude-frequency (m-f) relation:**

The probabilistic representation of how frequently avalanches of a specified magnitude are expected at a site. For avalanche areas, average magnitude and average frequency are separate variables characterized by different variable sets to determine them. In general, it is expected that as the average magnitude increases down slope into the runout zone the average frequency decreases. It is rare in Canada to have records of m-f with position in the runout zone for long return period avalanches (in the order of 100 years). In some cases, evidence of forest damage will provide information on return periods in the order of 10 to 100 years. Analysis of accumulated surficial materials in the runout zone of some sites may also assist in providing order of magnitude estimates of frequency. Therefore, in land-use planning the consideration of (theoretical) design avalanche effects is critical for zoning where return periods up to 300 years may be applied.

**3.8 Impact pressure (I):**

Avalanche force per unit area normal to a flat surface averaged over a length of time suitable to yield an average pressure. Avalanche impact pressures for flowing avalanches or powder avalanches are highly transient with peaks that exceed average pressures by as much as two to five times. The normal unit for impact pressure is a kilo-Pascal (kPa) equal to a pressure of 1000 $N/m^2$. Impact pressure is calculated as proportional to the product of density ($\rho$) of the flowing snow and square of the avalanche speed, $v^2$, (component of avalanche velocity perpendicular to the surface). Solid debris entrained within an avalanche can increase the destructive potential, where this debris impacts an exposed structure.

For **flowing avalanches**, which have a high volume fraction filled by solids (at least 30% or more), the conservative estimate of impact pressure: $\boldsymbol{\rho}\ \mathbf{v^2}$ can be adopted from the solid impact theory.

**Table I*: Typical impact pressures related to destructive effects.**

| Impact Pressure (kPa) | Potential Damage |
|---|---|
| 1 | Break windows |
| 5 | Push in doors |
| 30 | Destroy wood-frame structures |
| 100 | Uproot mature spruce |
| 1000 | Move reinforced concrete structures |

** Reprinted by permission of the authors (McClung and Schaerer, 1993).*

Normal practice takes impact pressure for the **powder component** of a flowing avalanche or for impact pressure from a **powder avalanche** as proportional to $\mathbf{1/2}\ \boldsymbol{\rho}\ \mathbf{v^2}$ where $\rho$ is density of the snow-dust air mixture at the top of the avalanche. This expression comes from fluid mechanics and is equivalent to the stagnation pressure for fluid flow at the centre streamline of fluid striking a surface perpendicularly (meaning v is the velocity component perpendicular to the surface). It is assumed that for the low volume fraction filled by solids (< 10%) in the powder component, the flowing material may be idealized as an incompressible fluid. In order to estimate impact pressures and the appropriate Reynolds number, the stagnation pressure must be combined with a drag or a lift coefficient appropriate to the geometry of the object to be struck. Drag coefficients are listed in building codes for wind loadings (National Research Council of Canada, 1995) and in fluid mechanics texts (e.g. Robertson and Crowe, 1985). Table II contains typical flow densities and volume fractions for both flowing avalanches and the powder component.

**Table II*: Typical flow density and percent solid concentration.**

| | Flow Density ($kg/m^3$) | Concentration of Solid Materials (%) |
|---|---|---|
| **Air Blast** | 1 | 0 |
| **Powder** | 10 | 1 |
| **Dry Flowing** | 100-150 | 30-50 |
| **Wet Flowing** | 150-300 | 30-50 |

**Revised from McClung and Schaerer, 1993*

**3.9 Maximum event:**

The highest destructive potential at an avalanche location. Concerns are destructive potential (avalanche size or impact pressures) and return period as a function of position in avalanche terrain. Likely characteristics in maximum events include: a fast moving, large (mass) dry flowing avalanche; a smooth running surface; a long return period (100 years or more); and an extreme runout distance.

**3.10 Avalanche protection forest:**

Forest which is designated as necessary to prevent avalanches from forming on a slope and threatening down slope resources, transportation routes, structures or other facilities.

## 4. Risk mapping problems and general data types

Two types of problems are encountered in avalanche risk problems related to mapping:

1) **Starting zone** – The objective is to express the frequency of avalanches of a given magnitude and expected consequences (e.g. in the design of clearcuts in forested terrain).
2) **Runout zone (and in the track)** – The objective is to express the frequency and consequences in a runout zone (e.g. in land-use planning for buildings or in risk based methods on transportation routes).

In general, two types of data are used for avalanche applications:

1) **Singular data** – Information and/or data that is collected for a specific case or appropriate for the specific site including avalanche observations, avalanche terrain characteristics, data about snow supply and others.
2) **Distributional data** – Information and/or data about similar situations in the past. This information is normally more general than singular data and may include experience, models with coefficients derived from similar situations and other types of information.

Accurate risk analysis and mapping practice should include both types of information conditioned by experience and professional judgement.

**4.1 Typical risk scenarios**

Planning for avalanche hazards involves a number of scenarios. Common examples follow:

**4.1.1 Total risk:**

Consideration of events of all different magnitudes (destructive potential) and frequency. Linear risk mapping for highway, railway and land-use applications are examples. This type of calculation may be used for mapping, decision-making and estimating costs. Good observations and estimates (including theoretical) of avalanche occurrences (including destructive potential) are necessary in this method. Applications call for the fraction of avalanches in each size class and the vulnerability vector as a function of size for the object at risk.

**4.1.2 Design event:**

Involves estimating the risk of an avalanche with a given return period or destructive effect at a specific location. This is the method of choice for applications such as land-use planning when estimates are required far into the runout zone where observations are minimal due to a long return period. Typically the task is to estimate the destructive potential (e.g. impact pressure) and avalanche frequency with position (down-slope and cross-slope) in the runout zone in order to determine risk levels.

**4.1.3 Risk-based design:**

Considers events of different magnitude (destructive potential) and frequency in design of defences, with the potential exclusion of the highest magnitude events (normally lowest frequency). The basis is that the higher frequency avalanches are normally smaller and an avalanche defence may be used to reduce the risk to an acceptable level by stopping these events.

## 5. Guidelines for use of avalanche terrain in Canada

Land use in avalanche terrain in Canada involves the following applications:

1) Work sites
2) Transportation routes
3) Energy and communication structures (transmission lines, surface pipelines and telephone lines)
4) Recreation operations (ski, other)
5) Forest harvest areas
6) Occupied structures

These applications are described below. Typical avalanche return periods, avalanche sizes or impact pressures required to initiate planning, mapping and mitigation are identified for each application. The threshold avalanche return periods to initiate action for the various applications described represent a range of potential return periods at or below the stated value.

