for which impact pressures (the usual, sole determiner of consequences in some European countries) are not practical for determining probable consequences. Salm (1997) states: "...(avalanche) dynamic(s) models not taking probabilities into account would be worthless for hazard mapping." This statement shows the linkage between destructive potential (impact forces) and avalanche frequency which is necessary to provide a complete picture of risk for land-use planning. The development below is based on this concept from a more general risk-based perspective for the common Canadian applications.

3. TYPES OF RISK AND MAPPING PROBLEMS IN CANADA

Canadian avalanche risk mapping applications include: 1. land-use planning for fixed facilities (including ski runs and structures in ski areas such as lift terminals and lift towers) and occupied and unoccupied buildings or structures during the seasonal snow season. Typically, the concern with definition of zones in the deposition or runout zones. 2. linear risk mapping for highway or railway applications. Typically, maps are prepared for relative risk along a line defined by the transportation route (highway or railway). 3. maps concerned with the initiation zone for planning of future forest clear-cuts accounting considering mitigation of future environmental damage to forest cover, prevention of damage to regenerating forest cover, streams, soil damage and threats to facilities including transmission lines and roads through future forested land. 4. maps concerned with avalanche events that may descend into future forest clear-cuts where clear-cuts are planned in the runout zone of existing avalanche paths.

4. DEFINITIONS AND THEIR QUALIFIERS

1. All probabilities given in this paper should be considered conditional unless otherwise stated but formulae may not show this conditionality explicitly. For example, if probabilistic risk to the travelling public is calculated for a road through an avalanche area, it is assumed implicitly that the road is open. If the road is closed and traffic is swept by highway personnel the risk to the travelling public is zero. Appendix A contains definitions of probabilities and symbols used in this document.

2. The definitions in this paper are sometimes given in prose as well as by mathematical formulae. In such cases, the mathematical definition always takes precedence.

3. Some terms have a number of different definitions from other literature. The definitions in this document are chosen to fit customary use in avalanche work and may differ from definitions in other documents. The definitions listed below are consistent with those published by Canadian Standards Association (1997).

4. The intention of a risk-based system is to provide some estimates of risk on the basis of order-of-magnitude assessment. Since there will be errors and accuracy associated with both destructive potential and return period, order of magnitude assessment represents the desired, possible accuracy. Mears (1992) argues correctly that the best possible accuracy for return period determination is about an order of magnitude and uncertainty about destructive potential (or probable consequences) may be comparable or greater. For example, in land-use planning about 3 levels of risk is all that can be expected to be achieved e.g. nominal (white zone), moderate (blue zone) and high (red zone). A common error of inexperienced risk planners is to include too many risk classes which are not definable in terms of meaningful parameters which can be determined at a site with suitable accuracy.

5. Risk analyses have to be designed so that actions and decisions do not imply that risk is too high or too low, i.e. desirable levels of risk acceptability actually fall within a band of risk. McClung [2002 (a),(b)] discusses this concept for avalanche forecasting decisions but the concept will also apply to risk and mapping applications. Inexperienced risk planners often focus only on the upper level of risk acceptability. However, being too conservative is also a mistake in planning. For example being too conservative can exclude valuable land from being occupied and used in land-use planning and in forestry applications such can add needless costs to the forestry industry. Typically government officials involved with land-use planning approvals focus only on the upper level of risk acceptability with decisions being needlessly conservative. Users of the land must be taken into account in specifying acceptable risk not just approval officials who will often want acceptability criteria that are too conservative to reduce chance of litigation. The risk based acceptability criteria in this paper represent either the upper limit of acceptable risk (such as in planning for occupied structures) or some limit at which protective actions should be initiated (such as for transportation corridors).

4.1 Definitions:

In general, definitions related to risk analysis and risk management vary considerably with application and users or stakeholders. Thus, any discussion of risk and its applications must include definitions in order not to be ambiguous. The definitions below are consistent with proposed Canadian standards definitions in CAN/CSA Q850-7 Risk Management: Guideline for Decision Makers (Canadian Standards Association, 1997). The definitions are also suitable for all applications in avalanche assessment including avalanche forecasting and back-country travel (McClung and Schaerer, 2006).

Risk: The probability, or chance, of death or losses. Losses may include adverse effects on health, property, the environment, or other things of value. It is assumed that all elements of risk may be represented in terms of probabilities. Risk, according to this definition, may be computed or estimated and compared to some level of acceptable risk although this is not frequently done. In avalanche mapping, risk potentially contains three elements: frequency, probable consequences and probable exposure which are connected through probability intersections. All three components may be potentially related to model calculations or historical data and they may be expressed quantitatively or qualitatively depending on application.

Risk in avalanche applications is of two general types (McClung, 2001): ordinary, everyday risk in which risk is not evaluated formally using probabilistic/statistical methods and engineering type evaluations for which formal probabilistic procedures form the basis. These types are not separate (e.g. both involve subjective, judgmental reasoning) but avalanche planning and mapping falls mostly under the latter category. Avalanche forecasting falls mostly under the dynamic first type of risk analysis.

1. frequency**:** The expected (average) number of events per unit time reaching and exceeding a location. Normally, one may envision frequency to have units in events per year but the true meaning is the annual probability of events. Frequency may be determined from empirical evidence in the field (e.g. Mears, 1992; McClung and Schaerer, 1993), avalanche occurrence records or as an exceedance probability from a probability density function describing events reaching and exceeding a position (Salm,1997; McClung, 2000). The term frequency used here is essentially equivalent to the term hazard as used by Varnes (1984) and Einstein (1988).

