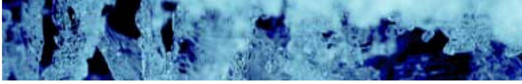

Avalanche risk assessment 3

3.1 PROTECTION FORESTS

In Europe, where extensive forest clearance occurred in past centuries, mid- and upper-slope forest areas are designated as having a "protection" role wherever downslope facilities are deemed to be at risk (Motta et al. 1999). Many villages are located in potential snow avalanche runout zones in the mountainous areas of Europe (Figure 66). Protection forests are not considered for harvest (Stethem et al. 1996). Holler (1994) reports that it may soon be necessary to extend some avalanche zone boundaries because of the deteriorating health of subalpine protection forests in Austria.

FIGURE 66 *Village protected by forest reserved from logging in 1937 following harvesting of adjoining slopes. An avalanche destroyed trees in the left section of the forest in 1951. Thereafter, additional steel supporting structures were built above the residual forest. Reforestation efforts continue.*

Where historic logging or wildfire has created openings in the protection forests, steel snow-supporting structures are often constructed in the start zones to hold snow in place and to encourage the regeneration of dense forest (Figures 67a and b). The design objective is to produce an overall increase in snowpack stability by adding compressive stresses and reducing shear stresses in weak layers. A second objective is to limit the size of any avalanche mass by retarding the motion or arresting it altogether. The design life of structures must be 50–100 years to allow time for new forests to become well established.

In Switzerland, where inhabited areas exist downslope of historically logged areas, slopes that range from 30° to 50° are generally considered to warrant avalanche-inhibiting structures. Structures are constructed up to the elevation of the highest expected fracture line. Continuous lines of structures are constructed across the slope 20–50 m apart. The height of a structure is critical for long-term protection, so detailed snow accumulation studies are undertaken as a part of each design. The criteria for design of the vertical height of structures is that they must correspond to at least the 100-year return period snow depth. Typical structure heights used in the Swiss Alps are 3 m, 3.5 m, and 4 m (Margreth 1996). Trees are planted between and below static defence structures.

a) A network of rigid snow-supporting structures installed to resist snow avalanche initiation.

b) Slab avalanche initiation in area not protected with defence structures.

FIGURE 67 *Avalanche start zone defence structures.*

The Swiss Federal Institute for Snow and Avalanche Research has published standard design specifications in the *Guidelines for Avalanche Protection Utilizing Structures in the Starting Zone* (1990). Installed costs can be of the order of 1 million Swiss francs per hectare (equivalent to about Can. $1 million/ha assuming similar construction costs). Switzerland currently spends 40–50 million Swiss francs annually on afforestation and associated structural measures for avalanche protection (Margreth 2000).

In North America, engineered supporting structures have been employed on very small avalanche paths where property has been placed at risk by logging (Figure 68).

FIGURE 68 *Snow support structures built in an opening above a subdivision, Big Sky, Montana. Forest is slowly regrowing between the structures. Such works require professional engineering design in British Columbia.*

Where life and buildings are potentially at risk, sensible land use planning in the runout zone will often be a much more cost-effective solution than trying to retain snow on open or harvested slopes. In many cases, it will be cheaper to relocate dwellings or realign a road rather than trying to protect against avalanches of Size 3 or greater. The proposed national standard for avalanche hazard mapping in Canada (McClung et al. 2002) stresses the protective role that forests can play.

Wildfire or logging on steep slopes in areas of high snow supply can create openings that avalanche so frequently that regeneration is exceedingly slow. In the Rogers Pass area, forest burnt over 100 years ago has not regrown beyond a sparse cover because of regular disturbance by snow avalanches (Figure 69).

Avalanches in British Columbia Forests

In the Interior Cedar-Hemlock (ICH) zone of British Columbia, it has been estimated that avalanche initiation may be suppressed if the stand density in potential start zones exceeds 1000 stems per hectare once the mean diameter at breast height (dbh) exceeds 12–15 cm. (However, there are no known surveys that confirm this opinion.)

FIGURE 69 *Dense forest that originally extended to the ridgetop west of Rogers Pass was probably destroyed by fire when the railway was built in 1885. The original railway track was at the bottom of the slope. Construction crews of the era often set the forest on fire to clear the area. Forest not burnt during construction often caught fire later from sparks released by steam engines.*

Projected stand information can be of value when considering the long-term avalanche risk associated with forest harvesting. A block's site index (a measure of optimum tree growth at the 50-year age class) is largely dependent on elevation, aspect, and soil type (Thrower et al. 1991), and can be used to predict rate of regrowth following replanting (Figure 70).

It is suggested that the reduction in avalanche potential in regenerating forests is due primarily to the effect of the canopy projecting above the snow surface, which alters the energy balance and layering of the snowpack. Reduction or elimination of processes that promote surface hoar formation are critical in the Columbia Mountains in particular. Mechanical reinforcement on the snowpack by trees is considered to be a secondary effect.

Successful forest re-establishment will, in the great majority of cases, eliminate the risk of further avalanches. Avalanche initiation is considered to be less likely when tree heights are greater than three times the maximum snow depth. Destructive avalanches start in standing timber only in exceptional circumstances. Conversely, the occurrence of one Size 4 avalanche may lead to permanent site degradation (soil loss) and inhibit forest regeneration.

Interpretation of the output of the forest growth modelling scenario in Figure 72 suggests that the avalanche potential will decrease markedly at

30–50 years after replanting, provided that no avalanches damage restocked areas in the interim.

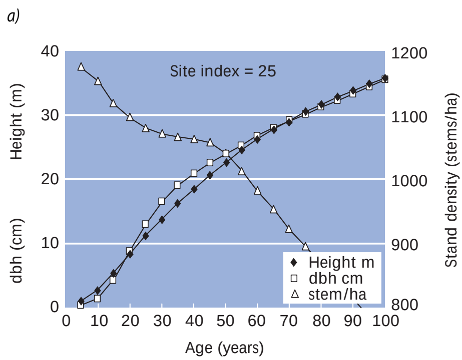

FIGURE 70 *Projections from TIPSY growth model (B.C. Ministry of Forests 1997). Curves are for a) a typical ICH valley floor site and b) a near-timberline site (site indices of 25 and 10, respectively).*

FIGURE 71 *Small avalanches may run regularly in long narrow gullies, but theses events are unlikely to have enough mass to cause significant damage or resource loss.*

3.2 AVALANCHE RISK CLASSIFICATION

Forestry work in British Columbia typically uses a simple engineering risk model whereby hazard and consequence are independently evaluated. "Hazard" is defined as the likelihood, or probability, of an event (MoF *Forest Road Engineering Guidebook* 2001; landslide risk chapter). Avalanche technicians in the province understand "hazard" to mean the potential to inflict death, injury, or loss to people or to the environment. Unless recognized, this difference in definition of "hazard" may lead to confusion when discussions are conducted between experts from forestry and avalanche disciplines.

Risk Assessment

The proposed Canadian national avalanche risk standard quantifies risk as the combination of avalanche frequency and magnitude (McClung [2002]). In the forest sector, avalanche risk assessments are required to address:

- Long-term (or spatial) problems, where the concern relates to prediction of future avalanche susceptibility (e.g., where an avalanche start zone might be created by forest harvesting or fire, at some time in the future, on previously unaffected terrain).
- Short-term (or temporal) problems, where the

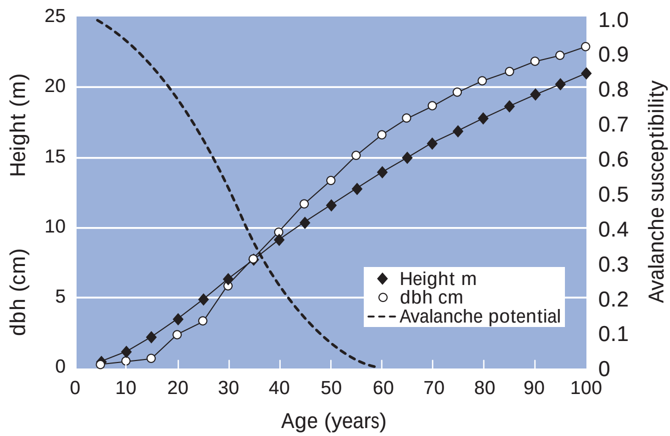

FIGURE 72 *Conceptual model of avalanche susceptibility in a regenerating opening in steep terrain with regular, high snow supply. Note that the precise shape of the "avalanche susceptibility" curve (dotted line) cannot be defined at this time. Tree height and dbh modelled for an ICH stand planted at 1400 stems/ha with site index 13; typical midslope cutblock regrowth. (Projected dbh and height from TIPSY growth model, B.C. Ministry of Forests 1997.)*

concern relates with real-time avalanche assessment and forecasting in recognized avalanche terrain. Public and worker safety, and resource protection, are key issues.

FIGURE 73 *Damage in a regenerating cutblock from a small avalanche that initiated in a clearcut above. Many similar small events go unnoticed each winter.*

In this handbook, the term "likelihood" is defined as an "expert's degree of belief" that an event will occur in a specified time period, given various data and site-specific information (Edwards 1992, p. 9; Vink 1992; Einstein 1997; McClung 2001a). When assessing snow avalanche risk, an expert will draw on background knowledge and experience, principles of engineering and geoscience, and site-specific climate and terrain information to assess the likelihood of an avalanche occurrence within a given spatial and temporal setting (Table 11).

Bayes' theorem may be used in avalanche risk assessment, to enable observational information to be combined with professional opinion, quantified as a subjective probability (Wu et al. 1996; Einstein 1997).

Tables 11–13 present an avalanche risk assessment method that is used to rate the avalanche risk prior to harvesting. The assessment equation has the form: risk = (frequency) × (magnitude [i.e. expected damage]).

At the landscape level, the key question to address in the Forest Development Plan is whether snow avalanches will initiate if clearcut harvesting is undertaken and, if so, what the consequences will be. During the planning process, it should be possible to locate mainline and secondary roads to minimize the avalanche risk. It is recommended that avalanche frequency be considered over the length of time that it will take for a closed-canopy forest to develop above the height of the 30-year maximum snowpack. That time will depend on the block's site index.

