A technical manual for assessing, mapping and mitigating snow avalanche risk

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ABSTRACT
The methods for assessing and mitigating snow avalanche risk have historically been scattered between research papers, design guides for specific structural defences (mostly from western Europe), and unpublished documents held by consulting firms and government agencies. In spring 2018 the Canadian Avalanche Association will publish a technical manual, entitled *Planning Methods for Assessing and Mitigating Snow Avalanche Risk*, that draws on these diverse sources. The book includes hypothetical examples and illustrations in which qualitative, semi-quantitative and quantitative methods are applied to situations in which elements-at-risk are exposed to snow avalanches. These situations include transportation corridors, occupied and unoccupied structures, transmission lines, worksites, and winter roads for over-snow vehicles. This book is intended for avalanche practitioners including engineers and geoscientists, consultants and those on their teams that assess, map or mitigate snow avalanche hazard or risk.

RESUME
Les méthodes d'évaluation et d'atténuation du risque d'avalanche ont été historiquement disséminées entre les documents de recherche, les guides de conception pour les défenses structurelles spécifiques (principalement d'Europe occidentale) et les documents non publiés détenus par des cabinets de conseil et des agences gouvernementales. Au printemps 2018, la Canadian Avalanche Association publiera un manuel technique intitulé Méthodes de planification pour l'évaluation et l'atténuation du risque d'avalanche de neige, qui s'inspire de ces diverses sources. Le livre comprend des exemples hypothétiques et des illustrations dans lesquelles des méthodes qualitatives, semi-quantitatives et quantitatives sont appliquées à des situations dans lesquelles des éléments à risque sont exposés à des avalanches de neige. Ces situations comprennent les corridors de transport, les structures occupées et inoccupées, les lignes de transport, les lieux de travail et les routes d'hiver pour les véhicules de déneigement. Ce livre est destiné aux praticiens des avalanches, y compris les ingénieurs et les géoscientifiques, les consultants et les membres de leurs équipes qui évaluent, cartographient ou atténuent les risques d'avalanche de neige.

1 INTRODUCTION

This book is about the methods used to assess and mitigate snow avalanche hazard and risk for land-use planning. The emphasis is on long-term planning and mitigation measures. The methods for assessing and mitigating snow avalanche risk have historically been scattered between research papers, design guides for specific structural defences (mostly from western Europe), and unpublished documents held by consulting firms and government agencies. In early 2018 the Canadian Avalanche Association (CAA) will publish a technical manual, entitled *Planning Methods for Assessing and Mitigating Snow Avalanche Risk (Jamieson 2018)* that draws on these diverse sources.

This book does not propose any new thresholds (i.e. guidelines) for acceptable avalanche hazard or risk for specific activities. Such guidelines are included in *Technical Aspects of Snow Avalanche Risk Management - Resources and guidelines for avalanche practitioners in Canada*, which the Canadian Avalanche Association published in 2016 (CAA 2016). Although the guidelines for human activity in snow avalanche terrain vary by jurisdiction, the methods to assess and mitigate avalanche hazard and risk generally do not. Hence, the methods in the technical manual should apply in Canada and internationally.

The methods follow the framework from ISO 31000 (CSA 2010) and CAA (2016) in which hazard or risk assessment consists of the stages: identification, analysis and evaluation, which are preceded by establishing the context, and followed by mitigation. Figure 1 shows these stages and how they relate to the chapters of the book. Chapters 2 and 3 summarize the current understanding of avalanche terrain and its interaction with avalanche characteristics. The steps in assessing avalanche hazard and risk for land-use planning usually include interpreting evidence such as vegetation damage (Chapter 4), statistical runout estimation for large avalanches (Chapter 5), analysis of snow climate data (Chapter 6), and modelling the velocity and runout of large avalanches (Chapter 7). Qualitative and quantitative methods for assessing avalanche hazard and risk are summarized in Chapters 8, 9 and 10. Information from Chapters 2 through 8 on the spatial extent of avalanches is summarized in maps as described in Chapter 11. The basic impact calculations for mitigating avalanche hazard are introduced