The frequency is often described in terms of the reciprocal of the return period: the expected time between events reaching or exceeding a given location. Return period (T) normally has units: years (per event) in avalanche work but mathematically it is the reciprocal of the (annual) exceedance probability. In avalanche work, expected frequencies can be very high, often as high as 20 events per year. Thus, if risk is defined in terms of a probability, the encounter probability (defined below) must be used in place of frequency. For a low frequency of events, the encounter probability reduces to the frequency.

2. probable consequences**:** The conditional probability of some attribute (Einstein, 1988) representing destructive potential to a facilities, people or some elements of the environment (e.g. forest cover, streams, soil cover) and avalanche occurrence. The attributes represent a set of mutually exclusive measures of destructive potential. For example, in Canada the five part system for avalanche sizes in Canada is based on destructive potential. For a given facility (B), probable consequences given an avalanche (A) at a location of size (S_i) could be represented as proportional to : $P_B(S_i|A)$. See Appendix A for probability definitions and symbols. In order to convert this estimate to a meaningful estimate of expected damage, the vulnerability of the item at risk would have to be considered to estimate the expected damage (see engineering risk definition below).

Using 1. and 2. above, with an attribute X_i [representing for example partial destruction of a wood frame structure (called facility B)], the risk could be represented as the probabilistic intersection of avalanche occurrence A and attribute, X_i: $P_B(A \cap X_i) = P(A)P_B(X_i|A)$ where P(A) represents the avalanche frequency at a location (e.g. calculated as the exceedance probability from a probability density function) and $P_B(X_i|A)$ represents probability of consequence (or attribute X_i) given avalanche occurrence at the site.

When maps are made on the basis of expected impact pressures and return periods (Switzerland, 1984) the above equation may be recognized for the design avalanche A_d (at a spatial location) as of the form: risk α frequency x expected impact pressure where frequency is represented as 1/T (T being return period at the location) and expected impact pressure α probability of attribute X_i given the design avalanche at the location.

The relationship specified for determination of zones in Switzerland (Switzerland, 1984, p. 16) can be shown (Appendix C) to be slightly different than the above relationship as impact pressure is weighted according to a logarithmic relationship with frequency rather than linearly proportional to impact pressure i.e. probability of attribute X_i α (impact pressure)^k where k may be less than, equal to or greater than 1. If $k = 1$, then from a risk acceptability perspective approximately equal weight is given to impact pressures and return periods in the acceptability criterion: this is equivalent to the Canadian standard. If $k > 1$ then higher impact forces are acceptable for the same impact pressure than if $k = 1$ and higher risk is accepted. This corresponds to the system in Switzerland (Switzerland, 1984). If $k < 1$ then the reverse is true: a more conservative estimate of impact pressure is allowed for the same return period than if $k = 1$. This is the position ($k < 1$) recently adopted in Austria (Austria, 1999). McCormick (1981) includes a product between frequency and non-linear relationship to expected damage (rather than linear) as an alternate definition of engineering risk (defined below).

3. probable exposure**:** This is the probability that people or facilities or environmental elements (e.g. forest cover or streams) are exposed to avalanche hazards in time and/or space. For fixed facilities entirely within avalanche paths the exposure may be taken as 1. For people moving, such as during evacuations or travelling by vehicles on highways, for example, the probable exposure is less than one.

For example, consider that the risk given that an avalanche (A_j) occurs in path j in an avalanche area, that a car C is exposed in the path (E_j) and that an avalanche of size i (S_i) occurs. The risk is: $P_C(A_j \cap E_j \cap S_i) = P_C(S_i|A_j \cap E_j)\ P_C(E_j|A_j)\ P(A_j)$ where the subscript C does not appear on the frequency component since avalanche occurrence on path j would not depend on what type of vehicle is exposed. The above equation may be recognized as having components multiplied together: frequency x probable consequences (S_i) x probable exposure [$P_C(E_j|A_j)$]. All probabilities are determined as conditional (unstated) that the road is open to the travelling public. In simplest terms, the probable exposure may be evaluated as the fraction of time people or objects of value are exposed. For example, if people occupy a structure half of every day (12 hours), the probable exposure is 0.5.

The Canadian avalanche size system (see Appendix B) implicitly accounts for spatial exposure since areal extent of damage increases with avalanche size.

Engineering risk: Engineers use a definition of risk which is related to that above by multiplying the probable consequences of expected losses for given attributes by the expected frequency. If $V_B(X_i)$ represents the Vulnerability: the fraction of loss for facility B for attribute X_i, the engineering risk is often given by: risk (X_i) x $V_B(X_i)$.

For a fixed facility (as considered above) totally exposed spatially, the engineering risk would be represented as: $P_B(X_i \cap A)\ V_B(X_i) = P(A)\ P_B(X_i|A)\ V_B(X_i)$ or normally stated as: expected frequency x expected damage (McCormick, 1981). This definition is essentially equivalent to the definitions of risk provided by Einstein (1988) and Varnes (1984). Note that since the definition includes a vulnerability (loss) vector corresponding to attributes [(called vulnerability by Varnes (1984)], this engineering definition of risk is not entirely based on probabilities. Keylock et al. (1999) used an engineering definition of risk for constructing engineering risk maps for avalanche applications with destructive potential based on Canadian sizes S_i. Such applications require considerable data to employ. Engineering risk can be modified to include probable exposure by including intersection with exposure as described above. The engineering definition of risk here is essentially equivalent to that used in statistical decision theory (Einstein, 1988).