A detailed risk assessment should be undertaken during block layout, ideally as part of the terrain stability field assessment, before specifications for the silviculture prescription are completed. Avalanche runout modelling should be undertaken for any downslope element at risk (e.g., a railway, highway, road, transmission line, fish stream, or water intake on a stream) and an estimate made of the vulnerability of that facility or feature. Measures to mitigate avalanche hazards faced by workers in winter should be addressed during preparation of the silviculture prescription.

TABLE 11 *Estimate of avalanche likelihood from site-specific observations and analysis of climate data*

Likelihood	Frequency range (one event in period)	Annual avalanche frequency	Description
Near certain	< 3 years	1:1	The event will probably occur in most circumstances.
Likely	3–30 years	1:10	The event should occur at some time (highly likely in a human lifetime).
Unlikely	30–300 years	1:100	The event may occur at some time (unlikely in a human lifetime).

The risk analysis matrices presented in Tables 12 and 13 can be used to rank both short- and long-term risk, but different management responses are appropriate, as recommended in Table 4.

Assessing Risk to Forest Cover

To prevent damage to the forest cover, the recommended acceptable risk 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 risk matrices below are constructed on the basis of three orders of magnitude, avalanche frequency, and consequences rated qualitatively (proportionally to the risk). Risk of damage to forest cover is rated as low (L), moderate (M), and high (H).

TABLE 12 *Risk ratings for expected avalanche size and expected avalanche frequency for forest harvest resulting in damage to forest cover (source: McClung [2002]). Risk is rated qualitatively as low (L), moderate (M), and high (H)*

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

[a] The proposed Canadian national avalanche risk standard for forest harvesting (Size 3 with 10-year return period; bolded), is considered to be on the border between moderate and high risk (McClung et al. 2002). However, due to uncertainty in the estimate, other categories have the same moderate risk rating. Moderate risk will normally warrant modification of the harvest design.

Notes:

- For damage to forest cover, the risk is nominal for avalanches of less than Size 2 (see p. 19 for avalanche size definitions).
- Avalanches of Size 4 or larger are unacceptable at any return period following logging. Size 4 avalanches initiating in cutblocks can create permanent new avalanche terrain by degrading soil and vegetative cover, which is unacceptable in an environmental standard. Size 4 avalanches may introduce significant amounts of soil, rocks, and logs to stream channels. The effects may be similar to large debris flows.
- 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).
- There may be additional site-specific instances where a Size 2 avalanche, at a 1 year in 10 return period, may pose risk to downslope or in-stream values, such as critical fish spawning reaches or locations where a stream blockage or avulsion is likely. In such instances the risk may be revised upwards, based on professional judgement.

Assessing Risk above Transportation Corridors, Facilities, or Essential Resources

When downslope transportation corridors (e.g., highways or railways), facilities (e.g., occupied or unoccupied structures), essential resources (e.g., registered community, domestic, or commercial 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. For this application, the recommended acceptable risk is a Size 3 avalanche with an average frequency of less than 1:30 years, or a Size 2 avalanche with an average frequency of less than 1:3 years. Table 13 shows the applicable risk matrix analogous to Table 12 for timber resources.

TABLE 13 *Risk ratings for expected avalanche size and frequency for forest harvest when downslope transportation corridors, facilities, or essential resources may be affected (source: McClung [2002]) Risk is rated qualitatively as low (L), moderate (M), and high (H)*

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

[a] The reference level of risk (Size 3 with 30-year return period; bolded) 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.

Notes:

- In the applications described (damage to downslope resources), the risk is minimal for avalanche sizes less than 2.
- 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 12.
- 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 downslope resource. 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.

Consequence

The revised *Forest Road Engineering Guidebook* (B.C. Ministry of Forests 2001) contains an in-depth discussion of landslide consequence and presents a matrix-based rating system, which differentiates between on-site, downslope, and downstream elements at risk. In the proposed Canadian national avalanche risk standard employed herein, impact forces and runout distances are modelled to determine consequence (McClung [2002]).

Figure 74 illustrates a potential snow avalanche situation where consequence varies markedly depending on what element at risk is under consideration.

TABLE 14 *Examples of risk management strategies*

		Appropriate risk management strategy	
Level	**Risk**	**Protection of forest resources Protection of environment**	**Public and operational safety issues**
H	High	Avoid development or forest harvesting. Mitigation or remediation usually too expensive compared to economic returns.	Risk to forest workers, downslope transmission and transportation corridors, or residents is unacceptable. Avoid.
M	Moderate	Qualified registered professional to assess avalanche risk during a terrain stability field assessment by estimation of destructive potential and return interval of avalanches at point of interest. Elements at risk identified and their vulnerability evaluated. Modification of clearcut harvesting prescriptions developed to reduce likelihood of avalanche initiation or lateral or lineal extension of existing avalanche paths. Roads and bridges relocated.	Responsibility for snow stability and avalanche danger should be clearly specified. Senior management committed to development and maintenance of avalanche safety program. Temporary shut down procedures accepted as part of work program. Risk may be avoided by scheduling harvesting for summer. Experienced avalanche technician with CAA Level 2 qualification retained to implement efficient avalanche control and closures.
L	Low	Quantify and accept the risk.	Manage risk by standard occupational health and safety regulations and safe work procedures.

Risk Management Strategies

Risk management strategies often draw a distinction between:

- High Likelihood – Low Consequence events and
- Low Likelihood – High Consequence events

Different risk management responses are often warranted for each of the combinations (Strahlendorf 1998) (Table 15).

FIGURE 74 *Any avalanche originating in this cutblock will be of low consequence with respect to the timber resource but the consequences for traffic hit by an avalanche on the road will be very high because of the water body below.*

TABLE 15 *Appropriate risk responses (source: Elms 1998)*

	Consequence	
Likelihood	**High**	**Low**
High	Avoid or reduce risk	Adopt quality safety management systems
Low	Treat very carefully Reduce consequence	Accept risk

The avalanche risk on snow-covered slopes over 60% can seldom, if ever, be reduced to zero (Figure 75). Whenever risk is judged to be excessive, reduction strategies generally adopt the "ALARP" principle: the residual risk should be "As Low As is Reasonably Practicable" (Canadian Standards Association 1997; Keey 2000). Fell and Hartford (1997) distinguish between risk tolerability and acceptability for developments in British Columbia.

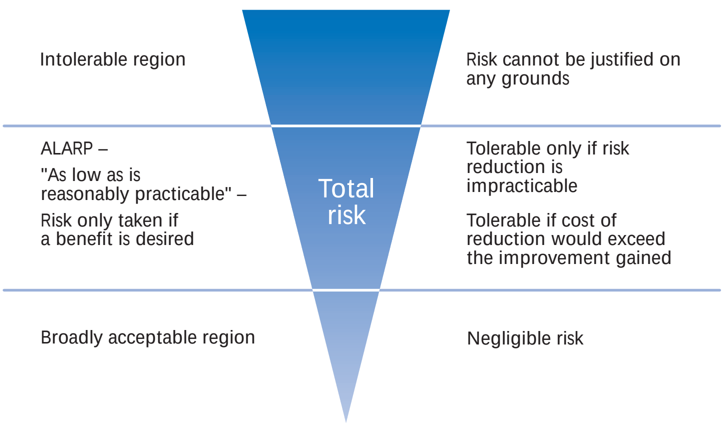

FIGURE 75 *ALARP framework for risk assessment and reduction. (After Canadian Standards Association 1997, p. 25; Morgan 1997)*

Risk management typically involves six steps (Figure 76). Risk communication with all stakeholders is an important part of each step.

Risk assessment is regarded as a continuous iterative process (Figure 77). The monitor and review process is important because ongoing forest development may increase the avalanche risk over time. Review gives management verification as to the success of risk reduction strategies in use. Continuous risk assessment not only applies to the day-to-day evaluation of snow stability and avalanche danger, but also to the overall avalanche risk in an operating area over time.

Forest managers should watch for "insidious" risks that may develop as harvesting moves onto higher, steeper terrain or, locally, where steep blocks are harvested above camps, mills, scales, residential areas, transportation corridors, bridges, or power lines.

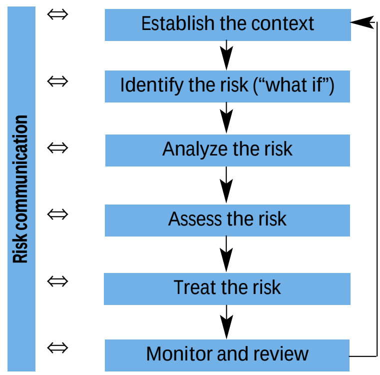

FIGURE 76 *Steps in the risk management decision-making process. (After Canadian Standards Association 1997, p.7; Keey 1998)*

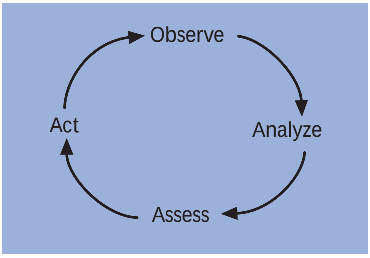

FIGURE 77 *Process of continuous risk assessment. (Elms 1998)*

Once a detailed risk assessment is complete, an experienced avalanche practitioner should be consulted to develop a suitable winter safety program.

Responsibility for Risk Management

Avalanche risk management is everyone's responsibility. Risk management should be integrated and owned throughout a company or operation. A sound objective is to develop a corporate safety culture above and beyond Workers' Compensation Board requirements. There should be one, clearly identifiable individual who assesses the overall situation each day during the avalanche season. That person shall be referred to as the "officer responsible for avalanche risk management." In larger organizations, that officer does not do all the work, but provides policy and advice on setting up risk management systems and then monitors what is being done.

An avalanche accident and incident log should be maintained to assess the frequency of avalanche hazards encountered in the forest. A proactive approach to record-keeping will function only if the workers and management view the process in a positive light with an objective of improving occupational health and safety. Contractors should not be penalized for tracking or reporting incidents or for making conservative decisions regarding their own safety.