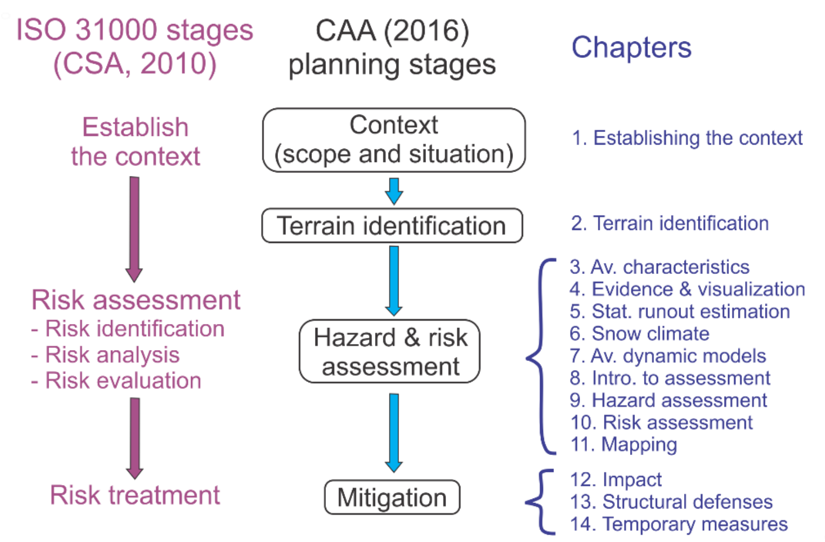

Figure 1: Stages of risk management based on CSA (2010) and CAA (2016) related to chapters of the book.

in Chapter 12. The advantages and limitations of various structural defenses, including protection forests, are summarized in Chapter 13, which also includes references to guides for designing structural defenses. Since avalanche hazard and risk are often managed with a combination of structural defenses and day-to-day mitigation operations, Chapter 14 outlines operational measures such as forecasting, detection systems, and exploders known as remote avalanche control systems (RACS).

Rather than include the detailed methods from design guides such as WSL-SLF (2007), Jóhannesson et al. (2009) or Rudolf-Miklau et al. (2015), the book describes the concepts and principles behind the design methods and provides references to the applicable design guides.

The extreme runout position (hereafter "runout") of avalanches is a key component for spatially assessing avalanche hazard or risk. Runout assessments are based on: written and oral records of long running avalanches; vegetation damage; statistical runout models; and dynamic models. The typical confidence in the runout estimates from these sources or methods varies between North America and western Europe. The records of extreme runout are often very good in the historically populated mountain valleys of western Europe and very limited in the areas proposed for development elsewhere. Also, the dynamic models are better calibrated in western Europe than elsewhere. In North America, statistical runout models have been calibrated for most major mountain ranges and are widely used. Also, vegetation damage near areas considered for development in North America is often a very useful indicator of the extent of previous extreme avalanches.

This book is intended for avalanche practitioners including engineers and geoscientists, consultants and those on their teams that assess, map or mitigate snow avalanche hazard or risk. It does not cover the operational (day-to-day) management of snow avalanche risk by avalanche workers such as forecasters and ski guides.

Each of the fourteen chapters is written by two or three of the following avalanche practitioners: Chris Argue, Ryan Buhler, Cam Campbell, Michael Conlan, Dave Gauthier, Brian Gould, Bruce Jamieson, Greg Johnson, Katherine Johnston, Alan Jones, Arni Jonsson, Alexandra Sinickas, Grant Statham, Chris Stethem, Scott Thumlert and Chris Wilbur.

The content of Chapters 2 to 14 of the book are summarized in Sections 2 to 14 of this paper, respectively.