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

Engineering type risk assessments may be easily adopted for estimating costs by multiplying the engineering risk by the total value of a facility, for example. If return periods are estimated in years, engineering risk x value is the ARC: Annual Risk Cost (e.g. Morgan, 1990).

Risk estimation in avalanche mapping will almost always contain judgmental estimates (from experience and field observations) as well as possibly quantitative estimates from models and statistical analysis of data. A formal way of thinking about judgmental processes is included below in relation to Bayesian Approaches. In general, avalanche hazard mapping can be much more quantitative than landslide mapping because a higher frequency of events (in the avalanche case) makes more models possible and more event occurrence information to possibly analyse.

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

Acceptable return periods for mountain slope hazards in British Columbia are sometimes stated by phrases such as "10% probability of occurrence (at least once) in 50 years (L)". Using formulae for the encounter probability, this implies return periods of 475 years for either formula. However, considering the accuracy with which return periods can be estimated for mountain slope hazards, this result implies a return period of 500 years.

The encounter probability is important for formulating the probable exposure for applications concerning moving or waiting traffic on transportation routes and exposure of people outside facilities.

The encounter probability may also be used to demonstrate accuracy in determining return periods at a site and the connection to data records. For an estimated return period, T, at a site, the number of years of record ,n, to claim that an avalanche occurs at least once at the site with probability E_p is given by: $n \geq [\ln (1-E_p)]/[\ln (1-1/T)]$ for a binomial distribution. For an estimated return period of 100 years, more than 69 years of good records would be needed to claim that an avalanche occurs at least once at the site with $E_p = 0.5$ (50% probability). In Canada, there is probably no place with 70 years of good avalanche records and it is clear that reliance on models (e.g. Salm, 1997; McClung, 2000) and evidence at sites, such as vegetation damage, must be used to estimate such long return periods. The implied accuracy of estimates from field observations and models can be much less than if good avalanche occurrence records existed. This simple analysis shows why return periods cannot be estimated better than about a factor of ten (Mears, 1992).

Magnitude: The magnitude of avalanches represents the destructive potential. In mapping applications it is represented either by expected impact pressure or the five part Canadian system for sizes of avalanches (McClung and Schaerer, 2006) which is given in Appendix A. The Canadian system for sizing avalanches is a five part scale which displays roughly an order of magnitude increase in destructive potential with size. The scale is similar in concept to the Mercalli scale for earthquake effects since it can be applied after the avalanche takes place. The Canadian size system falls naturally into risk and engineering risk estimates as described above since it forms a mutually exclusive set of attributes describing destructive potential. It is customary in Canada for avalanche observers to record avalanche events using half sizes. For mapping applications such as forestry or on transportation routes, the size system is essential for representing the consequence portion of risk.

The advantages of having such a size system as an alternative to specifying impact pressures as the consequence portion of risk cannot be emphasized enough. For the risk-based Canadian mapping system with a multitude of applications (transportation, land-use planning, forestry, planning for structures and others), the flexibility of using avalanche sizes (the historical record of destructive potential) as an alternative to theoretical impact pressure estimates is essential. When the Canadian size classification is used, typically the engineering risk is sought, i.e. one is interested in the probability of a given size of avalanche at the site (probable consequences) and the vulnerability of a given element at risk as a function of avalanche size at the site.

Magnitude-frequency relation**:** A magnitude-frequency relation is a probabilistic relation which describes avalanche magnitudes at an avalanche site or at a collection of avalanche sites (e.g. an avalanche area consisting of a number of paths). For a magnitude-frequency (m-f) relationship there is only one variable (some measure of magnitude) and the m-f relationship contains a probabilistic representation of how frequently magnitudes are expected at a site. For avalanche areas, average magnitude and average frequency are separate variables generally characterized by different variable sets to determine them. In general, it is expected that -at a site- as the average magnitude increases downslope into the runout zone the average frequency decreases. It is very rare in Canada to have records of m-f with position in the runout zone for an avalanche path. Therefore, in land-use planning, consideration of the effects of the (theoretical) design avalanche is the method of choice for zoning. In such cases, return periods will be on the order of 100 years and, for such positions, frequency data are usually not available. However, theoretical estimates are possible (McClung, 2000) if frequency can be estimated at a position up slope of the runout zone in combination with empirical, statistical runout data from a set of avalanche paths in the mountain range.

Impact pressures: Unless otherwise stated, impact pressures in this paper refer to avalanche force per unit area normal to a flat surface averaged over a length of time suitable to yield an average pressure. Avalanche impact pressures for flowing avalanches or powder avalanches are highly transient with peaks that exceed average pressures by as much as 2 to 5 times. The normal units for impact pressure are kPa (kilo-Pascal) equal to a pressure of 1000 N/m^2. Impact pressures are calculated relative to an index value as proportional to the product of density (ρ) of the flowing snow and square of the avalanche speed, v^2, (component of avalanche velocity perpendicular to the surface). Table 1 gives relation between destructive effects and typical damage expected.

Normal practice takes impact pressure for the powder component of flowing avalanche or for impact pressure from a powder avalanche as proportional to $1/2\ \rho\ v^2$ where ρ is density of the snow-dust air mixture at the top of the avalanche. This expression comes from fluid mechanics and is equivalent to the stagnation pressure for fluid flow at the centre streamline of fluid striking a surface perpendicularly (meaning v is the velocity component perpendicular to the surface). It is assumed that for the low volume fraction filled by solids (< 10%) in the powder component, the flowing material may be idealized as an incompressible fluid.