### 5.1 Work sites

Work sites are typically assessed for avalanche return periods in the range of less than 30 years to 100 years (dependent on permanence of the work site) with a critical avalanche size of 2 or greater. Typically avalanche safety/evacuation plans or a plan for avalanche control is in place, and locator maps or avalanche atlases are used.

For example, at a work site where the project is temporary (length is one winter or less), avalanche return intervals of less than 30 years are typically considered in avalanche safety planning. A locator map is used as the basic tool to identify the avalanche paths, and active avalanche control/closure/evacuation plans are developed at a level commensurate with the severity of avalanche risk at the site. At a long-term work site, where the project length extends over a period of years, avalanche return periods up to 100 years may be considered. In this case an avalanche atlas is a more appropriate tool for snow safety planning and operations.

Regulations for safety at work sites are usually described in provincial or territorial worker safety regulations. The basic premise is that potential hazards to workers must be identified and safety plans put in place to manage these. For example, in the forest industry in BC the snow avalanche risk must be assessed with a standard acceptable to the Workers' Compensation Board of BC (WCB of BC) and safe work procedures must be developed to meet that standard (Occupational Health & Safety Regulation 26.18, 1999). Safety training for workers must also be included. The onus is on the safety planner to propose a specific mitigation that is deemed acceptable to the WCB of BC.

### 5.2 Transportation

Decisions for transportation routes often involve combinations of avalanche control and closures, defences or structural protection and avoidance. Table III lists parameters for planning and mapping types.

**Table III: Typical parameters for transportation routes.**

| Land use | Typical threshold return period (years) | Critical avalanche size | Typical action or planning | Typical mapping |
|---|---|---|---|---|
| Highway<br>Railway[1] | 30 | >2 | Location planning; Avalanche Hazard Index or risk assessment; warning signs; occasional closure or explosive control; protection forest; safety regulations | Locator map for initial planning; Avalanche atlas |
| | 10<br>(Active program) | >2 | As above plus: active control[2] plan; structural protection at key sites; detection systems for railways | Avalanche atlas |

**Table III, continued: Typical parameters for transportation routes.**

| Land use | Typical threshold return period (years) | Critical avalanche size | Typical action or planning | Typical mapping |
|---|---|---|---|---|
| Industrial Road | 30 | >2 | Location planning | Locator map |
| | 1 – 10 (Active program depending on traffic volume) | >2 | As above plus: warning signs; intermittent control/closure; safety regulations | Locator map<br><br>Avalanche atlas for long-term use |

[1] *Avalanche deposits contaminated by rocks, woody debris and soil are critical on railways where derailment is a key risk consideration.*

[2] *Active control plan means formal avalanche forecasting and control procedures.*

As an example the typical progression for planning a new highway involves preparing a locator map and applying the Avalanche Hazard Index or linear risk analysis. This provides a comparison of risk between avalanche paths on the route, allows a comparison between route alternatives and compares the overall risk with that on other highways. Frequency and magnitude of avalanches, distribution and number of avalanche paths and potential traffic volume and type are essential factors in the analysis. This information is then applied in the alignment planning and avalanche control planning for the route.

An avalanche atlas is then prepared for the proposed or existing alignment. Polygons, which are outlined on avalanche atlas topographic maps for transportation, typically extend down the slope only as far as the route alignment. Where complete polygons are drawn (e.g. Geographic Information System applications), it is important to clarify the approximate nature of the runout and differentiate this map from an avalanche zoning plan for occupied structures.

Structures such as bridges and snowsheds are usually designed by taking into account avalanche impact pressures and snow loads with return periods in the order of 100 years.

### 5.3 Energy corridors and utilities

Planning for utilities exposed to avalanche hazards usually incorporates avoidance by location or structural protection against a design avalanche. Table IV contains typical planning and mapping choices.

**Table IV: Typical parameters for energy corridors and utilities.**

| Land use | Typical threshold return period (years) | Critical avalanche size | Typical action or planning | Typical mapping |
|---|---|---|---|---|
| Transmission line | 100 | >2 | Location; site-specific structural protection (100 year design pressures) | Locator map |
| Surface pipeline | 100 | >2 | Location; site-specific structural protection (100 year design pressures) | Locator map |
| Telephone line | 10 | >2 | Location; site-specific structural protection | Locator map |

***Note:*** *Avalanches that may contain rocks or woody debris are critical for considering potential damage to utility structures.*

The typical return intervals for action in Table IV reflect the risk of environmental damage (pipelines) or loss of service (transmission and pipelines) in the utilities. Replacement of a telephone line is relatively simple and a higher risk is typically accepted in planning. Snow avalanches do not usually affect a pipeline buried well below the ground surface; however, other natural phenomena may pose a hazard.

### 5.4 Recreation operations

Recreation operations include lift-served areas and commercial backcountry operations. For lift-served areas, mitigation options include avoidance by location, structural protection of facilities, and forecasting and control plans. For backcountry operations, options include operational safety plans, intermittent avalanche control and route selection by professional guides. Table V gives a summary of planning options and typical map types.

The Canadian Passenger Ropeway standards (Canadian Standards Association, 2001) Section 3.14.1.3 require that lift tower foundations be designed for or protected from avalanches. Section 3.35 further requires a snow safety plan for passenger ropeways located in areas with avalanche potential.

In typical practice, once a preliminary lift line alignment has been prepared, each proposed lift tower site is evaluated for avalanche risk. At a site that is exposed to avalanches larger than Size 2 with return periods of less than or equal to 30 years, the avalanche impact forces and flow depth are calculated and incorporated into design criteria for the exposed tower(s). At the lift base, given the concentration of people exposed, return intervals of up to 100 years may be applied to initiate action. In practice this long return period risk to the base is usually managed by a closure plan to reduce the human exposure during periods of high avalanche hazard.

**Table V: Typical parameters for ski operations.**

<table>
<tr><th>Land use</th><th>Typical threshold return period (years)</th><th>Critical avalanche size</th><th>Typical action or planning</th><th>Typical mapping</th></tr>
<tr><td>Ski lift bases</td><td>100</td><td>>2</td><td rowspan="2">Location; structural protection based on flow depth and impact pressure closure until the hazard is reduced</td><td>Site specific mapping for new lifts</td></tr>
<tr><td>Ski lift towers</td><td>30</td><td>>2</td><td>Site specific structures</td></tr>
<tr><td>Ski area terrain</td><td>10</td><td>>1</td><td>Active control plan; ski compaction; worker safety regulations</td><td>Avalanche atlas</td></tr>
<tr><td>Commercial backcountry operations</td><td>10</td><td>≥2</td><td>Operations safety plan; guided routes; intermittent control; safety regulations in effect</td><td>Route or area mapping and oblique photos</td></tr>
</table>

Typically, ski areas with avalanche terrain present within the ski area boundary will have a snow safety plan in place, which includes a photographic avalanche atlas depicting the avalanche terrain, a description of the operational avalanche hazard evaluation process, a description of the control methods and closures (both intermittent and permanent), and emergency procedures.