2 CHAPTER 2 TERRAIN

This chapter covers the basics of avalanche terrain starting with definitions of avalanche path, start zone, track and runout zone. The characteristics of a start zone are summarized, including slope angle, area, orientation to wind and sun, downslope and cross-slope curvature, elevation and vegetation as well as ground roughness. The chapter explains the role of many of these factors in producing the large infrequent avalanches that can threaten infrastructure

The key characteristics of avalanche tracks and runout zones are summarized, including discussion of the effects of terrain confinement (e.g. gullies). For example, where a gully changes direction, momentum causes large fast avalanches to run up on the outer gully wall (super-elevation) and potentially spill over the gully wall. Also, gullies tend to increase the runout distance of avalanches because confinement increases the speed and reduces lateral spreading in the runout zone.

3 CHAPTER 3 CHARACTERISTICS

Snow avalanches can start in wet or dry snow, as slabs or point releases. Most large and long-running avalanches start as dry slabs. In large paths, dry snow avalanches can reach speeds of 70 m s^{-1} and perhaps higher. Wet avalanches are typically slower than dry avalanches, but can also be very destructive because of higher flow density.

The flow density of large avalanches decreases with increasing height in the flow column. Mixed-motion (dry) avalanches can be described as a lower dense flow and an upper powder (suspension) layer. Detailed descriptions of avalanche motion include a saltation layer above the dense flow and below the powder layer. For large avalanches moving in the track, the maximum slope-parallel speeds are similar in these layers. However, in any specific mixed-motion avalanche, the dense flow typically stops before the powder layer.

The dense flow is very important for land use planning because of its greater impact pressure, which is a consequence of its density being greater than the upper layers and its speed being similar until it decelerates in the runout zone. The powder layer, which flows like a turbulent fluid, is often important because it impacts structures higher above the ground and can apply substantial overturning moment to tall structures such as power transmission towers.

For infrastructure planning, it is important to characterize the avalanches in a path by their frequency (or return period) and magnitude. In a given path, avalanche mass, flow depth, maximum speed and runout increase with increasing return period.

4 CHAPTER 4 EVIDENCE OF AVALANCHES AND VISUALIZATION METHODS

Evidence of past avalanches is important for estimating the runout and lateral extent of future large avalanches. Evidence can be obtained from written and oral records, and observations of vegetation damage. Away from developed areas, written and oral records are usually limited outside of western Europe, and are often poor with regard to dates and runout distances. Vegetation records from air photographs, satellite images as well as field studies are often important where avalanches runout in forests. Boundaries between vegetation of different ages are called trim lines. The age of vegetation upstream of the trim line indicates the years since the last avalanche reached the line. The age of vegetation can be estimated in a variety of ways including tree species, tree height, and tree rings in core samples obtained from increment borers.

Digital Elevation Models (DEMs) are now widely used, and LiDAR (light detection and ranging) technology is becoming more affordable and available for mountainous areas. Vegetation damaged by past avalanches as well as avalanche terrain are now increasingly visualized with Geographic Information Systems (GIS), which can overlay imagery, including air photos, onto a DEM. It is often advantageous to visualize terrain and vegetation damage in desktop studies prior to field studies.

5 CHAPTER 5 STATISTICAL RUNOUT ESTIMATION

Estimating extreme runout is important for land use planning including transportation corridors, recreational developments, industrial use and residential land use. While statistical runout estimation cannot be used for every path, for many paths especially in North America, it is one of several useful methods for estimating the extreme runout along the centerline of a path. The statistical models use runout data from paths in the range with known runout to provide an estimate of the extreme runout in a specific path to be mapped.

There are two basic models of statistical runout estimation used in practice: α β and Runout Ratio ($\Delta x/X_\beta$ in Fig. 1). The parameters for these models are determined using one extreme runout in each of many avalanche paths in a mountain range. For both models, the statistical parameters are unique for each mountain range. Both models use the β point as a reference point in the terrain. For tall paths with a vertical fall height > 350 m high, the β point is where the slope incline first decreases to 10° while descending the path centerline. The β point can be measured in the field or obtained from topographic maps or DEMs. β is the angle measured at the β point from a horizontal line to the top of the start zone. α is the angle measured at the extreme runout between a horizontal line and the top of the start zone. For the α β model, the α angle in a specific path is predicted from the measured β angle in the same path using regression parameters from paths in the surrounding mountain range. For the Runout Ratio model, the Runout Ratio for the α point is predicted using parameters from paths in the surrounding mountain range.