Table 1: Impact pressures and destructive effects from McClung and Schaerer (2006)

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

For flowing avalanches, which have a high volume fraction filled by solids, (at least 30% or more: McClung and Schaerer, 1985) the more conservative estimate $\rho\ v^2$ can be adopted as from solid impact theory (Mellor, 1968) where again, v is the speed (velocity component) perpendicular to the surface. Mears (1992) adopts the less conservative value of $1/2\ \rho\ v^2$ for flowing snow and, therefore, he idealizes flowing snow as analogous to a fluid. Mellor (1968) extended solid impact to include higher pressures for compressible impact but this is rarely used. McClung and Schaerer (2006, p. 134) provide approximate estimates of volume fraction filled by solids and flow densities for different types of avalanches. In calculating impact pressures rocks or woody debris can greatly increase pressures over estimates for snow only.

Maximum event: This is the avalanche characterized with the highest destructive potential at a location. Typically, one is concerned with both destructive potential (avalanche size or impact pressures) and return period as a function of position in avalanche terrain. Some likely characteristics in land-use planning include: 1. fast moving, large (mass) dry flowing avalanche; 2. long return period (order of 100 years); 3. very little snow entrainment (which slows avalanches). Sovilla et al., (2006) provided high quality data on the effects of snow entrainment on avalanche volume and speed. Their data showed that avalanche volume increased by as much as 700% from the initial release volume with avalanche speed slowing as mass was entrained;4. hard running surface; 5. extreme runout distance.

Spatial return period**:** Reciprocal of exceedance probability for probabilistic estimate of extreme runout. For example, spatial return period 1:10 means the avalanche runout distance for which 1:10 avalanche runout distances reach or exceed. It is calculated from a CDF (Cumulative Distribution Function) representing a set of extreme avalanche runouts in a mountain range.

In Norway (K. Lied, personal communication) extreme avalanche positions (region of nominal risk) for zoning purposes are characterized by a spatial return period of about 1:44 coupled with return period estimates of about 1000 years which corresponds to avalanche frequency entering the runout zone of about 1 event in 23 years.

Hazard: The term hazard is used to denote the potential of natural events (e.g. avalanches or other kinds of events) to inflict death, injury or loss to people, things of value and the environment. Hazard implies the coincidence (in space and time) of people, facilities or something of value within the reach of avalanches. Otherwise the hazard is negligible. Hazard is not given mathematical definition here and is not used in Canada for mapping standards. Hazard simply denotes a condition with the potential for causing undesired consequences (McCormick, 1981). The risk definitions above contain hazard within them but in a formal, mathematical structure.

The term hazard has different meanings even within disciplines (e.g. Weir, 2001) and is considered to be too imprecise and redundant to be used in mapping and risk evaluation. A line with an estimated avalanche return period of 300 years is a fairly clear descriptor. Conventionally, the hazard to a person present at such a place is nominal (or negligible). On the other hand, a term such as 'hazard line' begs the questions: "Which of many definitions of hazard is used? A hazard to what? Does it include only frequency (Varnes, 1984; Einstein, 1988) ? or Does it include some measure of consequences or vulnerability? How can something be labelled hazardous if consequences are not considered? The risk-based approach here contains frequency, probable consequences, probable exposure and vulnerability applied to locations on the ground so that redundant, imprecise terminology such as hazard is unnecessary.

Acceptable risk: Acceptable risk is the risk people will accept at a site. Acceptable risk is a societal question which depends on a number of factors such as cultural aspects, whether activities are voluntarily or involuntarily undertaken (almost always the case for mapping applications), the number of people exposed, the exposure of people, facilities or things of value exposed, how much the hazard is known to science or feared by people. Acceptable risk can be stated in many ways including: formal assessments of PDI (Probability of Death to an Individual, Morgan, 1990), combinations of quantities proportional to the risk (e.g. Switzerland, 1984) e.g. combinations of frequency (return period) and destructive potential in land-use planning. Morgan (1990) gave a formal prescription for comparing PDI to other risky activities to gauge acceptability but this is only one of many ways to state acceptability. For avalanche applications, it will rarely be possible to apply the formal prescription of Morgan (1991).

In most cases, human experience about acceptability based on return periods and destructive potential forms the basis of acceptability in avalanche work. The standards in the present paper were developed in the document (Canadian Avalanche Association, 2002) by avalanche experts in combination with peer reviewers. Earlier work by Cave (1992) produced matrices of acceptability criteria for building activities for various hazards including snow avalanches based on return period, type of building activity, potential number of people exposed. Cave (1992) varied return period with activity which is somewhat analogous to a combination of frequency and consequences as a measure of acceptable risk.

In Canadian avalanche mapping, often the concern is with estimates of destructive potential of events and return periods. Therefore, acceptable risk should be stated in terms of these parameters. Thus, for Canadian mapping standards, acceptable risk is mostly represented by a combination of return period (or avalanche frequency) and some attribute representing destructive potential (typically expected avalanche size S_i or expected impact pressure). In some cases, it will be possible to calculate the PDI or related measures for comparison to known acceptability. Such calculations are encouraged.

Theoretical design avalanche A theoretical avalanche used in land-use planning to delineate planning zones in the deposition (runout) zone or starting zone. The theoretical design avalanche contains definitions equivalent to acceptable risk: frequency (or return period) combined with some measure of destructive potential (e.g. avalanche size or impact pressure). For land-use planning in relation to occupied structures, the zones include:

1. White zone: Areas outside a line determined by a prescribed return period. For example, this may include any area with estimated return period greater than 300 years.

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

3. Blue zone: An area where the product of frequency period and impact pressure is less than 0.1 (10% of the initial (risk) value for the design avalanche) for return periods between 30 and 300 years. Appendix D contains a risk-based analysis which explains this standard.