Accident and Incident Logs

It must be recognized that while an incident and accident log can help a forest company plan its response to the avalanche hazard, it may fail to give adequate warning if the operating environment changes. Logging operations moving into steeper terrain or higher elevations, or operations that encounter an unusual combination of weather and snowpack conditions, may face an abrupt increase in the avalanche risk.

Many studies of industrial accidents indicate that a large number of non-injury incidents are precursors of accidents and fatalities (Figure 78).

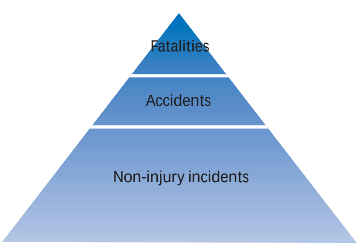

FIGURE 78 *Typical ratios of non-injury industrial incidents to injurious accidents and to fatalities.*

3.3 OWNERSHIP OF RISK IN FOREST OPERATIONS

It is recommended that an overview avalanche risk assessment be undertaken for portions of the operating area, as a part of "total chance planning," where harvesting is planned for slopes steeper than 30° (58%), especially in areas of high snow supply. This may be achievable by a combination of air photo interpretation, GIS analysis, and limited field verification. In high snow supply areas, it is appropriate for the qualified registered professional to incorporate a more detailed avalanche assessment at the block level as a part of a terrain stability field assessment.

During the harvest period, forest licensees or their contractors are required by law to take responsibility for avalanche hazards encountered during the winter and spring period. See Occupational Health and Safety Regulations 26.17 and 26.18 (Appendix 1).

With sound risk management policies, management commitment, staff training, and safe work procedures in place, avalanche risk can be managed successfully in winter operations (Figure 79).

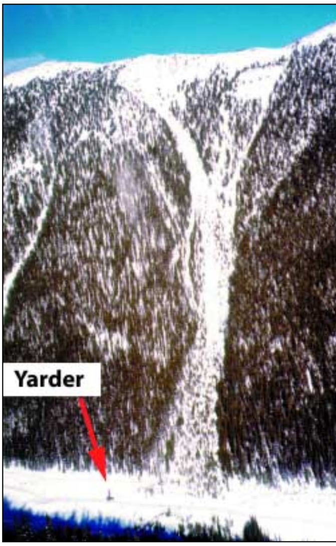

FIGURE 79
Managing the avalanche risk at a logging operation at Doctor Creek, southeast B.C. A yarder is working in the runout zone of a series of steep avalanche paths to winter harvest a block immediately below the photographer. Workers were trained in avalanche safety and rescue, and safe work procedures were implemented. Daily weather and avalanche observations were made and twice-weekly snow profile studies undertaken. Explosives used under controlled conditions triggered three avalanches (Size 1 and 2) from the large avalanche path above this work site.

At present it is not clear who owns the longer-term avalanche risk posed to downslope resources and facilities, especially in relation to logging on private land in British Columbia (Figure 80). The avalanche risk typically lasts for two or more decades until regrowth is sufficiently tall and dense to reduce the susceptibility of the area to generating large slab avalanches. In most forest tenures, the licensee's responsibility ends when the plantation becomes "free growing," which occurs well before avalanche susceptibility returns to preharvest levels. In a few cases, soil erosion by snow avalanches may mean that a forest will be very slow to regrow on newly formed avalanche paths and that the avalanche risk may endure for several decades.

3.4 LOGGING ABOVE HIGHWAYS

An interagency protocol, signed in 1992 by the B.C. Ministry of Transportation and Highways and B.C. Ministry of Forests, exists to minimize instances of increased snow avalanche risk posed to users of highways and transportation corridors in the province (Figures 81–83).

Under the protocol agreement, the Ministry of Forests is obliged to identify proposed cutblocks with the potential to generate avalanches that may reach a highway. In addition, the ministry is obligated to consult with the Ministry of Transportation over the licensee's Forest Development Plan and Logging Plan.

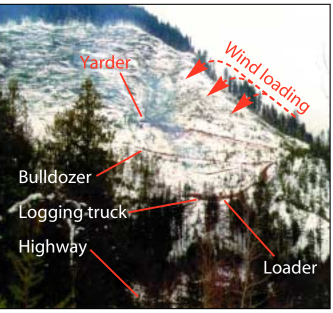

FIGURE 80 *Winter operations in potential avalanche terrain on private land at Enterprise Creek, Slocan Valley. The gully in which the yarder is working is likely to be subject to snow loading by the prevailing wind and may be prone to avalanching. Workers in the area may be at considerable risk unless daily snow stability evaluations are undertaken and safe work procedures are adopted. Avalanches from this path may pose a hazard to the travelling public on the highway below for two or three decades following harvest.*

FIGURE 81 *Steep terrain in a recently harvested cutblock on private land above Enterprise Creek may produce avalanches that run onto Highway 6. Who owns the risk?*

FIGURE 82 *Avalanches initiating in the steep harvested terrain above the Trans-Canada Highway in the Kicking Horse Canyon have the potential to affect the highway even though the area is not often subject to deep snowpacks.*

Risk Management Objectives

To minimize risk, the potential for logged slopes to avalanche must be addressed when planning a timber harvest.

The following benchmarks are offered as risk management objectives. The objectives acknowledge that there is residual risk associated with avalanche forecasting and control. The objectives are not intended to replace Workers' Compensation Board regulations (Appendix 1), which require due diligence and a high standard of care.

1. ***Workers on foot should not be put at risk of being involved with avalanches that could cause burial or injury.***

Objective: ***No avalanches greater than Size 1.5.***

2. ***Workers in trucks, industrial, or maintenance equipment should not be put at risk of being involved with avalanches that could damage a pick-up truck.***

Objective: ***No avalanches greater than Size 2.5.***

3. ***Avalanches of any size, resulting from explosive-based avalanche control should never run out onto a forest road or highway that is open to the public or industrial traffic, or onto occupied land.***
4. ***Avalanches triggered with explosives should, at most, cause only minimal damage to trees or minimal soil loss in or below any cutblock.***

Objective: ***No avalanches greater than Size 2.5.***

Note: No objective can be set for consequences of avalanche control undertaken in existing paths where natural avalanches have previously affected the forest.

These objectives were developed in consultation with participants of a workshop held in Revelstoke on March 16, 2000. Refer to Table 4 for details of the Canadian avalanche size classification system.

Two criteria are defined in the protocol by the Ministry of Transportation's Snow Avalanche Program:

- Maximum winter snowpack is greater than 0.5 m (a return period is not defined)
- Sighted angle from road to the top of block is greater than 25° (47%)

Foresters and consultants who undertake harvest planning and cutblock layout work in avalanche-prone terrain above highways or other facilities should consider the protocol methodology (Figure 84). An algorithm can readily be implemented in a geographic information system to identify potential areas of concern above public highways, railways, power transmission lines, or inhabited areas. A qualified registered professional should undertake on-site avalanche assessment and calculate the avalanche runout potential as a part of a detailed Terrain Stability Field Assessment for proposed cutblocks. A risk analysis should be undertaken for cutblocks that have the potential to reach the highway (see Table 13). The analysis should consider the exposure and vulnerability of persons or facilities.

FIGURE 83 *Harvesting was proposed in an even-aged pine forest along Highway 3 west of Castlegar, where red trees indicate insect attack. Inspection of the steep open talus slopes above the highway showed that avalanches impact the upper edge of the forest. Runout modelling indicated that avalanches initiating at the top of the steep open slopes and running on a smooth snow surface (e.g., where stumps and logging slash are buried by a deep winter snowpack) could reach the highway. Snow supply in the area is moderate. The south-facing aspect makes wet avalanches probable in spring. A risk analysis was undertaken to estimate the likelihood and expected frequency with which avalanches might reach the road edge. Mitigative measures proposed included retention of a timber buffer. Foresters then had to evaluate the potential for retained trees to succumb to insect attack.*

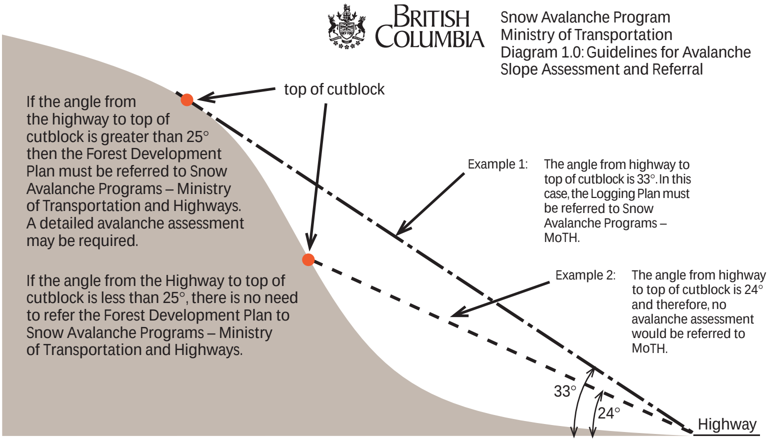

FIGURE 84 *Method used by MoF and MoT to identify proposed harvest blocks that may generate snow avalanches that could run out on public highways (25° = 47%). (Note: Protocol may be subject to revision. The term "logging plan" is now obsolete; the Forest Development Plan should be referred to the Ministry of Transportation.)*

TABLE 16 *Mapping methods that may be applicable for use in snow avalanche–prone terrain (after Gerath et al. 1996)*