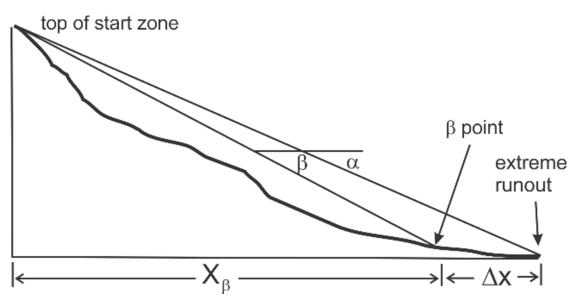

Figure 1. Two-dimensional avalanche path geometry for the center-flow of extreme avalanches.

Non-exceedance probabilities can be calculated for α β or Runout Ratio models. Higher non-exceedance probabilities correspond to longer (more conservative) runout in relation to other paths in the range and are often considered in residential zoning applications.

Both α β and runout ratio models tend to underestimate extreme runouts for shorter paths within the range, so parameters have been developed to apply specifically to shorter paths in some regions.

6 CHAPTER 6 APPLICATION OF CLIMATE DATA

The focus of this chapter is on extreme values of snow supply, which often relate to extreme avalanches. The relevant extremes are maximum values of a snow supply variable such as 3-day snow-water-equivalent or total snow height, for a given return period, e.g. 30 years.

Sources of snow supply variables include manual measurements at snow courses, automated measurements from snow pillows, as well as manual and automated measurements from weather stations above valley bottoms. Interpolated and elevation-adjusted values of these variables, such as from ClimateWNA (Wang et al. 2012), are used increasingly in North America.

Relevant snow climate variables include snowpack height HS or its water equivalent HSW, slab volume, release depth, avalanche volume or mass, 3-day increase in snow height, and monthly precipitation. For planning projects, extreme values of these variables are typically analyzed for return periods of 10 to 300 years. Some guidelines for increasing (or decreasing) some of these variables in slopes in the lee of (or windward to) prevailing winds are included in this chapter.

The chapter identifies some extreme avalanche winters in the mountains of North America and associated atmospheric flow patterns.

The methods for estimating the snow supply variables and adjustments for elevation and wind are empirical, and are often based on limited data. Application of these estimates involves uncertainty, and the fewer the source data, the greater the uncertainty in the estimated snow supply variables. Additional uncertainty arises from the spatial difference between the location where the data were measured, e.g. a snow pillow below treeline, and the location of interest, e.g. a leeward start zone 700 m above treeline and 10 km from the snow course. More expert judgment and – when practical – the inclusion of quantitative confidence, error or uncertainty intervals, are advantageous for the methods and data sources with greater uncertainty.

Some of the snow supply variables such as average release depth, HS and 3-day water equivalent of snowfall for the relevant return period have been traditionally used as design values in calculations of avalanche runout, flow height, mass, etc. Some analysts prefer to consider a range of values to reflect the uncertainty. For some applications, a probability distribution of the snow supply variable — sometimes simulated with the Monte Carlo method — can be useful.

7 CHAPTER 7 AVALANCHE DYNAMIC MODELS

Avalanche dynamic models have two distinct applications:

1. *Direct calibration* where friction coefficients and release parameters are fitted to match a known extreme runout in the path. A directly calibrated dynamic model yields velocity to calculate impact pressure at selected points along the path. Since there are more input variables, e.g. friction coefficients, than known outputs, e.g. runout, the choice of friction coefficients is guided by published values. For models that input the release area and slab height or depth, these inputs are constrained by knowledge of the start zone (Chapter 2) and knowledge of extreme slab depth in the region (Chapter 6). The calculated velocities and impact pressures are applied in Chapters 11 and 12.