In Canada, the theoretical design avalanche above is characterized by: estimated impact pressure less than 30 kPa (I_0) and return period greater than 30 years (T_0) for the top (beginning) of blue zone with extension to return period of 300 years (T_m) at the downslope end of possible blue zone. These, three numbers along with the definitions above completely characterize zone definitions downslope in the runout zone. The three numbers and colour scheme are identical to those used in Switzerland (1984); [see also de Quervain (1975)] to characterize the zones. However, the definition of a Blue zone is different in Canada according to combinations of expected impact pressure and return period (See Appendix D).

The Blue zone definition for Canada is more conservative than in Switzerland but not as conservative as new guidelines in Austria (Höller and Schaffhauser, 2001) concerning impact pressures. Formally, the Canadian standard representing the line between the Blue zone and the Red zone is given by:
$I/T < 0.1\ I_0/T_0$ ($T_0 < T < T_m$) whereas the Swiss standard is: $I/I_0 < \log_{10}(T/T_0)$; $T_0 < T < T_m$). The Canadian standard is equivalent to the assumption that risk is linearly proportional to avalanche frequency x expected impact pressure (equal weight given to impact pressure and return period for risk acceptability) whereas the Swiss assumption takes a logarithmic relationship allowing higher impact pressures for the same return period at short return periods than for the Canadian standard. This yields a less conservative assumption for the Swiss system. New guidelines for Austria (Höller, 1999) are slightly more conservative than the Canadian standard.

Normal activities according to zone colour are: 1. White zone (nominal risk) -New building normally permitted. 2. Red zone (high risk) - New building not normally permitted. 3. Blue zone (moderate risk) -New building possibly permitted with conditions specified. The conditions may include: structures reinforced for avalanche forces, construction of avalanche defences, requirement for evacuation plans or a combination of these. Special constructions where large numbers of people may gather or for essential services (hospitals, schools, multi-unit residences, police and fire stations) will normally be placed only in a White zone.

5. TYPES OF RISK PROBLEMS AND GENERAL DATA TYPES

In avalanche risk problems connected to mapping two general types of problems are encountered: 1. Starting zone (known as initiation zone in landslide applications). Applications here are encountered when one wishes to express some measure of probability that avalanches will start and the resulting expected consequences. An important example is design of clear cuts in forested terrain. 2. Runout zone (and sometimes in the track) (known respectively as deposition zone and transport zone in landslide applications). Applications here are encountered when one wishes to assess frequency and consequences in the runout zone. Examples include land-use planning for decisions about building permits and risk based methods on transportation routes.

In general two types of data are used for avalanche applications: 1. singular data: information and/or data about the specific case at hand collected or appropriate for the specific site including terrain information, data about snow supply , frequency and others and 2. distributional data: data or information about similar situations in the past. This information is normally more general than singular data and can include experience, models with coefficients derived from similar situations and other types of information. An important example of distributional data is extreme empirical runout data from a group of avalanche paths in a mountain range. Good risk analysis and mapping practice should include both types of information conditioned by experience and professional judgement.

5.1 Typical Risk Scenarios

Planning for avalanche hazards may involve a number of scenarios (McClung, 2005). Three common ones are described below.

1. Total risk **:** This scenario involves consideration of events of all different magnitudes (destructive potential) and frequency. Linear risk mapping for highway (McClung and Navin, 2001) and railway applications is an example. For land-use applications. Keylock et al. (1999) have provided an example. This type of calculation may be used for mapping, decision-making and estimating costs. Good observations and estimates (including theoretical) of avalanche occurrences (including destructive potential) are necessary to use this method.

2. Design event **:** This scenario involves estimating the risk for the probable maximum (design) event at a location. For applications such as land-use planning where estimates are required far into the runout zone where observations are normally lacking (long return period) this is the method of choice. Typically in land-use planning the problem is to estimate the destructive potential (e.g. impact pressure) and avalanche frequency with position (down-slope and cross-slope) in the runout zone to determine risk levels. This amounts to considering the effects of the design event relative to a theoretical design event (containing the elements of risk acceptability) as a function of position in the runout zone to make zoning maps related to decisions.

3. Risk-based design **:** This method takes into account events of different magnitude (destructive potential) and frequency with possible exclusion of the highest magnitude events (normally lowest frequency) from consideration in design of defences. The basis is that the highest frequency events are normally the small events and an avalanche defence may be used to reduce the risk to something acceptable by stopping these events. The method may be used in defence design to reduce environmental impact and cost but it normally would not be employed in mapping applications with the possible exception that mapping symbols might include notes about risk-based design.

5.2 Bayesian Approaches for Probable Consequences

Due to the uncertainty in risk problems and limitations of models, judgmental information must nearly always be used to complete maps and as input to other applications. A Bayesian approach gives a formal structure to the process by which judgmental information is included. Furthermore, in many Canadian applications the Canadian avalanche size system is used in the consequence portion of risk problems. In this section, a Bayesian approach for formulating probable consequences is given and the relation to the

Canadian avalanche size classification is provided. Appendix D contains a description of the Bayesian approach relevant to Canadian applications.

5.2 Future Events and Multiple Hazards

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

For multiple avalanche paths affecting a site, the union of probabilities (probability of one event or the other; probability of either event) is appropriate. For example, for avalanche paths 1 and 2: $P(A_1 \cup A_2) = P(A_1) + P(A_2) - P(A_1)\ P(A_2|A_1)$ or $P(A_1) + P(A_2) - P(A_1)P(A_2)$ if avalanche events on the paths are not conditionally related. If two avalanche paths do not intersect spatially, then the probability of event on either A_1 or A_2 is simply, $P(A_1 \cup A_2) = P(A_1) + P(A_2)$ for the area. This latter relationship shows how, for example, avalanche risk can be summed to make a linear risk map for a highway through an avalanche area considering non-intersecting avalanche paths. The addition formula is also the basis for Varnes' (1984) formulation for what he calls 'total risk': engineering risk summed over various elements.