	Name	Example	Strengths and weaknesses of method
A	Event Distribution Analysis	Avalanche atlas (Fitzharris and Owens 1983)	• Objective and qualitative • Creates a useful database of existing avalanche paths • Does not predict likelihood of new start zones being formed in harvested terrain
B	Event Activity Analysis	Inventory map drawn from a series of old air photos or from avalanche observation database	• Objective and qualitative • Creates a useful database of avalanche paths. Documents activity at different time periods • Does not predict likelihood of new paths being formed in harvested terrain
C	Event Density Analysis	Mapping of paths per unit land area (km^2); "susceptibility" mapping	• Objective and qualitative • Creates a useful database of avalanche paths. Some predictive value • Does not account for snow supply gradients caused by orographic enhancement of precipitation
D	Subjective Geomorphic Analysis	Polygon-based mapping; interpretation of slope, elevation, aspect, land form and length of fetch; French "Probable avalanche location" maps (Borrel 1992)	• Subjective, qualitative, and flexible • Terrain stability/avalanche hazard class criteria are often unspecified • Requires expert skill and judgement • Creates a useful database of avalanche paths and some terrain attributes • Difficult to review
E	Subjective Rating Analysis	Likelihood mapping; Hazard rating algorithms are developed for local areas and applied via GIS (Kelly et al. 1997)	• Subjective and qualitative to semi-quantitative. Flexible • Specified terrain stability/avalanche hazard classification criteria are often unspecified • Requires skill and judgement of an avalanche expert • Work can be delegated and checked. • Creates a useful database of many relevant terrain attributes • May present danger of over-simplification
F	Relative Univariate Analysis	Mapping based on statistically significant correlation of slope angle with avalanche occurrence	• Objective and qualitative to semi-quantitative • Relatively statistically based • Shows effect of individual terrain attributes • Data- and analytically intensive • Relies on quality data

TABLE 16 *Continued*

	Name	Example	Strengths and weaknesses of method
G	Probabilistic Univariate Analysis	No known examples	• Objective and quantitative • Probabilistic–statistically based • Simple to implement and test • Danger of selection of wrong terrain attributes • Data- and analytically intensive • Relies on quality data
H	Probabilistic Multivariate Analysis	Mapping based on statistically significant correlation of several terrain variables (slope angle, elevation, aspect) with avalanche occurrence	• Objective, and quantitative, precise • Probabilistic–statistically based • Danger of selection of wrong terrain attributes • Removes experience and judgement of mapper • Relies on high-quality data • Analytically intensive
I	Slope Stability Analysis	Stochastic modelling using Monte Carlo simulations; factor of safety approach (Conway and Wilbour 1999; Conway et al. 2000)	• Objective, and quantitative, precise • Can be reviewed • Difficult to use for mapping a large area • Shows influence of terrain attributes • Requires precise estimates of slope geometry, snow strength properties, and weather conditions • May not be process driven • Danger of oversimplification
J	Hazard Consequence	Consequence mapping	• Subjective and qualitative • Simple; no separate mapping required • Runout characteristics not mapped
K	Runout Zone	Swiss (red, blue, yellow, white) zoning maps; Icelandic risk maps, (Keylock et al. 1999)	• Method can be subjective or objective, qualitative, semi-quantitative, or quantitative • Simple to complex delineation of risk zones • Practical for planning decisions
L	Linear Path Movement	Norwegian Geotechnical Institute mapping (Lied et al. 1989)	• Subjective and qualitative • Suited to linear movement • Field-intensive and analytically intensive • Relies on quality data
M	Linear Risk Mapping	Highway avalanche risk map (McClung and Navin 2002)	• Suited to linear transportation corridors • Field-intensive and analytically intensive • Relies on quality data

Where the slope within the proposed block is less than 25° (47%), the likelihood of avalanche initiation may be low or very low, though the likelihood rises rapidly for slopes above 30° (58%). Alternatives to large clearcuts may be appropriate in higher-risk situations. In some cases, the risk to life and limb or potential liability may be too great.

3.5 AVALANCHE MAPPING

Mapping of existing avalanche paths is useful for identifying risks to worker safety, especially on winter access roads. Mapping of areas that have the potential to generate avalanches following timber removal is a much more difficult task.

Identifying avalanche-prone terrain is a strategic tool for assessing the long-term risk following forest harvesting. At present, there is no widely accepted method of mapping post-harvest avalanche risk. The following discussion gives some ideas of possible approaches (see Table 16).

The Ministry of Forests inventory mapping of environmentally sensitive areas (ESAs) includes snow avalanche susceptibility (ESA-Ea). In practice, ESA mapping for avalanche risk is seldom used and has not been applied consistently across the province (P. Jordan, MoF, pers. comm.). The British Columbia terrain classification system presents a classification and a single on-site symbol for snow avalanches (Howes and Kenk 1998) (Appendix 6). To date, most avalanche mapping undertaken in the province's forests relates to geomorphic processes as opposed to avalanche susceptibility or risk.

No agreed standard has been set for avalanche susceptibility mapping within the province, a situation similar to that existing for terrain mapping in the 1980s. By contrast, European cartographers have developed a broad range of mapping symbols (e.g., Borrel 1992; Lambert 1992).

Mappers and forest managers should review the merits of the various methods listed in Table 16 before initiating major projects. Management objectives, expectations, and outcomes should be carefully defined before mapping is undertaken. Mapping of existing avalanche paths is straightforward; the challenge is to map the terrain factors that might become start zones if the forest were removed.

Air Photo Interpretation

Oblique colour photographs taken in the spring from fixed-wing aircraft or helicopters are very useful at the start of an investigation into avalanche activity in an area. Active start zones may become bare much earlier than adjacent slopes of similar aspect because much of the snowpack may be removed by avalanching. By contrast, avalanche deposits may remain in the valley floor and gullies long after the snowline has receded up a mountain or melted from all but high-elevation, shaded alpine cirques and plateaus.

Avalanche mapping projects generally begin with the stereoscopic interpretation of vertical air photographs and with the study of topographic maps (Figure 85). The air photo interpreter should have experience in identifying avalanche start zones and tracks in the field and have an understanding of the processes involved in the formation and motion of avalanches. Inferences made during air photo interpretation should be

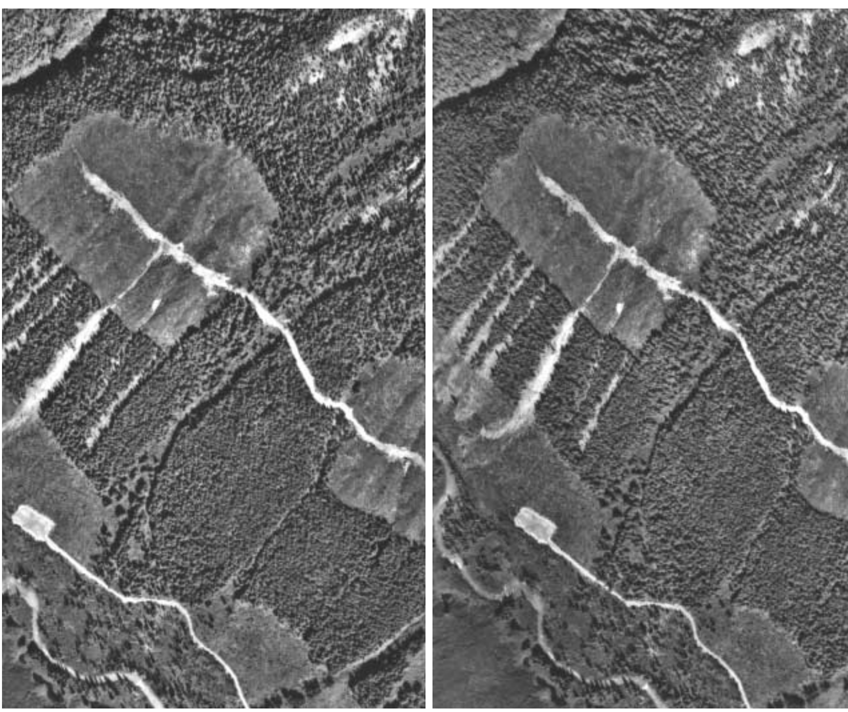

FIGURE 85 *Stereopair of Nagle Creek avalanche path. A low-power pocket stereoscope is required to see the terrain in three dimensions. Scale approximately 1:15 000 (Airphotos 30 BCB97061 nos. 272 and 273).*

verified in the field. Conclusions should be reached only after one has taken into account a combination of clues and considered the interactions of terrain and vegetation.

Use of air photos at a scale slightly larger than that of the finished map is preferred. Small-scale photos from high-level flights (scale between 1:25 000 and 1:80 000) allow the identification of paths in avalanche-prone areas and the study of complete individual paths. Large-scale photos taken from low-level flights (scale between 1:10 000 and 1:25 000) are best suited for detailed study of avalanche start zones, tracks, and runout zones. Air photos are usually taken late in the summer when the area of interest is free of snow. Colour photos are helpful when available, but black-and-white photos are satisfactory.

Small-scale Terrain Features

The forest cover on air photos often conceals many small-scale terrain features.

Air photo interpretation of potential avalanche terrain under a forest cover is unlikely to reveal the details of the steepness of the terrain, the slope breaks, the shallow gullies, the rock bluffs, and surface roughness. These detailed terrain features may contribute to generating potential avalanches once the forest cover is removed, and should be assessed in the field.

Examining older, monochrome, vertical air photos (if available), can give interpreters an appreciation of the growth and age of the forest in avalanche paths, which in turn can lead to inferences about the frequency of major avalanche occurrences and/or the degree of vegetative recovery.

Avalanches that initiate in the alpine zones but descend through the forest are usually obvious. Avalanche start zones located within the forest cover are less distinct. However, subtle changes in the height, grey tone or colour, and density of the trees or other vegetative features can provide good clues to experienced air photo interpreters. Short paths, where avalanches may initiate from over-steepened road cut-banks or in small shallow channels, may not be identifiable on large-scale vertical air photos.

Field Checking

Air photo interpretations and mapping should be field verified at an appropriate terrain survey intensity level. The *Mapping and Assessing Terrain Stability Guidebook* (B.C. Ministry of Forests 1999) discusses terrain survey intensity level in relation to map scale. For 1:5000 to 1:10 000 scale mapping projects, Ryder (2002) recommends ground checking 75–100% of terrain polygons. For these scales, terrain polygons will be in the order of 2–5 and 5–10 ha, respectively.

Ortho-rectified, monochrome air photos (orthophotos), overlain with the B.C. 1:20 000 scale Terrain Resource Inventory Map (TRIM) digital contour data, can be used very effectively with a planimeter and scale rule to determine start zone and runout zone areas, slope angles, and lengths of avalanche track. Avalanche paths outlined on orthophotos can be digitized and the underlying TRIM data used to plot longitudinal profiles and to calculate areas (Figure 86).