2. *Indirect calibration* where friction coefficients from other nearby paths with known extreme runouts and/or published values are adjusted with expert judgement using regional and sometimes local knowledge and then used to predict runout in the path to be mapped (Chapter 11). For models that input the release area and slab height, these parameters are constrained as described above. In a few countries such as Switzerland, friction coefficients and slab heights are regionally well calibrated, which contributes to confidence in predicting runout from dynamic models. However, in many countries, the friction coefficients and slab height or release mass are not well constrained, resulting in decreased confidence in runout predicted by indirectly calibrated dynamic models.

The sensitivity of the output, e.g. velocity at a specified point, to uncertainty in the input parameters, e.g. friction parameters, can be modeled with multiple runs with various input parameters or with a Monte Carlo simulation, which requires that probability distributions of the input parameters be assumed. Sensitivity analysis can improve confidence in the output of dynamic models.

Five dynamic models that are currently used in practice, Voellmy-Salm, PCM, PLK, AVAL-1D and RAMMS, are summarized. All five models use an empirical coefficient for “dry” sliding friction μ_k and another coefficient that is applied to velocity-squared in the underlying equation of motion. All five of these practical models use depth-averaged flow, i.e. they neglect shear within the dense flow.

The Voellmy-Salm model, PCM and AVAL-1D can be run for the dense flow or separately for the powder flow. However, there is less experience with and knowledge of the friction coefficients for powder flow — especially with PCM — than for the dense flow.

PLK and AVAL-1D implement entrainment of additional mass, notably in the lower start zone and track. However, there is currently little validation for any implementation of entrainment.

AVAL-1D and RAMMS allow topography such as the start zone dimensions to be input from a GIS. RAMMS allows orthophotos and maps to be overlaid and areas of vegetation to be defined as areas of increased friction.

Increasingly, visualization of the deposit is proving useful for adjusting the input parameters to match the deposit from an extreme avalanche or, more often, from expert estimation of it. PLK and AVAL-1D output a cross-section of the deposit along the centerline of the path, whereas RAMMS outputs a visualization of deposition on 3D terrain, which can be reviewed in cross-section or across the deposit width.

AVAL-1D and RAMMS allow the practitioner to visualize the flow height along the path, which can be important for tall structures that are vulnerable to an overturning moment.

8 CHAPTER 8 INTRODUCTION TO HAZARD AND RISK ASSESSMENT

This chapter introduces the terminology, concepts and components of avalanche hazard and risk for Chapter 9 (hazard assessment), 10 (risk assessment) and 11 (mapping).

The methods can be either qualitative, semi-quantitative or quantitative, each having their own advantages and limitations.

Uncertainty can be found in most components of avalanche hazard and risk and in the ways the components are combined. Uncertainty – even if it cannot be quantified - should be identified and carried through the stages of assessing avalanche hazard or risk and communicated to the risk owner.

Avalanche problems can be assessed in terms of hazard or risk. More than one scenario may be considered, although this is more common for risk assessments than for hazard assessments. Hazard includes components of avalanche frequency (or likelihood or probability) and magnitude, e.g. destructive size or runout. At its simplest, avalanche risk includes a component for frequency and one for consequence. However, for many assessments, avalanche risk is analyzed with components for

- frequency (or likelihood or probability),
- magnitude (or runout),
- exposure of elements of value (including people), and
- the vulnerability of elements of value

for one or more scenarios, in which the class of magnitude is part of the defined scenarios.

For some avalanche situations and analyses, the components of hazard or risk, e.g. avalanche frequency, exposure, vulnerability, can be quantified as a probability, which requires additional analytical skill and is not always practical. Due to limited data for avalanche frequency, exposure or vulnerability, expert estimation is often required. However, the need for expert estimation in quantitative analysis does not, by itself, mean that qualitative methods are preferable (Ho et al. 2000).

Hazard or risk evaluation, i.e. comparing the output of analysis with criteria, is the final stage of an assessment. Sometimes the hazard or risk is neither tolerable nor acceptable and must be mitigated or the activity discontinued. Sometimes the hazard or risk is tolerable in view of the benefits, in which case the hazard or risk requires ongoing monitoring and review of available mitigation. In other situations, the assessed hazard or risk is broadly acceptable.