6. EXAMPLES OF RISK-BASED ACCEPTABILITY IN CANADA

For applications except land-use planning risk acceptability in Canada is based on expected avalanche size and expected frequency of events at sites. For land-use planning, the basis at present is a combination of expected frequency (represented by return period) and expected impact pressure to represent the consequences portion of risk. Examples are given in this section. For some applications, such as transportation routes, acceptability is based on threshold avalanche size in combination with return period as determiner for actions such as instituting avalanche control by explosives or placing static defences.

6.1 Risk Basis for Forestry Applications

Two important applications of acceptable risk concerning clearcut logging are: Type I: Avalanche initiation in clearcuts and Type II: Clearcuts made where avalanches enter from above. For these applications, it is best to use the Canadian size system for characterizing the destructive potential. The applications may be described engineering risk as: $P(A \cap S_i)V(S_i) = P(A)P(S_i|A)V(S_i)$ where S_i represents avalanche size, A represents avalanche occurrence at site, and $V(S_i)$ represents a vector component of vulnerability corresponding to avalanche size i. This equation has the form: engineering risk = frequency x expected damage. The conditional probability above could be expanded to: $P(S_i|A)\ \alpha\ P(S_i)\ L(S_i|A)$ by Bayes Rule where $P(S_i)$ is the fraction of avalanches of size i for clearcut logging in steep terrain with good snow supply (general information) and $L(S_i|A)$ is the likelihood of size i for parameters observed at a site.

The standard for acceptable risk in Canada for the two applications described above (Type I and Type II) to prevent environmental damage is: Avalanche of size 3 with average annual frequency once in ten years. The matrix below is constructed on the basis of three orders of magnitude avalanche frequency and consequences rated qualitatively (proportionality to the risk) with risk rated as: LOW (L), MODERATE (M) and HIGH (H) for environmental damage to forest cover. The standards below for risk acceptability (Tables 2,3) have been developed on the basis of research performed by the Avalanche Research Group at the University of British Columbia on behalf of Forest Renewal BC.

Table 2: Qualitative risk ratings for forest harvest related to damage to timber.

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

6.1.1 Clear-cut Logging Affecting streams and Other Ecological Effects

When streams may be affected by avalanche initiation resulting from logging, the acceptable risk must be more conservative than if timber resources are affected as considered above in Table 2. For this application, the Canadian acceptable risk standard is Avalanche Size 3 with avalanche frequency once in 30 years. Table 3 below gives the applicable risk matrix analogous to Table 2 for timber resources. Other types of ecological damage may also be included within this acceptable risk matrix including sewage lagoons, fuel storage or other toxic waste facilities. Avalanche effects should be assessed on a case by case basis by a qualified registered professional.

Table 3: Risk ratings for forest harvest when facilities are threatened including environmental elements at risk.

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

6.1.2 Logging Affecting Highways, Railways and Main Thoroughfares

It is possible that logging operations may be close to highways, main roads or railways. In this case, the Canadian standard for risk acceptability for avalanches reaching the roads must be estimated taking into account traffic volume, potential length of highway or thoroughfare intersected, expected avalanche frequency, expected maximum avalanche size, proximity to adjacent avalanche paths and terrain configuration below the highway (e.g. steep below the highway or gentle slope) and access by avalanche operational forecaster/control personnel for closures. It is recommended that formal risk calculations taking into account these variables be undertaken if avalanche size reaching the highway is expected to exceed size 2 for frequency greater than 1:10 events per year (return period less than ten years). Avalanches larger than size 2 with annual frequency 1:1 are unacceptable for affecting thoroughfares with significant traffic volumes. Table 3 above contains the qualitative risk matrix covering this case.

warning signs are sufficient. However, when avalanche frequency is about 1:10 events/a or higher an active avalanche control programme is called for with structural protection at key sites and avalanche detection systems on railways. In British Columbia, on major highways there are approximately 70 avalanche areas that need some form of closure and/or explosive control and every major railway is subject to avalanche threats. Table 5 contains threshold frequency and avalanche size criteria . See the publication Canadian Avalanche Association (2002) for more detailed information in regard to planning choices and more details.

6.2 Risk Acceptability for Utilities and Facilities

When decisions are made about placement and design of facilities (roads, railways, parking s, oil, gas, telephone lines, ski lift terminal areas) it is not always appropriate to specify a an acceptable return period and an accurate measure of destructive potential. Since avalanche frequency is the main determining factor for placement and design of such facilities, an acceptable return period is specified and expected impact pressure is estimated for the design avalanche at the site. Table 4 lists acceptable frequencies and critical avalanche size for certain utilities and facilities in Canada. Impact pressures would also have to be determined at the facilities or utilities (excluding terrain) using an avalanche dynamics model.

Table 4: Risk parameters for utilities and facilities

Useage	Threshold frequency (events/a)	Threshold avalanche size
Transmission line	1:100	>2
Surface pipeline	1:100	>2
Telephone line	1:10	>2
Ski lift bases	1:100	>2
Ski lift towers	1:30	>2
Ski area terrain	1:10	>1
Back country terrain	1:10	≥2

6.3 Risk Acceptability for Transportation Routes

Major highways, railways and industrial roads subject to avalanches must rely on risk-based methods to determine if avalanche control by explosives, structural defences or warning signs should be in place. For low avalanche frequency (typically < 1:30 events/a), typically occasional closures, avalanche explosive control and

Table 5: Risk parameters for transportation routes.