### 5.5 Areas proposed for timber harvesting

Areas that are proposed for timber harvesting within avalanche terrain are assessed for risk based on expected avalanche frequency and avalanche size. Risk is estimated in terms of low (L), moderate (M) or high (H) as defined below for two applications: threats to forest cover; and threats of down-slope impact on transportation routes, community watersheds, or other down slope resources, facilities or concerns. Normally, a preliminary analysis of avalanche potential is completed using locator maps. For a planned cutblock this is based on identification of:

1) **Snow supply** sufficient for initiation of destruction avalanches;
2) **Slope angles** equal to or greater than 30°, which would likely become avalanche starting zones (the probability of avalanche initiation on slopes less than 30° is about 0.08, based on slope inclines measured in 91 cutblocks where destructive avalanches started in the cutblock and where the minimum slope angle was 26º as identified by the UBC Avalanche Research Group);
3) **Expected magnitude/frequency** of avalanches in existing paths that intersect potential harvest areas.

Following the preliminary assessment, a risk analysis of key variables at selected sites is calculated, and polygons for protective forest zones and modified harvest plans are identified on maps.

### 5.5.1 Risk basis for forestry applications

Two important applications of acceptable risk in forest harvest are:

- Type I – Avalanche initiation in new avalanche starting zones in cutblocks.
- Type II – Cutblocks where avalanches entering from above in pre-existing paths gain destructive potential in the harvest area.

In these applications, it is best to use the Canadian size system for characterizing destructive potential. These applications describe the risk as: $P(A \cap S_i)V(S_i) = P(A)P(S_i \mid A)V(S_i)$ where $S_i$ represents avalanche size, A represents avalanche occurrence at the site, and $V(S_i)$ represents a vector component of vulnerability corresponding to avalanche size $S_i$. This equation has the form: risk = (frequency) x (expected damage).

To prevent damage to the forest cover, the recommended acceptable risk in Canada for these applications (Type I and II) is a Size 3 avalanche with an average frequency of less than 1:10 years or a Size 2 avalanche with an average frequency of less than 1:1 years. The matrix below is constructed on the basis of three orders of magnitude avalanche frequency and consequences rated qualitatively (proportionality to the risk) with risk rated as low (L), moderate (M) and high (H) for damage to forest cover. The guidelines for risk acceptability (Tables VI-VII) have been developed on the basis of research by the Avalanche Research Group at UBC, on behalf of Forest Renewal BC.

**Table VI: Risk ratings for expected avalnche size and expected avalanche frequency for forest harvest resulting in damage to forest cover.**

Risk is rated qualitatively as low (L), moderate (M) and high (H).

| Frequency range (events/a) | Average frequency (events/a) | Qualitative risk for avalanche size | | |
|---|---|---|---|---|
| | | 2 | 3 | >3 |
| >1-1:3 | 1:1 | M | H | H |
| 1:3-1:30 | 1:10 | L | **M** | H |
| 1:30-1:300 | 1:100 | L | L | H |

**Notes:**

- For the applications described (damage to forest cover), the risk is nominal for avalanche sizes less than 2.
- The reference level of risk (Size 3 with 10-year return period) is bolded and is considered on the border between moderate and high risk. However, due to uncertainty, other categories have the same moderate risk rating. Moderate risk will normally require modification of the harvest design.
- Forest harvest practices that are likely to result in avalanches of Size 4 (or larger) are unacceptable. Size 4 avalanches initiating in cutblocks can create permanent new avalanche terrain (modify existing terrain).
- Frequent Size 2 avalanches can damage small seedlings and branches during regeneration. This, with the inherent uncertainty associated with the field estimation, produces moderate risk for annual avalanches (1:1).

### 5.5.2 Cutblocks with down-slope transportation corridors or resource impacts

When down-slope transportation corridors (e.g. highways or railways), facilities (e.g. occupied or unoccupied structures), essential resources (e.g. registered community use, domestic use or commercial use watersheds or important fisheries), or other concerns may be affected by avalanche initiation from logging, the acceptable risk must be more conservative than if timber resources alone are affected (Table VI). For this application, the recommended Canadian acceptable risk is a Size 3 avalanche with an average frequency of less than 1:30 years or a size two avalanche with an average frequency of less than 1:3 years. Table VII shows the applicable risk matrix analogous to Table VI for timber resources.

**Table VII: Risk ratings for expected avalanche size and frequency for forest harvest when down-slope transportation corridors, facilities or essential resources may be affected.**

Risk is rated qualitatively as low (L), moderate (M) and high (H).

| Frequency range (events/a) | Average frequency (events/a) | Qualitative risk for avalanche size 2 | 3 | >3 |
|---|---|---|---|---|
| >1-1:10 | 1:3 | M | H | H |
| 1:10-1:100 | 1:30 | L | **M** | H |
| <1:100 | 1:300 | L | L | H |

**Notes:**

- In the application described (damage to essential down slope resources), the risk is minimal for avalanche sizes less than 2.
- The Canadian reference level of risk (Size 3 with 30-year return period) is bolded and is considered on the border between moderate and high risk. However, due to uncertainty, other categories have the same risk rating. Moderate risk will normally require modification of the harvest design.
- In rail applications, forest harvest practices that are likely to produce avalanches contaminated with debris (other than snow) onto the rails are unacceptable in practice.
- In general, avalanches greater than Size 2 are unacceptable on thoroughfares in Canada when open to the travelling public. Moderate risk will imply efficient control and closure procedures.
- Roads with low traffic volumes, such as logging roads, may follow the less conservative matrix given in Table VI.
- Avalanches of Size 4 (or larger) that are likely to result from forest harvest are unacceptable in practice. Such avalanches can create permanent new avalanche terrain above the location of concern, which can mean a high frequency of avalanches reaching the down slope resource. In general, Size 4 avalanches can contain significant amounts of soil cover and other debris (e.g. logs, rocks) and the destructive effects may be considered comparable to large debris flows.

## 5.6 Risk basis for occupied structures – zoning plans

There are two classes of occupied structures: residential and other permanently occupied structures; and industrial plant and temporarily occupied structures. Both classes require a zoning plan based on a combination of expected impact pressures and return periods of avalanches. Industrial plants are normally categorized under worker safety regulations.

### 5.6.1 Avalanche risk zones for occupied structures

Recommended zones for land-use planning in Canada (where occupied structures are proposed) include:

1. **White zone:** An area with an estimated avalanche return period of greater than 300 years, or impact pressures less than 1 kPa and a return period greater than 30 years.