Orthophotos overlain with TRIM contours, enlarged to 1:10 000 or 1:5000 scale, are useful for marking positions and noting the location of small gullies and other features. However, such mapping is no more accurate than 1:20 000 TRIM; it is simply easier to use in the field.

During field inspection, a detailed road survey should be undertaken. It should focus on specific features such as steep cutbanks, over-steepened fill-slopes, rock bluffs, gully or other channel crossings,

Map Scale

It is important to recognize the limitations of information portrayed on maps in relation to scale. For example, 1:20 000 TRIM data often fail to show local scale features such as steep gullies, rock bluffs, and road cutslopes. Topographic mapping at 1:5000 scale should be commissioned when working in high-consequence areas.

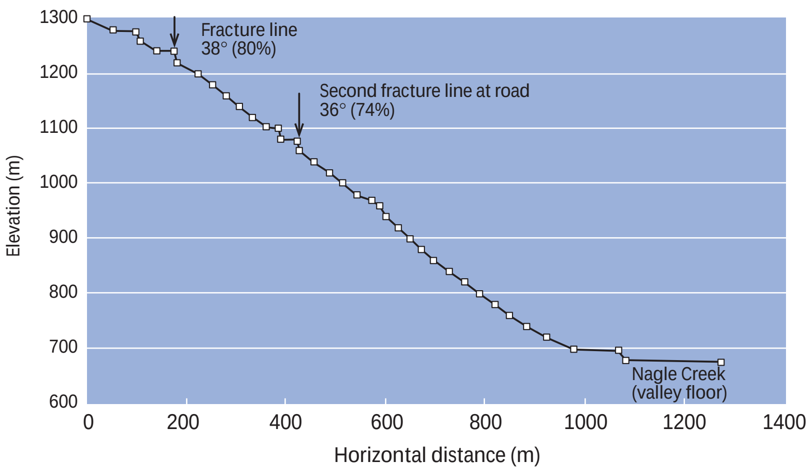

FIGURE 86 *Slope profile of the Nagle Creek avalanche path plotted from 20-m TRIM contours.*

and existing avalanche path crossings. The road distance (kilometre) position of these important features should also be noted. The location of the road with respect to the cutblock (e.g., whether the road traverses the top, centre, or bottom of steep cutblocks). A pocket stereoscope and air photo stereopairs should be taken into the field for reference and corroboration.

The Canadian Avalanche Association's *Guidelines for Avalanche Risk Determination and Mapping in Canada* (McClung et al. 2002) and a Joint Practice Board skillset for snow avalanche assessments (JPB 2002) presents guidance for qualified registered professionals carrying out Terrain Stability Field Assessments in snow avalanche-prone terrain.

Avalanche Mapping for Land Use Planning

Switzerland

In Switzerland, where the observational record of avalanche activity spans many centuries, avalanche mapping incorporates a zoning based on a calculation of impact pressure and an estimate of return period. These are:

- High hazard (Red) zone—an area where impact pressures are greater than 30 kPa, with an annual exceedance probability of up to 1 in 300; or any area likely to be affected by any avalanche with an annual exceedance probability of more than 1 in 30. New buildings and winter parking are prohibited. Existing buildings must be protected and evacuation plans prepared.
- Moderate hazard (Blue) zone—areas affected by flowing avalanches where the maximum impact pressure is less than 30 kPa, with an annual exceedance probability of 1 in 30 to 1 in 300, or any area likely to be affected by powder avalanches with impact pressures less than 3 kPa. Public buildings where people may gather should not be constructed. Special engineering designs are required for private residences. The area may be closed during periods of avalanche danger. Evacuation plans must be prepared.
- Low hazard (Yellow) zone—an area where flowing avalanches are possible, with an annual exceedance probability of less than 1 in 300 (i.e., rare); any area likely to be affected by powder avalanches with impact pressures of less than 3 kPa with an annual exceedance probability of less than 1 in 30. Structural defence measures may be recommended.
- No hazard (White) zone—an area where there are no building restrictions.

Gruber and Bartelt (2000) describe how the Swiss zoning system performed when tested by the severe European winter of 1999. Deficiencies in the delineation of Yellow zones were noted and attributed to the under-estimation of runout distances.

Norway

The Norwegian Geotechnical Institute (NGI) has undertaken overview mapping of avalanche areas (on 1:50 000 scale, 20-m contour interval base maps) using computer digital terrain modelling techniques (Lied et al. 1989). Potential start zones are identified as areas steeper than 30° (58%) and not covered in dense forest. Potential avalanche trajectories are drawn downslope from previously identified start zones by an operator at a computer workstation. The system computes a longitudinal profile, then calculates the maximum probable avalanche runout distance based on the alpha and beta angle (α and β) slope profile analysis method (Lied and Toppe 1989; see Figure 30).

All NGI maps are checked against stereopairs of vertical air photographs to verify the reasonableness of the modelled runout. The maps are then field-checked. The maps do not contain any information on avalanche frequency. No distinction is made between avalanche paths that run once in 100 years and those that may run annually. (Note: Use of the alpha-beta model implies an annual probability of 1:100.)

The NGI notes that the use of 20-m contour base mapping creates an inherent weakness (in common with TRIM map data) in that locally steep slopes with a vertical interval of up to 20 m may not be identified.

France

In France, mapping of "probable avalanche paths" is undertaken at scale of 1:25 000 (Borrel 1992; Furdada et al. 1995). Conventional avalanche maps produced by a combination of fieldwork and air photo interpretation have been integrated with digital terrain modelling analysis of avalanche runout using the NGI's techniques. The French maps display the expected maximum runout, but do not contain information on impact pressure or frequency (Figure 87).

Note: Avalanche mapping systems are currently under review in several European countries, as large avalanches have overrun previously mapped runout boundaries. Recent avalanche disasters have occurred in both France and Austria (Lambert 2000).

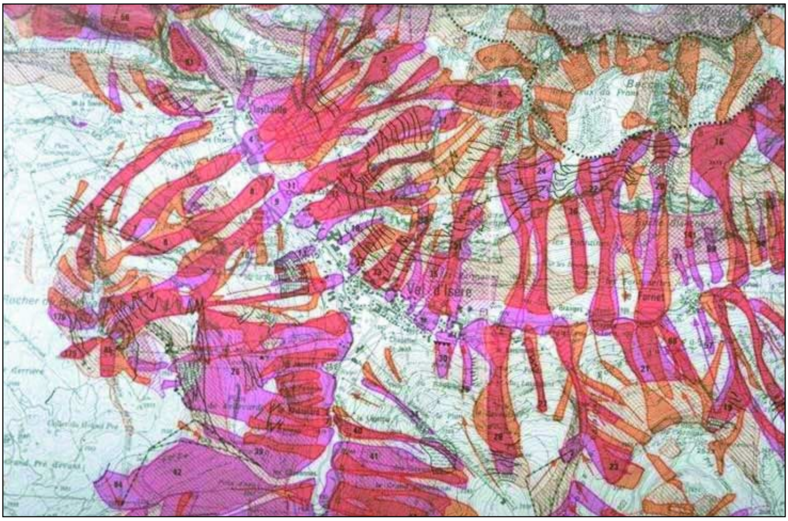

FIGURE 87 *Avalanche mapping for Val d'Isère, France (scale 1:25 000). Mapping in orange is from air photo interpretation. Mapping in magenta is based on field surveys, interviews with local witnesses including Forest Service rangers, and ski patrollers. Solid cross-hatching implies more certainty than areas delineated with broken cross-hatching. (After Borrel 1992)*

New Zealand

Avalanche mapping has been completed on many high-use alpine hiking trails in New Zealand and on one tourist highway. Avalanche mapping was undertaken at 1:30 000 on a 28 km length of the Milford Road where 50 major avalanche paths plunge from alpine areas subject to very high precipitation (8000–10 000 mm/yr) through remnants of forest to a narrow valley floor (Fitzharris and Owens 1980).

For a time, the mapping undertaken along the route was considered by road authorities to over-estimate avalanche runout distances but a series of heavy winters in the mid-1990s, when additional areas of old forest were destroyed, proved the mapping to be conservative. No frequency was implied in the mapping, but estimates were given in an accompanying technical report. Active avalanche control undertaken above the highway in heavy winters increased the frequency of major avalanching on most paths by at least an order of magnitude above the estimates made by the mappers.

The mappers used the hazard index concept developed for British Columbia's highways (Schaerer 1989) for both the Milford Road and avalanche-prone walking tracks in New Zealand. Observational data have subsequently been reworked to estimate a "probability of death for an individual" (PDI) traversing the road (Weir 1998).

Iceland
Mapping undertaken above a village in Iceland represents one of the first applications of risk-based mapping to snow avalanches (Keylock et al. 1999). Vulnerability of the village inhabitants was assessed based on the construction of the dwellings (reinforced or non-reinforced). Risk contours, produced via simulation of extreme avalanche runout, were plotted across the runout zone and expressed as a PDI (Figure 88).

The critical difference between the risk mapping approach and the traditional Swiss method or other hazard line techniques is that risk is treated as a gradient, measured in terms of potential for loss of life. There is no indication of acceptability of risk in this method compared to the more traditional zoning systems.

United States
Vail, Colorado and Ketchum, Idaho have introduced land use planning ordinances based on avalanche influence zones modelled on the Swiss approach (Mears 1992). Land use restrictions are enforced.

Canada
Technical guidelines for avalanche risk determination and mapping in Canada have recently been prepared (McClung et al. 2002). The guidelines propose a risk-based land use zoning system, calculated as the product of avalanche return period and impact pressure. Training courses will be offered in association with the guidelines. Readers should check with the Canadian Avalanche Association or the B.C. Forestry Continuing Studies Network for course schedules.