The criteria used to evaluate *hazard* are always specific to the activity. The criteria used to evaluate *risk* are sometimes broader. For example, the acceptable risk to life for landslides and snow avalanches can potentially be compared, and the risks due to different hazards can be summed in some cases.

9 CHAPTER 9 HAZARD ASSESSMENT

Avalanche hazard is defined in terms of the spatial and temporal distribution of avalanche magnitude. For land-use planning – the focus of the book – the emphasis is on the spatial distribution of frequency and magnitude of avalanches.

Avalanche hazard assessment consists of the three stages: identification, analysis and evaluation. For land-use planning methods, identification asks the question: Are the terrain and snow climate favourable to avalanches? The hazard analysis typically involves developing a frequency-magnitude distribution over terrain. For the hazard evaluation, the hazard is compared to criteria or thresholds, sometimes provided by the jurisdiction or operational guidelines, that usually results in ratings such as Low, Moderate or High for the application.

Various mitigations are often applied based on the hazard rating and the human activity (e.g. Chapter 9 of CAA 2016). The mitigation can include restrictions on use (prescriptions), which are sometimes provided by the jurisdiction or guidelines, e.g. Swiss (Switzerland 1984) or CAA (2016).

10 CHAPTER 10 RISK ASSESSMENT

Avalanche risk is defined as the combination of avalanche frequency (or likelihood or probability) and consequence for one or more scenarios. The analysis can be qualitative, semi-quantitative or quantitative.

Most qualitative and semi-quantitative risk assessments are summarized in a risk matrix, usually with rows for likelihood or frequency, and columns for consequence. A smaller number of rows or columns often indicates greater uncertainty in the available data or assessment method. When the assessment includes an evaluation of the risk, cells of the matrix can be marked or colored to indicate the level of risk associated with the combinations of avalanche frequency and consequence.

For quantitative assessment, avalanche risk is analyzed in terms of the probability of an avalanche reaching one or more elements-at-risk that are exposed over space and/or time, and the consequences to those elements, for specified scenarios. The risk to property includes the value of the property. The risk of loss of life includes the number of people exposed. Assessment for specific scenarios is advantageous for mitigation planning since the mitigation is often different for frequent, less destructive, avalanches than for larger infrequent avalanches even when these scenarios have the same level of risk. The risk due to all the identified scenarios yields the total risk, which can be compared to the risk due to other hazards or activities, or to the cost of mitigation.

For quantitative methods, vulnerability is defined as the fraction of loss when property is exposed, and probability of death when people are exposed. When people and property are both exposed in the same situation, the risk of death often dominates the risk assessment. Examples of quantitative vulnerability are given for various elements of value including buildings, people in buildings, people in vehicles, and people in the backcountry (terrain where avalanches are not controlled).

Quantitative risk can be visualized - usually for more than one scenario - in a risk graph with axes for probability and consequence. Uncertainty is – ideally – displayed as whiskers or bars extending from the marks for the expected value for each scenario. The tolerable or acceptable level of risk – when it is known – can be shown as a diagonal line drawn on the graph.

The latter part of the chapter includes five illustrations, which show different analytical methods (e.g. qualitative, quantitative with expected values, quantitative with Monte Carlo simulations of uncertainty) and different applications including transmission lines, fixed structures, and transportation corridors.

While this chapter does not include an avalanche risk assessment method for every common situation and application, it does provide a toolkit of assessment methods, which can be adapted to many situations and applications.

11 CHAPTER 11 AVALANCHE MAPPING

This chapter introduces five common types of avalanche maps: locator maps, path maps, terrain class maps, hazard zoning maps, and risk maps. The typical applications, terrain survey level of effort (TSLE), and methods used to prepare the maps are shown in Table 1.

Hazard and risk maps are spatial applications of the assessment methods introduced in Chapter 9 and 10.