2. **Red zone:** An area where the return period is less than 30 years and/or impact pressures are greater than or equal to 30 kPa, or where the product of impact pressure (kPa) and the reciprocal of the return period (years) exceeds 0.1 for return periods between 30 and 300 years.

3. **Blue zone:** An area where the product of frequency and impact pressure is less than 0.1 for return periods between 30 and 300 years and impact pressures greater than or equal to 1 kPa and less than 30 kPa, which lies between the red and white zones.

The recommended Canadian guideline for the definition of zones is risk-based from the perspective of design avalanche effects. The values (30 kPa, 30 years and 300 years) and colour schemes are similar to those used in Switzerland (Switzerland, 1984). Formally, the Canadian definition representing the line between Blue and Red zones is given by: $I/T < 0.1\ I_0/T_0$ (30 y < T < 300 y) for $I_0$ = 30 kPa and $T_0$ = 30 y. The Canadian definition of the Blue/Red zone boundary is more conservative than that in Switzerland from a risk perspective but not as conservative as the 1999 guidelines for Austria (Höeller and Schaffhauser, 2001).

For the Blue/White zone boundary, the Canadian and Austrian definitions are equivalent (1 kPa impact pressures for return periods greater than 30 years) whereas in Switzerland the Blue zone may extend to zero impact pressures for return periods from 30 to 300 years.

It is important to recognize that in the alpine countries of Europe there are established systems of public avalanche hazard warning and evacuation for residential areas. Similar systems do not yet exist in Canada, except in a few isolated locations. Land use planners must recognize the importance of developing such systems where occupied structures and meeting places are exposed to the avalanche hazard.

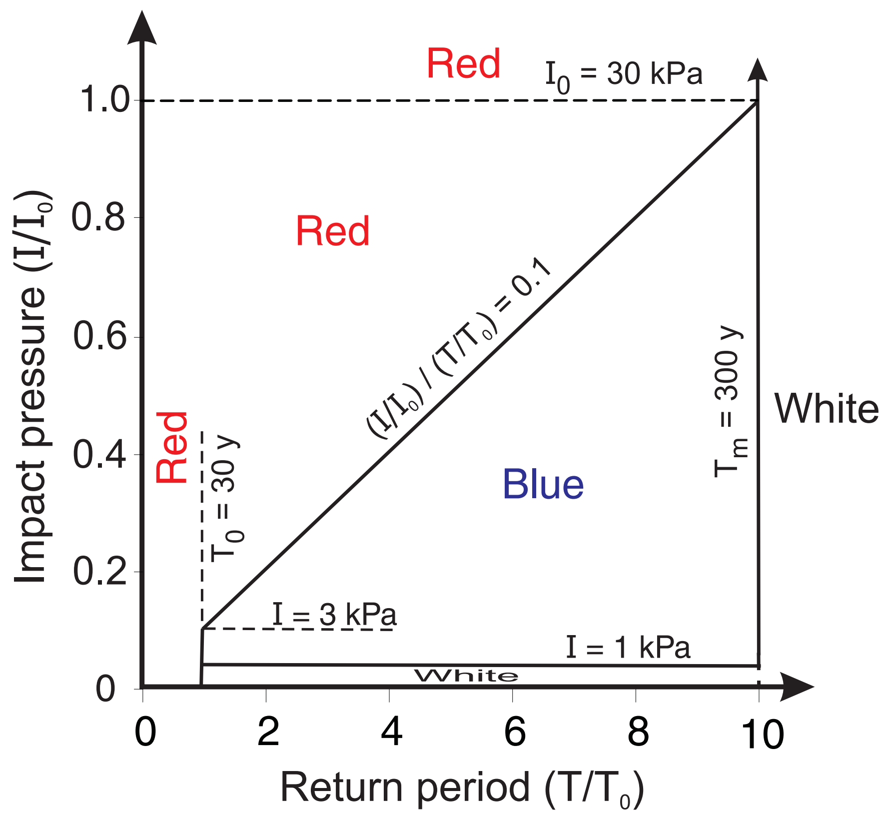



**Figure 1:** Definitions of red, blue and white zones for land-use planning.

Recommended activities according to zone colour in Canada are:

1. White zone (low risk) – Construction of new buildings, including permanentally occupied structures, normally permitted.
2. Red zone (high risk) – Construction of new buildings *not normally permitted.*
3. Blue zone (moderate risk) – Construction of new buildings, such as industrial plants and temporarily occupied structures, possibly permitted with specified conditions. Conditions may include structures reinforced for avalanche forces, construction of avalanche defences, and requirement for evacuation plans or a combination of these.

Special structures where large numbers of people may gather, multi-unit residences or structures used for essential services (hospitals, schools, police and fire stations) must be placed only in a White zone and where there is a high confidence that the avalanche risk is low. Properties rented during winter, in which the tenant may not be aware of or have accepted the risk, should only be placed in the White zone.

### 5.7 Multi-user terrain

An area with more than one user group is an important consideration when planning to harvest a forest. For instance, helicopter and snow-cat ski operations in BC have licensed permits for the same area of land as forestry companies. In these cases, critical threshold and risk matrices should be considered, and an assessment of the potential impact on other users should be completed. For example, avalanches of Size 2 or greater (that might be triggered by skiers) are a significant risk in backcountry ski operations, whereas a Size 3 avalanche is the reference level of risk for forest damage. This demonstrates the possible conflicts between user groups with different levels of acceptable risk. Costs and benefits and multi-users must be carefully assessed.

### 5.8 Multiple hazards and future events

Applications may be encountered where future events (other than avalanches) can affect avalanche risk. Areas of protective forest should be designated where future loss of forest is unacceptable, and a discussion of dynamic effects (e.g. growth or disappearance of forest cover, changes in climate) should be mentioned if they affect avalanche risk. Consider the example in which a fire (F) occurs in forested terrain. The risk may be estimated as: $P(F \cap A)$ - the probability that fire occurs followed by avalanche occurrence (A). The intersection may be expanded as: $P(F \cap A) = P(F) P(A \mid F)$ where P(F) is the general probability that fire occurs for the area (usually much less than avalanche probability in steep alpine terrain) and $P(A \mid F)$ is the conditional probability that avalanching occurs given that fire takes place. The conditional probability will depend on the severity of the fire (roughness and stems left after the fire), snow supply, terrain steepness and other factors.

For multiple avalanche paths affecting a site, the union of probabilities (probability of one event or the other; probability of either event) is appropriate. For example, for avalanche Paths 1 and 2: $P(A_1 \cup A_2) = P(A_1) + P(A_2) - P(A_1) P(A_2 \mid A_1)$ or $P(A_1) + P(A_2) - P(A_1)P(A_2)$ if avalanche events on the paths are not conditionally related. If two avalanche paths do not intersect spatially, then the probability of an event on either $A_1$ or $A_2$ is $P(A_1 \cup A_2) = P(A_1) + P(A_2)$ for the area. This latter relationship shows how, for example, avalanche risk can be summed to make a linear risk map for a highway through an avalanche area considering non-intersecting avalanche paths. This formula is also the basis for a “total risk” (Varnes, 1984) formulation (sum of specific risks to determine total risk).