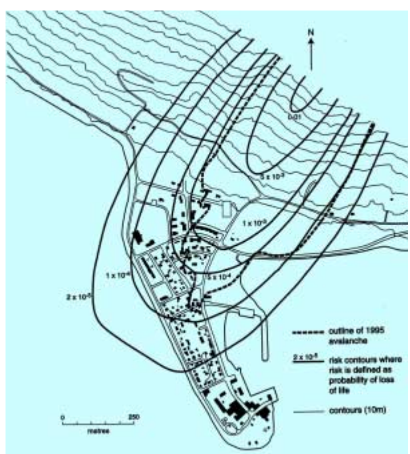

FIGURE 88 *Risk map produced by simulation of avalanche runout (based on probability of risk exceedance). Dotted line is extent of runout of an event in 1995 that occurred in Iceland. Solid contours map risk as probability of loss of life. (After Keylock et al. 1999)*

Highways in British Columbia

In British Columbia, the Ministry of Transportation's Snow Avalanche Program has mapped almost all avalanche-prone highways (Figure 25). Expert judgement, observational data, and air photo interpretation are used to make a best estimate of the likely avalanche runout on individual paths. Each path is shown on an oblique air photo and on a 1:50 000 scale strip map (Figure 89). The Ministry's avalanche atlases contain a table of expected avalanche frequency that is updated as more observational data become available (e.g., B.C. Ministry of Transportation and Highways 1991). Observational data from previous winters are available to avalanche technicians from a computer database.

The Ministry generally does not map maximum expected runout, because that is not of great importance in transportation planning. The length of road affected and proximity to other avalanche paths, in combination with likely vehicle speed and length, are more important than the runout distance, as these variables determine the exposure of a driver to avalanches.

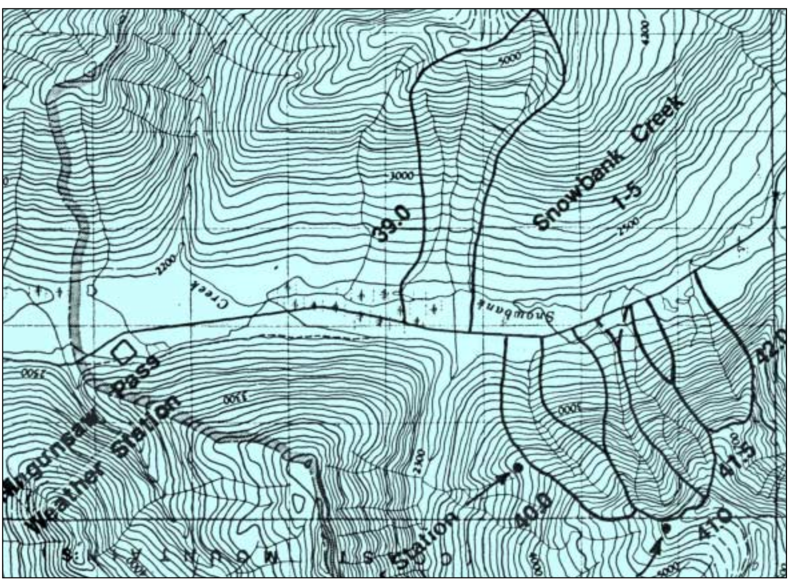

FIGURE 89 *Ministry of Transportation avalanche mapping showing distribution of avalanche paths above highway at Ningusaw Pass, between Bob Quinn Lake and Stewart, B.C. (scale: 1:78 125). (No indication of frequency or maximum runout distance implied.)*

The Ministry has responsibility for approving access to subdivisions in unincorporated areas in British Columbia.; snow avalanches are one of a number of slope hazards considered in the approval process. The Snow Avalanche Program has defined a "hazard line" in Stewart, B.C. to delineate a boundary for potential avalanche influence from Mt. Rainey. Evacuation of defined areas, including the log sort and port, may be implemented in extreme avalanche conditions.

Regional Districts in British Columbia
No common approach has been adopted for land use planning in the regional districts of British Columbia. A zoning system developed in the Fraser Valley Regional District employs hazard acceptance thresholds for dealing with snow avalanches and other natural hazards (Cave 1992). The Fraser Valley Regional District employs a matrix to prescribe responses to development applications for various types of projects on lands subject to snow avalanches for a range of annual exceedance probabilities (Table 17). The column headed "1:500–1:10 000" is considered redundant because it is impossible to distinguish between that class and the "1:100–1:500" return period class. The column headed "greater than 1:10 000" defines a non-restrictive response for areas where avalanche events have not and will not occur.

The Fraser Valley Regional District has applied the avalanche planning restriction to projects in the Hemlock Valley area where poorly restocked clearcuts, harvested in the 1960s, continue to pose an avalanche hazard to private land downslope. This example underscores the serious implications that may follow ill-considered clearcut logging on steep slopes that have the potential to run out into developed areas. The loss in value of potentially affected residential properties will often outweigh the value of the timber resource.

Because of the great destructive potential of avalanches and the dread associated with the phenomenon, the response of the Fraser Valley Regional District is essentially one of avoidance rather than mitigation. Interestingly, the planning response to floods, a more familiar hazard, is less restrictive.

TABLE 17 *Fraser Valley Regional District snow avalanche planning response (source: Cave 1992)*

	Snow avalanche expected return period				
Proposed project	**< 1:30**	**1:30–1:100**	**1:100–1:500**	**1:500–1:10 000**	**> 1:10 000**
Minor repair (<25% value)	5	4	4	4	1
Major repair (>25% value)	5	4	4	4	1
Reconstruction	5	4	4	4	1
New building	5	4	4	4	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Hazard-related planning response:

1 Approval, without conditions relating to hazard.

2 Approval, without siting conditions or protective works, but with a covenant including a "save harmless" clause.

3 Approval, with siting requirements to avoid the hazard, or with requirements for protective works to mitigate the hazard.

4 Approval, as in (3) above, but with a covenant including a "save harmless" condition, as well as siting conditions, protective works,
or both.

5 Not approvable.

Terrain Stability Mapping in British Columbia

Terrain stability mapping is a derivative process that draws on known attributes of surficial materials, landforms, slope steepness, and geomorphic processes within the natural landscape that control slope stability. Two types of terrain stability maps are undertaken to assist with forest management in British Columbia—detailed and reconnaissance maps. Reconnaissance terrain stability mapping uses air photo interpretation, but little field-checking, to delineate areas (polygons) of stable, potentially unstable, and unstable terrain within a particular landscape. By contrast, detailed terrain mapping involves a substantial field campaign to categorize, describe, and delineate landscape characteristics and to investigate active geomorphological processes. Detailed terrain stability mapping uses a five-class system (Class I to V) to rate stability following forest harvesting and road building. Ryder (2002) gives a complete discussion of the differences in the methods.

Existing snow avalanche paths are mapped with onsite symbols (arrows) and described in terrain polygons with the geomorphic process qualifier "-A" (see Appendix 6 and Figure 90). Rollerson et al. (2000) propose an extension to adopt the "-A" notation to indicate that the terrain may be avalanche-prone following harvesting.

Avalanche Mapping for the British Columbia Forest Sector
Topographic analysis using a GIS and a digital elevation model identify slopes between 30 and 50° (60–120 %) as a first pass in filtering terrain

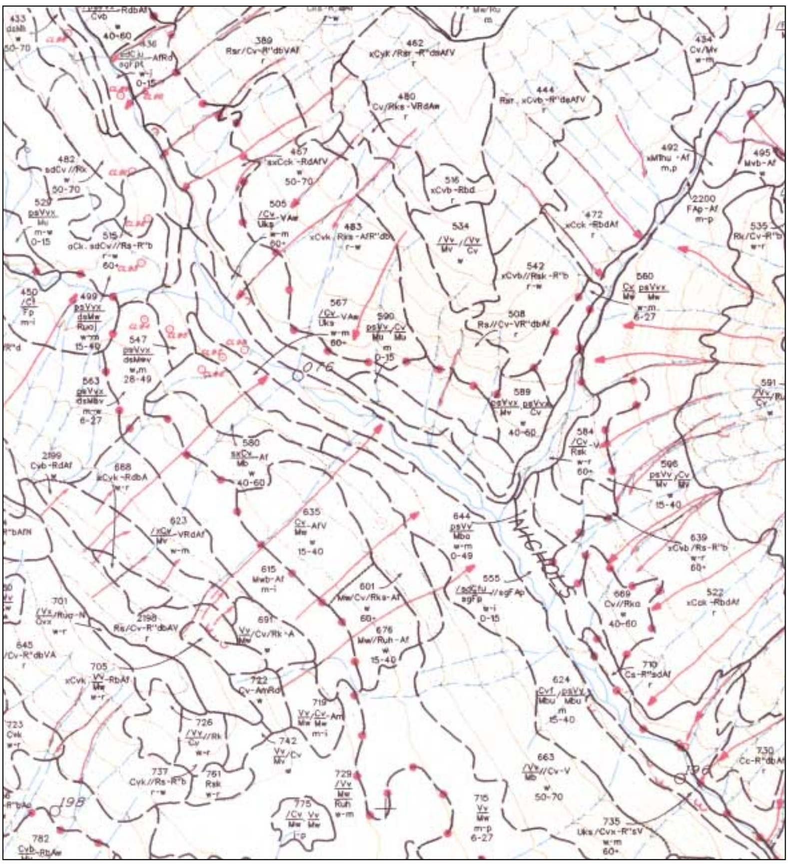

FIGURE 90 *Terrain mapping for an area in the Interior of British Columbia that has both major and minor avalanche paths (scale 1:20 000, TSIL C and E; TRIM map sheet 93J.084). Solid-head arrows indicate existing avalanche paths, small-headed arrows indicate landslide tracks. See Appendix 6 for details of terrain mapping legends that relate to snow avalanches. (Source: J.M. Ryder and Associates, Terrain Analysis Inc.)*

likely to generate snow avalanches, given an unstable snowpack and sufficient loading. Slope maps can be readily produced. Analytical techniques can be employed to identify convex slopes and gully systems where avalanches may initiate. Topographic exposure and the length of fetch from any upwind plateau or other topographic feature can be computed. This approach has been applied in the Revelstoke–Columbia Forest District by Kelly et al. (1997) in an effort to delineate areas with a moderate or high likelihood of avalanche initiation following clearcut harvesting.