For hazard and risk maps, and potentially for path maps, the extent of the center-flow can be estimated in two stages. First, each of the methods/sources is spatially adjusted, usually extrapolated, for the required return period. Second, the confidence in each method/source is assigned a numerical weight and the weighted average is calculated. Where none of the sources/methods have good confidence and the consequence of underestimating the extent of the runout is high, an uncertainty buffer or factor can be applied.

Since hazard mapping is well defined in western Europe and can be applied to zoning for occupied structures where mapping errors have high consequences, the methods for hazard mapping are presented in more detail than for other methods. The methods are illustrated with a hypothetical example.

12 CHAPTER 12 AVALANCHE IMPACT

Impact pressures are proportional to flow density ρ and flow velocity v squared. A coefficient C can be applied to include the effect of flow regime, heterogeneity of the flow, impacted area, structure shape, structure stiffness, structure orientation to the flow, and confinement. Peak impact pressures can be substantially higher than average pressures because of heterogeneities and velocity variations in the flow. The peak pressures from medium to large avalanches are often in the hundreds of kPa.

Table 1. Typical methods and applications for five common types of avalanche maps.

Type of map	Typical methods/ sources for estimating runout	Typical methods of estimating lateral boundaries	TSLE (CAA 2016)	Typical application and return period of boundaries.
Locator	Vegetation damage (trim lines) as seen in photos/imagery, plus expert judgement	n/a	C or D	Early stage of planning. No return period implied.
Path	Vegetation damage plus expert judgement	Vegetation damage plus expert judgement	B to D	Atlases, especially for transportation corridors. Return period typically 100 years for dense flow avalanches.
Terrain class	Expert judgement plus vegetation damage	Expert judgement plus vegetation damage	C or D	Identify areas of terrain for selected factors relevant to avalanching. Backcountry recreation, roving workers, etc. Return period often ~30 years for dense flow avalanches.
Hazard	Expert judgement as well as extrapolation and confidence weighted averaging of written records, vegetation damage, statistical runout models, dynamic runout	Expert judgement, vegetation damage, and optionally a 2D dynamic model	A	Occupied structures, industrial developments. Widely used. Return period for Low hazard zone depends on the jurisdiction but is often 100+ years. Dense flow and powder impact often considered.
Risk	Same as for hazard maps	Same as for hazard maps	A	Same as for hazard maps. Limited use at present.

Simple formulas are presented for avalanche impact on wide structures and drag on narrow structures. For design calculations of impact (normal pressure and tangential stress) on wide structures, drag forces on narrow structures as well as the heights over which these pressures and forces act, design guides such as Jóhannesson et al. (2009) or Rudolf-Miklau (2015) are recommended.

13 CHAPTER 13 STRUCTURAL DEFENCES

Structural defenses are used to reduce the avalanche risk to a wide variety of elements of value, including communication structures, recreationists at ski resorts, towers for passenger ropeways, passengers and vehicles in transportation corridors, as well as occupied and industrial buildings.

Table 2 summarizes structural defenses that are commonly used to reduce the avalanche risk for various applications. The table shows the common applications of structural defenses and where they are commonly located (fetch, start zone, track or runout zone). Protection forests are considered a type of start zone defense structure.

14 CHAPTER 14 TEMPORARY MITIGATION MEASURES

Temporary mitigation measures including warnings, temporary closures and controlled release (intentional triggering) of avalanches depend on avalanche forecasting. Although algorithms exist and are being improved to help forecast avalanches, human forecasters are currently essential to the forecasting process. The inputs to forecasting include weather, observed or modelled snowpack information, and observations or signals from recent avalanches. The spatial distribution of these factors over terrain is complex, but understanding the distribution is important to effective forecasting.

Systems to detect avalanches such as infrasound and radar are increasingly used by forecasting programs, notably for public transportation applications.

During closures, many forecasting programs trigger avalanches intentionally (controlled release), which usually shortens the closure, reducing costs associated with the closure. The chapter includes an overview of many of the methods for intentionally triggering avalanches, including conventional explosive charges that may be placed by ground crews, or deployed from a helicopter. Alternatively, remote avalanche control system (RACS) in or near start zones can trigger avalanches by explosive charges or gas explosions. RACS tend to have higher capital cost but can triggered regardless of daylight or visibility, and often reduce the length of closures because they can be used at the optimal time during or following a storm.