Descriptor	Threshold frequency (events/a)	Threshold avalanche size	Typical action or planning
Highway, Railway	1:30	>2	Occasional closure/ control
Highway, Railway	1:10	>2	Continuous control plan; Defences at key sites
Industrial road	1:30	>2	Location planning; safety regulations
Industrial road	1:1 to 1:10	>2	As above plus warning signs ; Occasional closure/ control

7. FUTURE CHANGES FOR OCCUPIED STRUCTURES

For the occupied structures, adopted from European methods, acceptable risk has been specified in terms three zones [Red (no building), Blue (defences, evacuation plan required), White (nominal risk)]. These zones are based on a combination of expected return period (representing the frequency component) and impact pressure (representing the consequence component) where impact pressures are derived from an avalanche dynamics model to predict speeds along the incline.

The Canadian standards (and European standards as well) include the definition of a Blue zone for areas in the runout zone with impact pressures less than 30 kPa. Such a definition is reliant on the impact pressure to drop off slowly in the runout zone to produce a Blue zone with any significant length in the downslope direction. If avalanche speeds drop off rapidly in the runout zone then the impact pressure also does so which implies that a blue zone may have very limited downslope length. However, avalanche speed data (Gubler et al., 1986) consistently show that deceleration is extremely rapid in the runout zone for large avalanches. This, coupled with the uncertainty in predicting avalanche speeds, suggests that such zoning schemes are not viable. McClung (1990) and Borstad and McClung (2008) have illustrated this point by modeling the measured avalanche speeds of Gubler et al. (1986).

The root of the problem lies within the avalanche dynamics models used to predict avalanche speeds from the early work of Voellmy (1955) and still used today in the alpine countries. Instead of relying on speed data, zoning schemes were developed from Voellmy's (1955) avalanche dynamics model and its variants (e.g. Salm, 1993) and Bartelt et al. (1999). Such models contain two friction terms: a constant term representing a dynamic, Coulomb like friction and another dynamic term with a dependence on v^2. For such a model in the runout zone, as the speed slows, overall friction drops to allow slow deceleration.

There are two major problems with this approach: 1. It conflicts with avalanche speed data (McClung,1990; Borstad and McClung, 2008) and 2. There is no experimental confirmation that the v^2 friction term exists based on experimental basal friction measurements by Dent et al. (1993) and data from flowing snow experiments by Platzer et al. (2007). Further, such a friction term is incompatible with theoretical and experimental results on a dense mixture of granular material rapidly deformed (McClung, 1990; McClung, 2002).

Thus, it is suggested that major changes can be expected in acceptable zoning schemes for occupied structures in Canada in the future. Accordingly, , I expect that avalanche dynamics may disappear from risk acceptability specification. Instead, I suggest that empirical methods for estimating return period and runout distance far into the runout zone will dominate to specify acceptable risk for occupied structures. The role of avalanche dynamics models to determine expected impact pressures for engineering design will remain, however.

APPENDIX A: DEFINITION OF PROBABILITY SYMBOLS

Intersection: Let A and B be events, then $A \cap B$ denotes that event A occurs and then B occurs after A has occurred. Thus, $P(A \cap B)$ denotes the probability that event A occurs followed by event B.

Conditional probability: The conditional probability: $P(A|B)$ of event A is the probability of A under the assumption that B has occurred (it is assumed that the probability of B is positive). The probability for the product of two events is defined by: $P(A \cap B) = P(A)P(B|A) = P(B)P(A|B)$. If events A and B are independent, then $P(A \cap B) = P(A)P(B)$.

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

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

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

Bayes Rule:

Bayes Rule may be stated in the form: $P(H_k|A) \alpha P(H_k) L(H_k|A)$ where in prose, $P(H_k|A)$ is termed Posterior Probability, $P(H_k)$ is termed Prior Probability and $L(H_k|A)$ is Likelihood. The Likelihood of hypothesis H_k is then proportional to the conditional probability $P(A|H_k)$ up to an arbitrary constant.

For example, for the Canadian avalanche size system (a set of mutually exclusive sizes i = 1,...5): $P_B(S_i|A) \alpha P_B(S_i) L_B(S_i|A)$: the probability of an avalanche of size i given data on avalanche occurrence A (data about some defined characteristics) is proportional to the probability of avalanches of size i at location B (normally the fraction of avalanches of size i at a location from general, prior information) times the Likelihood of avalanches of size i at location B given site specific data there or results of models. In mapping applications, often the Posterior is determined from the Prior only unless large data bases of avalanche occurrences are available. Thus, Bayes Rule provides the formalism for this common application. If site specific data are included in the analysis, either mathematically or judgmentally, then the Posterior Probability has been updated accordingly.

Clearly, the set of hypotheses could be the attributes at a particular site for a given building type e.g. X_1 - nominal damage, X_2 - partial destruction or X_3 - total destruction with the Posterior Probability constructed from application of avalanche dynamics modelling for the site based on friction parameters determined from other sites (Prior information) and site specific data (terrain profiles, snow supply, roughness and others).