The Canadian guidelines and standards for avalanche risk and hazard mapping give an example of a forestry risk zone map, which designates a protection forest above a highway (McClung et al. 2002).

Mapping and Acceptable Risk

Persons undertaking avalanche mapping should not attempt to define risk acceptability (as is implicit when a hazard line or zone boundary is drawn on a map). Instead, risk acceptability should be established by society through a consultative land use planning process based on informed debate (the Land and Resource Management Planning process may offer a suitable model). Consultation should take place in an environment of open risk communication (Canadian Standards Association 1997). Risk mapping provides a good tool to promote open communication.

Map Use and Interpretation

It is important that avalanche maps contain a detailed explanation of the methods used to establish avalanche likelihood and risk. The accuracy, reliability, and limitations of data should be defined. As with terrain stability maps, a detailed technical report should accompany any avalanche map. That report should include a risk assessment, conclusions, and recommended mitigations (CAA 2002).

Gerath et al. (1996) note that unless users of quantitative risk assessments understand the limitations of the methods and consider the data employed then they may be misguided by the apparent precision provided by the numbers presented. Conversely, a drawback to using a qualitative rating is that terms such as "low," "medium," and "high" mean different things to different people, and hence map users may interpret meanings other than those intended by the mapper.

3.6 DOCUMENTING EXISTING AVALANCHE PATHS

Licensees operating in moderate- or high-risk areas may wish to document all recognized avalanche paths in an avalanche atlas. Each path should be plotted on an oblique aerial photograph and on a topographic base map (preferably 1:20 000 scale or larger). Basic terrain features can be analyzed by map interpretation or digital terrain modelling, but should be confirmed by field inspection.

An overview map displaying all identified paths in the area should be presented, along with a summary of climate and snowfall records. An analysis of the avalanche risk should also be provided (Fitzharris and Owens 1980).

Figure 92 is excerpted from a B.C. Ministry of Transportation and Highways avalanche atlas for the Terrace area. The likely maximum affected area is outlined on an oblique photo of the area. Avalanche mapping undertaken for highway projects is generally not concerned with runout that extends below the road. Risk assessment considers the period of time that a vehicle will be exposed in the path (a function of road grade and vehicle type).

3.7 RUNOUT PREDICTION

Dynamics Modelling Approach

Avalanche runout modelling should be undertaken when some element located downslope of a proposed road or opening may be at risk from avalanches initiating in a forest opening (e.g., Figure 91).

The traditional approach to avalanche runout modelling is to survey the slope in question and use an avalanche dynamics model to predict the speed of the avalanche mass (Figure 93). The most commonly applied method employs the Perla, Cheng, and McClung model (PCM) or some derivative of it (Perla et al. 1980; Mears 1992). The PCM model can be coded in a programming language or implemented on a spreadsheet and the output graphed. Experience and expert judgement are used to select friction coefficients and to calibrate the modelled runout against

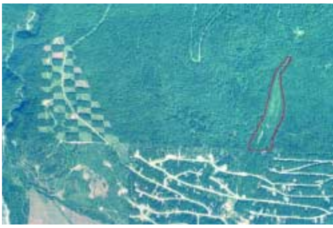

FIGURE 91 *A landslide initiating below an old road created an opening in the forest (outlined in red). A subdivision was subsequently developed in the landslide deposition zone. Residents have expressed concern about the potential for snow avalanches and further landslides (Kamloops Daily Sentinel, Sept. 15, 1976). Avalanche runout modelling can be employed to establish whether an avalanche initiating at the head of the landslide track might reach the subdivision (see Figure 93). In this instance, snow supply, likely avalanche size, and avalanche return period determine the risk. (Ross Creek area below Crowfoot Mountain; map sheets 82L 094 and 95)*

Shames #3 – Avalanche Path Summary

NAME	**Shames #3**	NUMBER: 12.9
LOCATION	On the Shames River road leading to Shames Ski Area. 12.9 km from the junction of Highway #16	
MAP	103 I / 7 W	
AERIAL PHOTOS	B.C. 7728: 213-214 (1:24 000)	

DESCRIPTION

ELEVATION: (metres above sea level) Start zone: 670 m Runout Zone: 365 m			Vertical Fall: 305 m
START ZONE AREA: 20 hectares			
START ZONE ASPECT: South-south-west			
SLOPE ANGLE: Start zone: 40°		Track: 30°	Runout Zone: Level
Beta Angle (β) *	Not specified	Measured angle from the (Beta) point where the path gradient falls to 10° up to the top of the start zone.	
Distance to Beta point (X_{β}) *	Not specified	Measured horizontal distance from the top of the path to Beta point.	
Start zone	A steep logged slope with numerous stumps and fallen timber. Locally oversteepened by road cut and fill.		
Track	A steep logged slope. The upper road crosses this slope and the lowest road is at the base of the slope.		
Runout Zone	Beyond the lowest road.		
Elements at Risk	Public travelling to ski area and industrial road users. No other facilities at risk.		
Comment	Length of public highway affected is 1000 m on the lower road and 800 m on the upper road. Good forest regeneration noted Feb. 2000.		

HISTORY:

	Total Recorded Avalanches	Recorded Avalanches on Highway	Recorded Average Depth on Highway (m)
1999-2000	0	0	
2000-2001	0	0	
TOTALS	0	0	

Notable Avalanche Occurrences:
No avalanche incidents have been recorded for this path.

* See Figure 94 and accompanying Section 3.7 on runout prediction for an explanation of beta angle and distance to beta point.

FIGURE 92 *Typical page from an avalanche atlas (after B.C. Ministry of Transportation and Highways Snow Avalanche Program 1991.)*

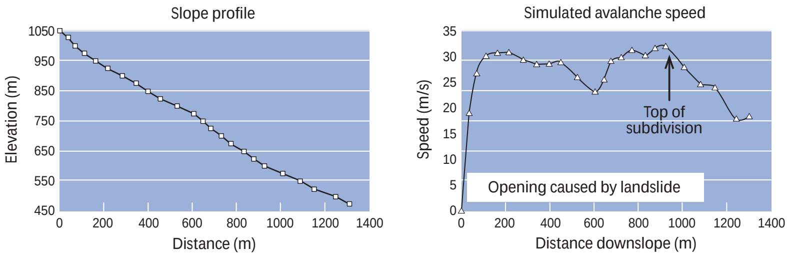

FIGURE 93 *Deterministic application of the PCM avalanche dynamics model to the area shown in Figure 91.*

- *Avalanche predicted to attain maximum speed of 30 m/s (110 km/h) within first 100 m of slope.*
- *A sensitivity analysis should be undertaken using a range of values for the friction coefficient (μ).*
- *Avalanche speed at the point of interest is critical for any estimate of likely impact pressure.*

known large events. Considerable research has been undertaken on this topic in Europe (Salm and Gubler 1985).

Deterministic versus Stochastic Modelling

Avalanche dynamics models are traditionally applied in a deterministic way, which yields a simplistic "yes or no" result to the problem of whether an avalanche will impact some point of interest (POI). In the discipline of landslide failure analysis, recent work is moving towards stochastic modelling, which yields a probability that a failure may occur (Hammond 1992; Wilkinson and Fannin 1997). Similarly, it is possible to run a Monte Carlo simulation, using a spreadsheet add-in application, to stochastically model avalanche runout via the dynamics approach.

The avalanche dynamics approach has been criticized because of the lack of objective criteria available for the selection of friction coefficients for paths and mountain ranges other than those where the original research was undertaken. Uncertainties about the mechanical properties of flowing snow and its interaction with terrain make this method speculative.

Probabilistic Modelling Approach

An alternative method for predicting extreme (100-year) avalanche runout based on simple terrain variables, originally proposed by the Norwegian Geotechnical Institute (NGI), has become the preferred method in North America for runout prediction (Lied and Toppe 1989). Terrain variables are used to specify an angle, alpha (α), which is defined by sighting from the point of extreme runout to the top of the start zone (Figure 94). Alpha angles can vary from 15 to 50° (27–120%) depending on the terrain (McClung and Mears 1991). The Ministry of Transportation–Ministry of Forests avalanche protocol employs an alpha angle of 25° (see Figure 94).

The NGI runout model assumes a parabolic slope profile. It should employ relationships established by regression analysis of data from the mountain range under study. Alternatively, the model can be calibrated against known extreme avalanche paths in the study area.

The return period of extreme avalanche runout may be modelled in space and time through application of extreme value statistics. McClung (2000) shows how Gumbel parameters used for runout modelling are related to climate and terrain.

The ratio of the horizontal distance that an avalanche runs beyond the beta point (Δ_x) to the horizontal distance from the start point to the beta point (X_β) is termed the "runout ratio" (Δ_x/X_β). This is considered to be a better predictor of runout distance than that based on regression of the alpha angle (α) (McClung et al. 1989). The method is applicable to small and truncated data sets, which makes it attractive for use in situations where detailed information on avalanche runout is limited.

The runout ratio can be fitted to an extreme value distribution (Gumbel distribution) to facilitate the prediction of high-frequency snow avalanches (Smith and McClung 1997; McClung 2001b) (Figure 94).