Warning systems for occupied areas are briefly summarized. These systems are currently more common in Europe than in North America.

Table 2. Selected structural defenses and typical placements for various applications
Placement: f = fetch, s = start zone, t = track, r = runout zone. Bold indicates a common defense and location for the particular application.

	Application (elements at risk)						
Structural defense	Transportation corridors, vehicles, passengers	Communication corridor / structures	Ski runs at resorts	Passenger ropeway	Non-occupied buildings	Forests in track or runout zone	Occupied buildings/ occupants
Snow collection fence	f		f	f	f		**f**
Protection forest	**s**	s	s		s	**s**	s
Snow support structures	**s**	s			s	s	**s**
Dikes and deflectors	**t, r**	**t, r**	t, r	**t, r**	**t, r**		**t, r**
Dam	r						**r**
Catchment	**r**						
Splitter		**s, t, r**		**s, t, r**	s, t, r		t, r
Shed	**t, r**						
Retarders	**r**				**r**		r
Ramp					**s, t, r**		t, r
Design and reinforcement		s, t, r		**s, t, r**	**t, r**		**r**

Examples are provided in which temporary mitigation measures have been combined with defense structures to reduce the hazard or risk to people and/or objects of value.

15 OUTLOOK FOR THE BOOK

The e-book and, hopefully, the print book will be available in time for GeoHazards 7 in Canmore, Alberta, Canada.

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REFERENCES

Canadian Avalanche Association (CAA). 2016. *Technical Aspects of Snow Avalanche Risk Management - Resources and Guidelines for Avalanche Practitioners in Canada* (Campbell, C., Conger, S., Gould, B., Haegeli, P., Jamieson, B. and Statham, G., eds.). Canadian Avalanche Association, Revelstoke, BC, Canada.

Canadian Standards Association (CSA). 2010. *Risk management – Principles and guidelines*. CAN/CSA-ISO 31000-10 (International Standards Association 31000:2009, IDT).

Ho, K., Leroi, E. and Roberds, B. 2000. Quantitative risk assessment: Application, myths and future direction. *Proceedings of the International Conference on Geotechnical and Geological Engineering GeoEng 2000*, Melbourne, Australia, Vol. 1, 269-312.

Jamieson, B. (ed.), 2018. *Planning Methods for Assessing and Mitigating Snow Avalanche Risk*, (contributions by Jamieson, B., Jones, A., Argue, C., Buhler, R., Campbell, C., Conlan, M., Gauthier, D., Gould, B., Johnson, G., Johnston, K., Jonsson, A., Sinickas, A., Statham, G., Stethem, C., Thumlert, S., Wilbur, C.). Canadian Avalanche Association, Revelstoke, BC, Canada.

Jóhannesson, T., Gauer, P., Issler, D. and Lied, K. (eds.). 2009. *The Design of Avalanche Protection Dams. Practical and theoretical developments and results.* (contributions by Barbolini, M., Domaas, U., Faug, T., Harbitz, C.B., Hákonardóttir, K.M., Issler, D., Naaim, F., Naaim, M., and Rammer, L.), *European Commission* EUR 23339,

Rudolf-Miklau, F., Sauermoser, S., and Mears, A.I. (eds.). 2015. *The Technical Avalanche Protection Handbook* (English edition). Ernst & Sohn, Berlin, Germany.

Swiss Federal Institute for Snow and Avalanche Research (WSL-SLF). 2007. Defence structures in avalanche starting zones. 134 pp.

Switzerland, 1984. Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten. Bundesamt für Forstwesen, EISLF, EDMZ, Bern, 34 pp.

Wang, T., Hamann, A., Spittlehouse, D.L. and Murdock, T.Q. 2012. ClimateWNA — high-resolution spatial climate data for western North America. *J. Appl. Meteor. Climatol.,* 51: 16–29. doi: http://dx.doi.org/10.1175/JAMC-D-11-043.1