## Appendix A: Typical methods for avalanche hazard mapping

To determine the extent of avalanche hazard or risk, avalanche consultants use the following methods. Often, not all methods are relevant to a particular problem. The methods described are those typically applied by avalanche specialists at the time of the publication of this document and different methods are preferred in different parts of the world. These methods, in particular models of avalanche runout and avalanche dynamics, continue to evolve.

### A.1 Terrain analysis from maps and air photos

In areas that receive sufficient snow, the location and character of avalanche paths can usually be identified from contour maps and air photos. The area, slope angle and character of the starting zone, the slope angle, character and width of the track, and the character and slope angle of the runout zone are estimated prior to field studies.

In addition to terrain features, snow deposited by wind or avalanches can sometimes be observed in air photos. This often justifies air photo flights after large avalanche winters.

### A.2 Field studies of terrain

In the field, the profile and width of the avalanche path can be measured with surveying techniques similar to those used in forestry. The boundaries of the starting zone, track and runout zone (estimated from maps and air photos) can be refined. Subtle terrain features and ground roughness and their influence on avalanche formation and motion can be identified. Fieldwork often includes studies of vegetation and surficial materials. Consequently they are usually performed when there is no snow on the ground.

### A.3 Study of vegetation for signs of past avalanches

A wealth of historical avalanche information can be obtained from the location and types of vegetation (trees, bushes and perhaps lichen) in the avalanche path. Large avalanches often leave a boundary between damaged and undamaged vegetation (trim line). From dated air photos, damage to the forest cover over time can be identified, yielding information on the timing of destructive avalanches. Tree growth rings, sampled in the field, are used to determine the extent and date of previous large avalanches.

### A.4 Oral and written records of avalanches

In addition to analyzing records from highways, railways, parks, ski areas and other operations, the avalanche consultant will often interview residents who have been in the area for many years, and may research archives, and newspapers.

### A.5 Weather and snow records

Since avalanches that release more snow from the starting zone typically run farther and produce greater impact pressures, the avalanche consultant estimates the maximum snow depth for the specific application. The basis for these depths may be extreme-value statistical estimates based on historical measurements in nearby snow courses or weather stations. Such estimates often have to be adjusted for differences in the elevation of the measurement site and starting zone. If the closest measurement site is in a different snow climate, then further adjustments must be applied. Often these estimates are adjusted for additional snow deposited by wind in the starting zone.

In addition to maximum snow depths, the consultant uses similar techniques to estimate how often threshold snow depths (sufficient for destructive avalanches), or how often extreme storm snowfalls are expected.

The consultant typically investigates the weather (precipitation, wind and temperature) associated with large avalanches, information determined from written records and oral accounts. For example, if the weather leading up to a large avalanche has only occurred twice in the previous 20 years of weather measurements, then avalanches of that size may have an estimated return period of approximately 10 years.

Certain types of weather events, such as cold temperatures with minimal wind, are known to create weak snow layers that remain weak for months and release deep slabs later in the winter or spring. The consultant assesses the propensity of the starting zones for such conditions and subsequent large avalanches.

### A.6 Surficial materials

Large avalanches often transport tree debris, rock and soil. During the field study, the consultant will usually inspect the runout zone (when there is no snow on the ground) for transported materials, and try to relate these deposits to large avalanches. Old forest debris may be obscured by more recent growth.

Some organic material, such as woody debris or peat, can be carbon-dated and potentially associated with avalanches with long return periods (Boucher and others, 1999).

### A.7 Application of topographic-statistical models

Information on extreme runouts within the same mountain range and similar snow climate may be used to statistically estimate the runout for a particular path. There are two commonly used methods (Fig. A 1), Alpha-Beta and Runout Ratio. Both models use the Beta ($\beta$) point which is where the slope angle of the path first decreases to a certain angle, usually 10° (18%).

In the Alpha-Beta model (Lied and Bakkehöi, 1980), Alpha ($\alpha$) is the angle from the toe of the extreme runout to the top of the starting zone, and $\beta$ is the angle from the $\beta$ point to the top of the starting zone. Based on the $\beta$ angle for a particular path and on the statistical relationship between $\alpha$ and $\beta$ from paths in the surrounding range, the $\alpha$ angle (for the extreme runout) is estimated for the particular path.

The Runout Ratio model (McClung and Mears, 1991) takes into account the horizontal distance ($X_\beta$) from the top of the starting zone to the beta point and the horizontal distance from the $\beta$ point to the toe of the runout ($\Delta X$). Extreme runouts are determined by fitting the runout ratio ($\Delta X/X_\beta$) to an extreme value probability distribution, similar to water discharge from floods. These statistical estimates of extreme runouts can be related to return periods (McClung, 2000).

Short slopes less than approximately 250 m in height run proportionally farther than taller slopes and separate data sets are required for short slopes (Jones, 2002).

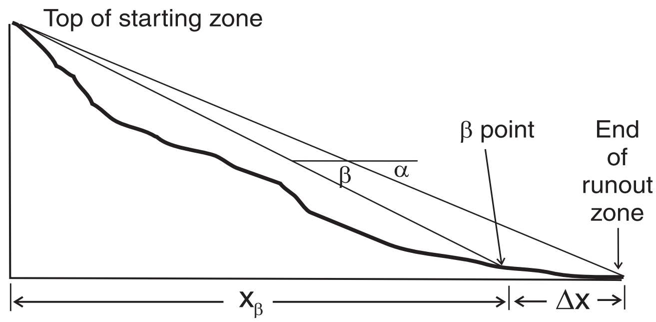



***Figure A.1*** *Profile of a hypothetical avalanche path showing measurements used for topographic-statistical runout models.*

## A.8 Application of dynamic models

Avalanche dynamics models are needed to estimate speeds along the incline for calculating impact pressures from flowing avalanches. A European Commission report (Brugnot, ed., 1999) contains an extensive review of models. Basically the models are of two types:

1. models requiring solution of the conservation of momentum assuming the avalanche is a point mass (e.g. Perla and others, 1980; Salm and others, 1990)

2. models requiring simultaneous solution of the conservation of mass and momentum (e.g. Norem and others, 1987, 1989; McClung and Mears, 1995).

To apply the models one must estimate basal friction as a function of position from data, experience or both. In addition, friction between snow particles must be included to estimate active/passive snow pressure in some of the models (2. above) and such models may also be used to predict flow depth. Since dynamics models require friction parameters for which there is considerable uncertainty, they should be used cautiously when estimating runout distances.