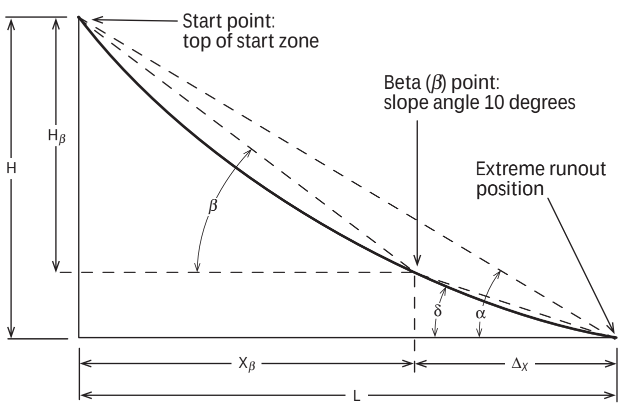

FIGURE 94 *Terrain parameters used in runout calculation:*

- β *(beta) is the measured angle from the (beta) point where the path gradient falls to 10° up to the top of the start zone*
- α *(alpha) is the predicted angle from the end of maximum runout to the top of the start zone*
- δ *(delta) is the angle from the point of extreme runout to the beta point*
- X_β *the measured horizontal distance from the top of the path to the beta point where the gradient first falls to 10°*
- Δ_x *the predicted distance (m) between the beta point and the extreme runout position*
- L *the horizontal distance from top of the path to the extreme runout point*
- H *the total vertical fall (m)*
- H_β *the vertical fall (m) from the top to the elevation of the beta point*

(After Lied and Toppe 1980; McClung and Mears 1991)

McClung and Mears (1991) define a runout ratio (Δ_x / X_β), a dimensionless measure of extreme avalanche runout, for the prediction of zones affected by high-frequency avalanching as:

$$\frac{\Delta_X}{X_\beta} = \frac{\tan\beta - \tan\alpha}{\tan\alpha - \tan\delta}$$

Tables 18 and 19 shows how extreme runout summary statistics vary with the terrain properties found in different mountain ranges (Smith and McClung 1997; McClung 2001b).

TABLE 18 *Avalanche runout summary statistics: mean values (source: Smith and McClung 1997)*

Mean values	Canadian Rockies $n=127$	Coastal Alaska $n=52$	B.C. Coast Range $n=31$	Columbia Mtns* $n=46$
α	27.8	25.4	26.8	32.5
β	29.8	29.6	29.5	34.2
δ	5.5	5.2	5.5	34.2
H	869	765	903	538
L	–	–	–	8702
Δ_x	168	302	229	38
Δ_x / X_β	0.114	0.25	0.159	0.064

**Note: The Columbia Mountains data describe high-frequency avalanche runout (i.e., less than 100-year events).*

TABLE 19 *Avalanche runout summary statistics: extremes (source: Smith and McClung 1997)*

Values	Canadian Rockies $n=127$	Coastal Alaska $n=52$	B.C. Coast Range $n=31$	Columbia Mtns $n=46$
α min	20.5	18.9	20.4	25.4
β min	23.0	23.0	22.8	27.0
δ min	-21.5	0.0	-5.0	-25.0
H min	350	320	426	125
L max	–	–	–	2372
Δ_x max	542	790	1150	217
Δ_x / X_β max	0.40	0.66	0.56	0.32

Note: A negative delta angle indicates upslope avalanche runout (i.e., run-up on the opposite valley wall).

The prediction of maximum runout for large avalanches is difficult and cannot be done with definitive precision. A probability or risk-based estimate may be the most reasonable approach to the problem.

McClung (2000) has demonstrated that the prediction of extreme avalanche runout in both space and time, based on application of a Gumbel analysis to describe the spatial distribution and Poisson process to describe the temporal distribution, can be extended to model width in the runout zone.

Statistical Concepts

In some fields of earth science (e.g., flood hydrology of major river systems), there are sufficient high-quality data to characterize the frequency and magnitude of large events. Although more data exist on snow avalanches than on other, less frequent, mass movement phenomena (such as debris flows and landslides), observational data in British Columbia typically extend back only 25 years and may be available only for narrow corridors.

Some of the terms that are commonly used for land use planning with respect to floods are also used when describing avalanche frequency, magnitude, and runout distance. However, it is critical to recognize the limitations of the available avalanche occurrence data in comparison to hydrological databases.

When estimating the frequency of large avalanches at some critical point of interest (e.g., at a road or bridge), an extreme event can be regarded as a random variable with a given probability of occurrence. A probabilistic analysis is appropriate because the critical combination of weather variables (snowfall, wind, and temperature)—given the pre-existence of a weak layer in the snowpack—is highly unpredictable. A probabilistic approach is further justified because, in many interior British Columbia environments, avalanche magnitude cannot be correlated with frequency of major storms.

When applying probabilistic methods to snow avalanches, it is important to be clear as to whether the modeller is discussing runout distance or event magnitude. The following discussion is limited to runout distance.

The important probabilistic concepts used in discussion of runout distance are:

Annual Exceedance Probability (AEP).
The probability (P) that an avalanche runout (A) will exceed a given point of interest (a) in the avalanche path at least once in a year:

$$\text{AEP} = P(A > a)$$

Annual Non-Exceedance Probability (ANEP).

The probability that an avalanche will not reach the point of interest in the avalanche path in any given year:

$$\begin{aligned}\text{ANEP} &= P(A < a) \\ &= 1 - P(A > a)\end{aligned}$$

Return Period (T) (also called the **recurrence interval** of an event).

The average length of time between consecutive events that reach the point of interest. Return period and AEP are inversely related:

$$T = 1/\text{AEP} \quad \text{or}$$
$$\text{AEP} = 1/T$$

The following examples consider a hypothetical avalanche that reaches a given point in its runout zone, on average, once in 30 years. If a structure such as a bridge is to be placed at that point, then an engineer might call that 30-year event the "design avalanche." Any event that overruns that given point (i.e., exceeds it) will damage or destroy the bridge.

The probability that an avalanche will run beyond the 30-year design point in any one year is:
$\text{AEP} = 1/30 = 0.033$

The probability that an avalanche will not run past the 30-year design point in any one year is:
$1 - \text{AEP} = 1 - 1/30 = 0.967$

Jargon in Risk Communication

The phrase "return period" is often used in civil and structural engineering, when a structure or protection system is designed to withstand an impact of a certain magnitude event. In that context, a 100-year "design avalanche" is assumed to have a certain size, speed, and impact pressure at the point where the structure is proposed.

The phrase "a 100-year return period avalanche" does not mean that an avalanche will occur only once in 100 years. A 1 in 100-year return period avalanche is better described as an avalanche with a 1 in 100 chance of occurring annually.

Here, the use of "return period" can lead to considerable confusion and should be avoided in other than highly technical discussion.

3.8 IMPACT PRESSURES

Impact pressure is a function of density (ρ) of the flowing speed, multiplied by the square of the speed (v), expressed as units of force per unit area on an object positioned perpendicular to the flow direction. The force is normally averaged through the time of the avalanche to give an average impact pressure.

Impact pressure (in kilopascals) = $\rho \times v^2$
where 1 kPa = 1000 N/m^2
Large, high-speed dry flowing avalanches are likely to exert the greatest impact pressures.

Studies from Rogers Pass, B.C. and elsewhere have shown that the maximum impact pressure occurs as the frontal pulse of an avalanche strikes an object perpendicular to the flow direction. Maxima occur within the first second or two of impact (McClung and Schaerer 1993, p. 112). In a dry flowing snow avalanche, peak pressure may be two to five times the average impact pressure. Large dry snow avalanches typically have impact pressures in excess of 100 kPa (≈10 t/m^2).

In recent field measurements in Switzerland, recorded impact pressures averaged around 80 kPa for the first 6 seconds during a large avalanche, with many peaks of 200–400 kPa and a few strong peaks of up to 1200 kPa (Figure 95; Dufour et al. 2000).

Keylock and Barbolini (2001) discuss vulnerability relationships for different-sized snow avalanches, as a function of runout distance. Table 22 gives typical relationships between impact pressures and potential damage.

TABLE 20 *Relation between impact pressures and potential damage (after McClung and Schaerer 1993)*

Impact pressure (kPa)	Potential damage
1	Break windows
5	Push in doors
30	Destroy wood frame structures
100	Uproot mature spruce trees
1000	Move reinforced concrete structures

Note: Impact pressures are often expressed as tonnes force per square metre rather than the SI unit of kilopascal (100 kPa is approximately equal to 10 t/m^2).

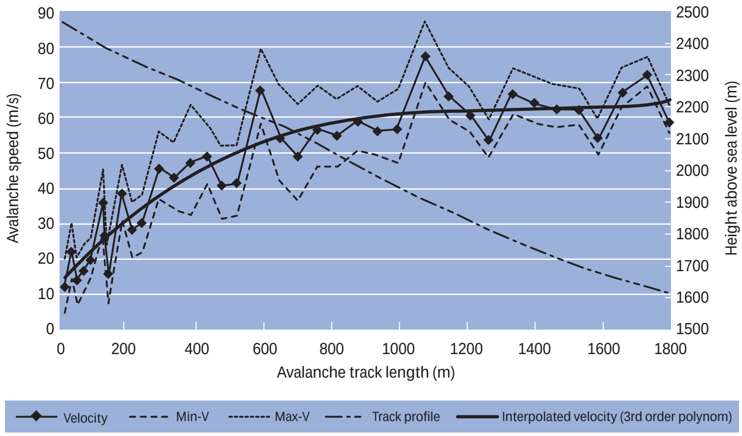

FIGURE 95a *Radar speed measurements of the frontal pulse of a large avalanche gave a maximum of 80 m/s (290 kph) (dashed lines indicate error ranges associated with the measurements). The path falls 900 m. (Dufour et al. 2000)*

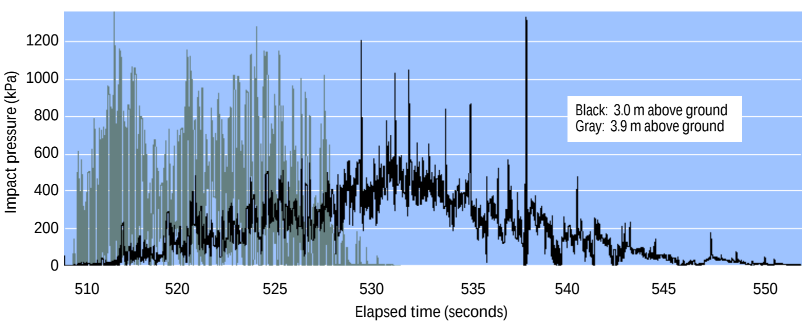

FIGURE 95b *Impact pressures measured at two heights on a tower located in the path shown above. At 3 m above the ground quasi-static pressures were around 500 kPa for 30 seconds, with distinct peaks of up to 1200 kPa. (Dufour et al. 2000)*

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