## A.9 Combined estimates from various methods

While not all methods outlined in this chapter are applicable to every avalanche path or problem, several methods will produce estimates of the runout distance and return interval. The consultant must carefully consider the confidence in each method to determine the best estimate of avalanche runout. The combined estimate must be for the return period relevant to the particular problem. For example, when estimating whether an avalanche path might reach a highway, a 30-year return period may be considered, whereas for residential subdivision zoning, a 300-year return period would be more relevant.

Since most current dynamic and statistical models do not predict the lateral extent of extreme avalanches, the consultant usually bases the estimate of avalanche width on an analysis of terrain (from maps, air photos and ground observations), field studies of vegetation and experience with large avalanches.

# Appendix B: Canadian avalanche size classification

The Canadian avalanche size classification is based on estimated destructive effects of avalanches. The system is similar in concept to the Mercalli Scale for earthquake intensity, and like the Mercalli Scale it is possible to estimate destructive potential. Guidelines for sizing depend on avalanche mass, distance moved along an incline, estimated destructive effect to people and objects such as vehicles, trees and houses, and estimated maximum impact pressure. This is a five-class system with an estimated order of magnitude in destructive potential for each size increase. In general, the frequency of avalanches decreases as size increases. We recommend use of whole sizes in land-use planning, however due to uncertainty in Canada avalanche observers record events using half sizes (e.g. Size 2.5).

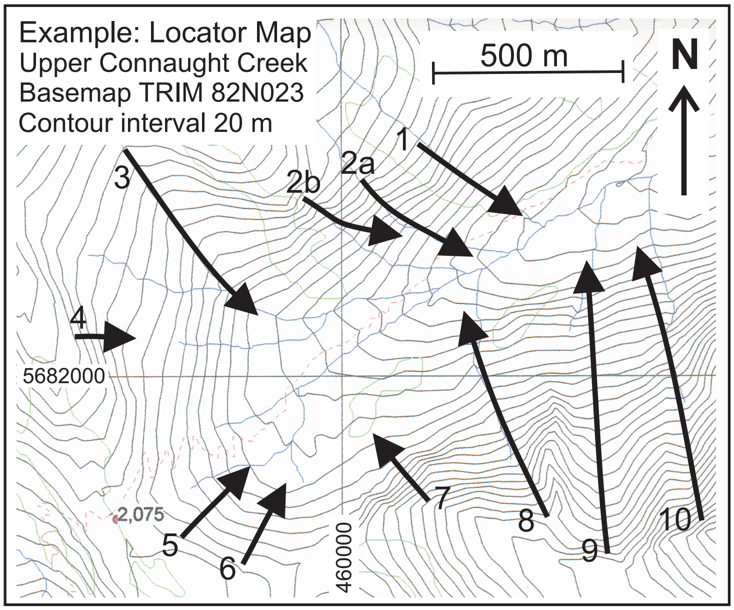
**Table B.1. Canadian classification system for avalanche size (McClung and Schaerer, 1981)**

| Size | Destructive potential (definition) | Typical mass (t) | Typical path length (m) | Typical impact pressure (kPa) |
|---|---|---|---|---|
| 1 | Relatively harmless to people. | <10 | 10 | 1 |
| 2 | Could bury, injure or kill a person. | $10^2$ | 100 | 10 |
| 3 | Could bury a car, destroy a small building*, or break a few trees. | $10^3$ | 1000 | 100 |
| 4 | Could destroy a railway car, large truck, several buildings or forest with an area up to 4 hectares (ha). | $10^4$ | 2000 | 500 |
| 5 | Largest snow avalanches known; could destroy a village or forest up to 40 ha. | $10^5$ | 3000 | 1000 |

* e.g. a wood frame house

# Appendix C: Examples of map types

**C.1 Locator map**




Avalanche Locator Map Legend

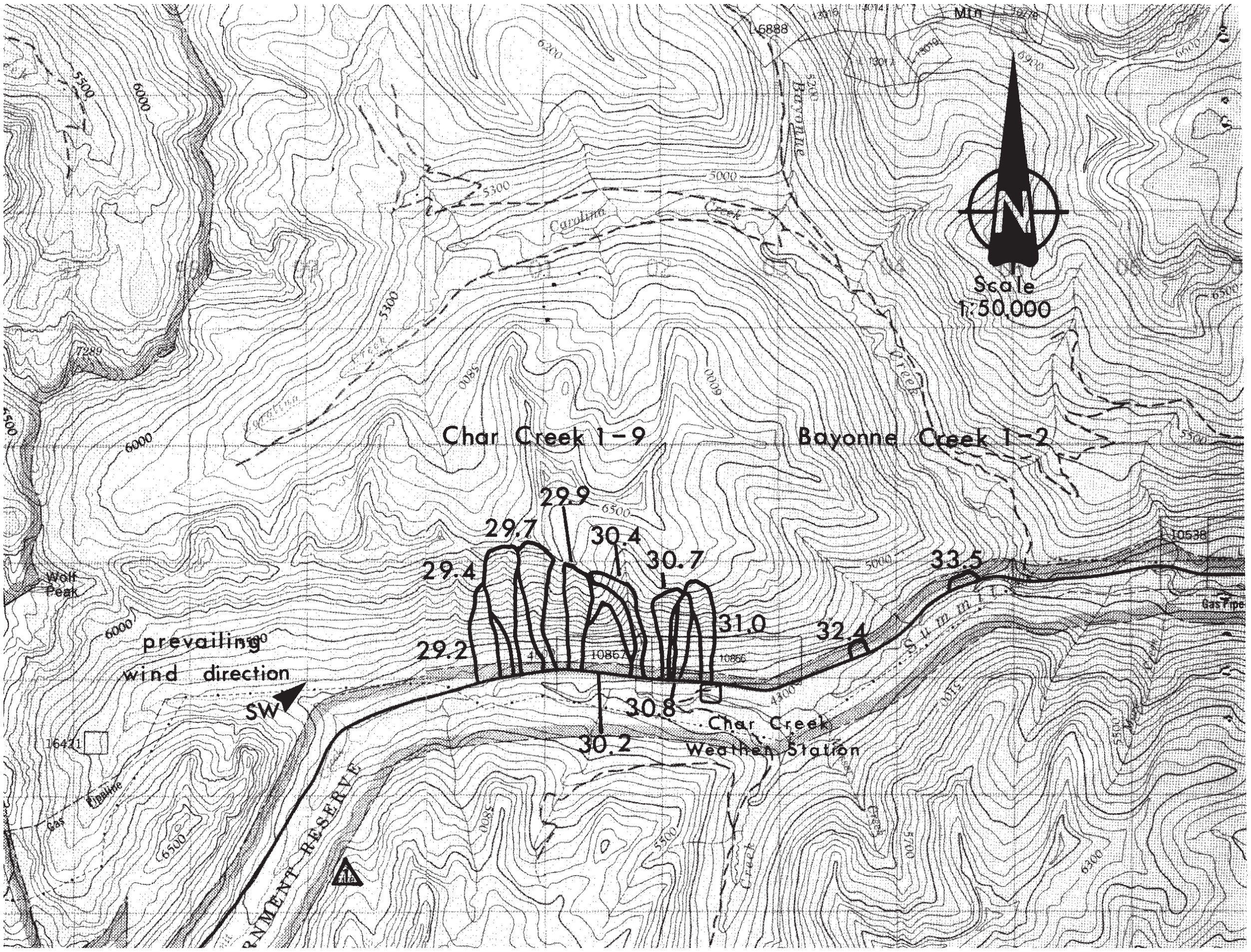
Avalanche Path Location:

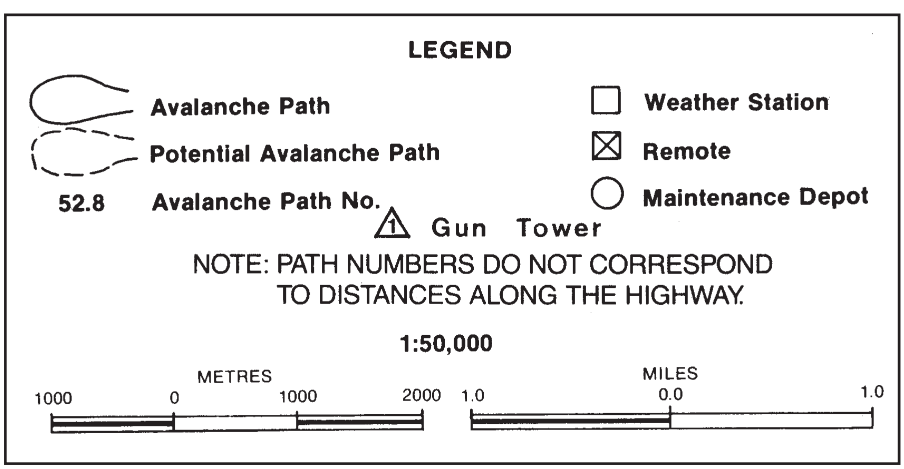
Path Identifier: 2 a

(Usually a sequential number in the study area, a road km number, or drainage reference)

A locator map will usually include a base map reference, author (drawn by), a scale, contour interval and north arrow.

**C.2 Avalanche atlas (BC Ministry of Transportation & Highways, 1989)**



KOOTENAY PASS
AVALANCHE PATH SUMMARY

NAME: Char Creek #2 NUMBER: 29.4

LOCATION: 6.1 km east of Kootenay Pass Maintenance Depot
27.4 km west of Summit Creek bridge

MAP: 82 F/2

AERIAL PHOTOGRAPHS: BC 81034 189–190 (1:16,000)
BC 5348: 118–119 (1:32,000)

DESCRIPTION:

ELEVATION: (above sea level)

Starting Zone: 2020–1890 m Runout Zone: 1430–1390 m

VERTICAL FALL: 630 m VERTICAL FALL TO HIGHWAY: 620 m

STARTING ZONE ASPECT: South-south-west

INCLINE:

Starting Zone: 37° Track: 31° Runout Zone: 20°

STARTING ZONE: is a large, shallow bowl containing many ridges. Vegetation consists of sparse, mature coniferous trees.

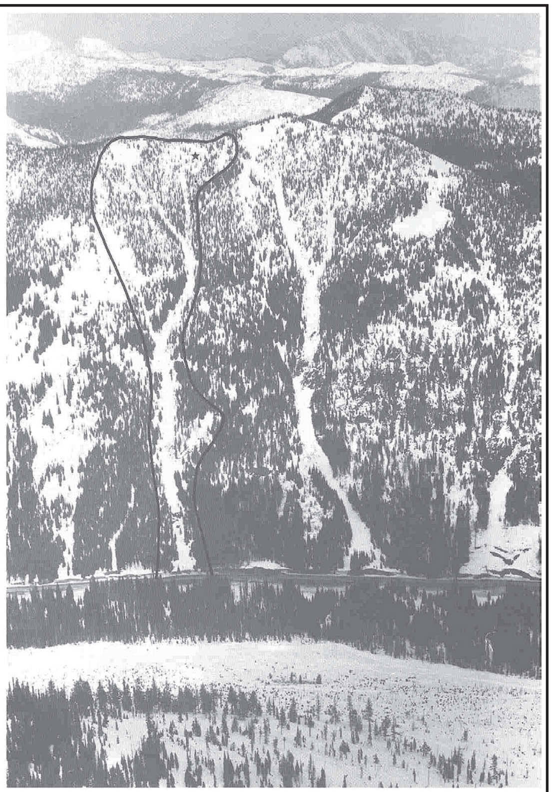
TRACK: begins as three gullies which converge in the upper portion. The main gully is bordered by dense, mature coniferous vegetation. A small, narrow gully joins the main gully midway down the track.

RUNOUT ZONE: begins 100 m above the highway as a narrow, alluvial fan. Most avalanches run out above the highway, but some may cross the highway and travel 50 m beyond.

AVALANCHE ACTIVITY: Length of highway affected is 100 m. Avalanches are estimated to affect the highway an average of once in twenty years.

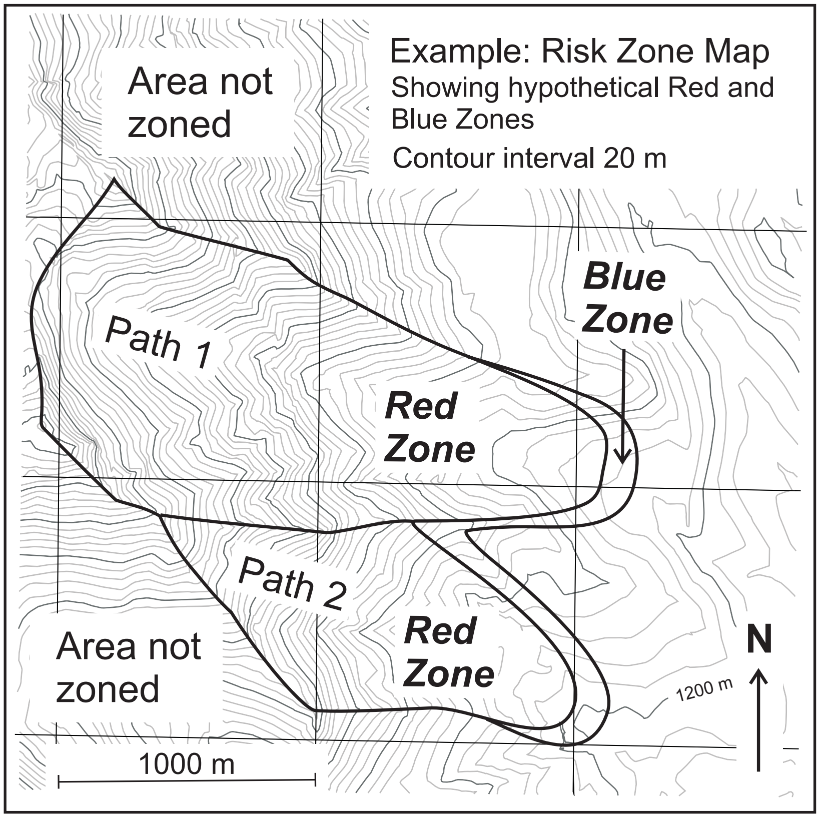
Example data sheet for an individual avalanche path in an avalanche atlas. Actual data on the history of avalanche observations is also included, when available.

29.4



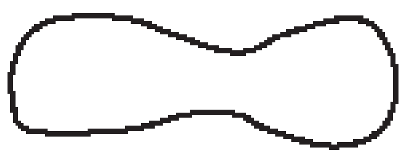
Example oblique photograph of the avalanche path for an avalanche atlas. The paths may be outlined individually on the photograph (as in the example) or several avalanche paths maybe outlined on a single photograph.

### C.3 Zoning map for occupied structures




Risk Zone Map Legend

Path boundary (polygon):



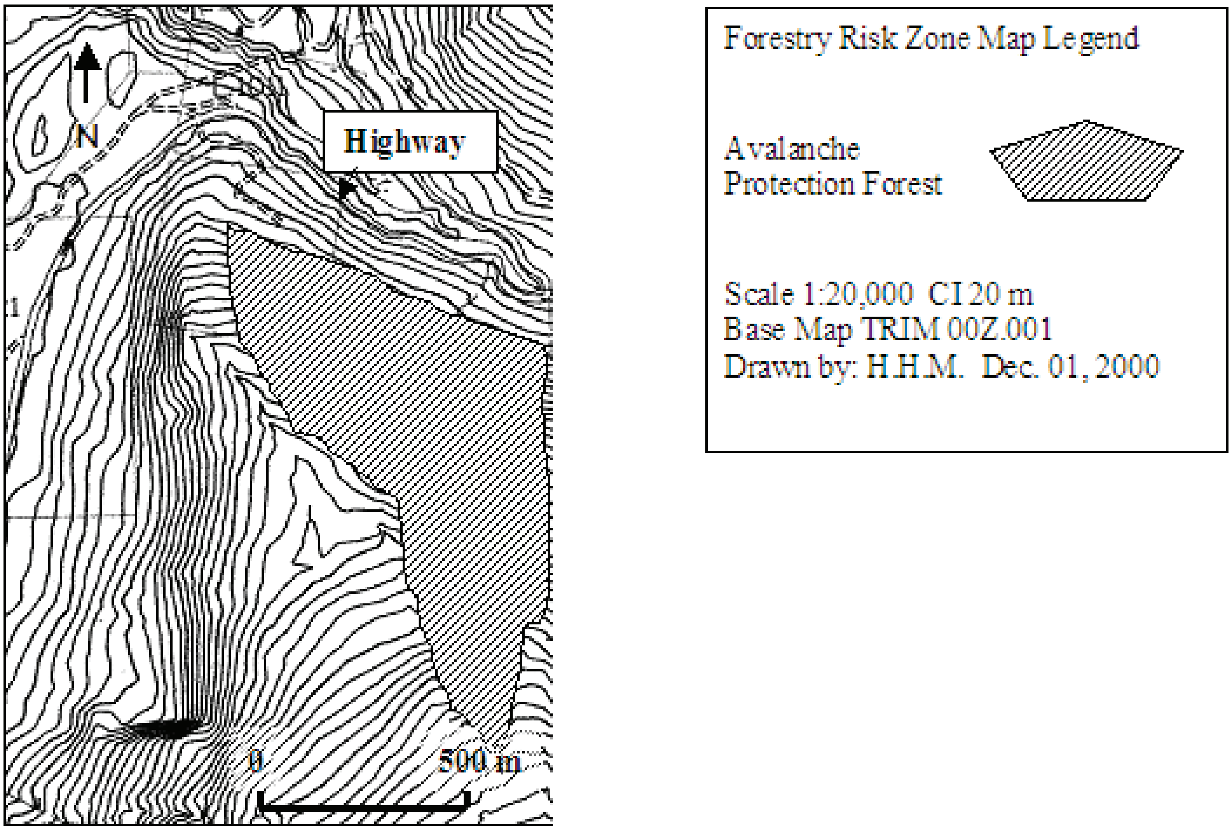
Path Name or Number: Path 1

Zones: Red, Blue

(Red and blue zones are usually identified by colour coding or text on the map. The white zone is that area beyond the toe of the blue zone except where identified as area not zoned)

A zone map will usually include a base map reference, author (drawn by), a scale, contour interval and north arrow.

**C.4 Forestry risk zone map identifying avalanche protection forest for highway below**



## Appendix D: Definition of probability symbols

Intersection: A and B are events where $P(A \cap B)$ denotes the probability that both A and B occur. Intersection is commutative, thus $P(A \cap B) = P(B \cap A)$.

Conditional probability: $P(A \mid B)$ of event A is the probability of A under the assumption that B has occurred (it is assumed that the probability of B is not 0). The probability for the product of two events is defined by: $P(A \cap B) = P(A)P(B \mid A) = P(B)P(A \mid B)$. If events A and B are independent, then $P(A \cap B) = P(A) P(B)$.

Likelihood: The likelihood, $L(H \mid D)$, of hypothesis H given data D, and a specific model, is proportional to $P(D \mid H)$, the constant of proportionality being arbitrary. With probability, D is the variable and H is constant; with likelihood, H is the variable for constant D. For example, if H is an attribute, such as partial destruction of a building, the likelihood of H is estimated given various data and information at the site. Likelihood might be estimated from models or other methods.

Multiple events: If events $A_1, A_2, A_3 \ldots$ can occur then $P(A_1 \cap A_2 \cap A_3 \cap \ldots) = P(A_1)P(A_2 \mid A_1)P(A_3 \mid A_1 \cap A_2) \ldots$

Addition theorem: The probability of the union of two events (A or B) is: $P(A \cup B) = P(A) + P(B) - P(A \cap B)$. For mutually exclusive events:
$P(A \cup B) = P(A) + P(B)$.

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# Notes

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