APPENDIX B: CANADIAN AVALANCHE SIZE CLASSIFICATION

The Canadian avalanche size system is based on estimating the destructive effects of avalanche events. The system is similar in concept to the Mercalli Scale for earthquake intensity and like the Mercalli Scale, it is possible to estimate destructive potential. Guidelines for sizing depend on: avalanche mass, distance moved along the incline, estimated maximum impact pressure and water content of the debris: dry snow avalanches or wet snow avalanches. The system has been developed from experience and measurements to cover snow avalanche destructive potential for snow avalanches of all known size. The system has 5 classes for which approximately an order of magnitude in destructive potential is estimated for each increase in size. In general, the frequency of avalanches decreases as the size increases. The paper by McClung and Schaerer (1989) contains the theoretical argument and data on which the system is based. It is customary in Canada for avalanche observers to record events using half sizes (e.g. size 2.5). However, due to associated uncertainty, whole sizes are used in this document to describe destructive potential. In land-use planning, it is recommended to use only whole sizes. Tables B1.1 and B1.2 contain the size system.

Table B1.1: Canadian avalanche size classification system (McClung and Schaerer, 2006) and destructive effects.

Size	Destructive effects
1	Relatively harmless to people
2	Could bury, injure or kill a person
3	Could bury a car, destroy a small building or break trees
4	Could destroy a railway car, large truck, several buildings or a forest of about 4 ha.
5	Largest snow avalanches known; could destroy a village or a forest of about 40 ha

Table B1.2: Canadian avalanche size system with quantitative descriptors.

Size	Typical mass (t)	Typical path length (m)	Typical impact pressure (kPa)
1	10	10	1
2	100	100	10
3	1000	1000	100
4	10000	2000	500
5	100000	5000	1000

APPENDIX C: CANADIAN AND SWISS STANDARDS COMPARED IN THE RUNOUT ZONE

In this Appendix, the relationship between impact pressure and return period for the theoretical design avalanche is derived from simple assumptions. The design avalanche is characterized by three numbers: initial impact pressure (I_0) at arrival in the upslope start of the runout zone (30 kPa for Swiss and Canadian standards), initial return period at arrival in the upslope start of the runout zone T_0 (30 years for Swiss and Canadian standards) and return period T_m at the downslope end of the blue zone (300 years for Swiss and Canadian standards). Assumptions are: 1. impact pressure decreases linearly with distance,x, into the runout zone. This assumption is compatible with the Swiss Guidelines (1990) and the model of McClung and Mears (1995) where flow density is assumed approximately constant (incompressible flow). 2. It is assumed that extreme runout follows a Gumbel distribution as a function of x governed by a spatial non-exceedance probability P or a spatial return period T_s related to P by: $P = 1 - 1/T_s$. Since impact pressure and spatial return period are both assumed to vary with x, it is possible to relate these quantities in the runout zone by eliminating x. With the model of McClung (2000), it is possible to relate return period in the runout zone to x and T_0 so that return period and impact pressure are determined analytically in the runout zone.

C.1 Spatial Return Period and Return Period in the Runout Zone

From McClung and Mears (1991) and McClung (2000), it is assumed that extreme runout obeys a Gumbel distribution with scale parameter (b) and location parameter (u) for a given mountain range. This gives the expression:

(C1) $x = u + b[-\ln(-\ln P)]$

Now if $T_s >> 1$ (as in the runout zone) this expression can be written:

(C2) $x \approx u + b \ln (T_s)$ or alternatively

(C3) $T_s = \exp [(x-u)/b]$

From McClung (2000), the return period in the runout zone may be written:

(C4) $T = 1/[1 - \exp-(1/(T_sT_0)]$ where it assumed that avalanches arrive in the runout zone according to a Poisson process with initial return period T_0 (see McClung, 2000 for details).
Expansion of expression (C4) when the product $T_sT_0 >>1$ yield the expression:

(C5) $T = T_0 \exp [(x^*)/b]$ where x* is a reference position for beginning the runout zone (x* = x - u).

C.2 Speed and Impact Pressure in the Runout zone

From the Swiss Guidelines (1990) and from McClung and Mears (1995), the speed in the runout zone may be given by:

(C6) $v^2 = v_0^2 (1 - x^*/x_L)$ where x_L represents the stop position where the return period has the maximum value for the design avalanche (T_m). Equivalently, for constant density, the impact pressure [from (C6)] may be expressed as:

(C7) $I = I_0 (1 - x^*/x_L)$

From (C7) and (C5) x* can be eliminated and with $T = T_m$ when $x^* = x_L$, the relationship between impact pressure and return period for the theoretical design avalanche becomes:

(C8) $I = I_0 [1 - \log_{10}(T/T_0)]$ where $T_0 \leq T \leq T_m$.

It may then be said that if risk is taken proportional to impact pressure x 1/(return period) that risk (for the theoretical design avalanche) is proportional to : I/T where I is given by (C8).

The Canadian standard relating impact pressures and return periods for the blue zone is then taken to be:

(C9) $I/T < 0.1\ I_0/T_0 \quad T_0 \leq T \leq T_m$

or 10% of the initial risk (proportionality) of the design avalanche at the beginning of the runout zone. The risk is considered nominal for estimated impact pressures ≤ 1 kPa in the Canadian standard.

For comparison, the Swiss standard (Switzerland, 1984; p.16) relating impact pressures and return periods for the blue zone is:

(C10) $I/I_0 < \log_{10} (T/T_0)$ where $T_0 \leq T \leq T_m$

For impact pressures less than 3 kPa, the Swiss standard stipulates that zone colour may be blue or yellow in the return period range given (Switzerland, 1984; p. 16).

The risk-based Canadian standard I/T <0.1 can be seen to be slightly more conservative than the Swiss standard McClung, 2005).. The Canadian standard gives equal weighting (from a risk perspective) to impact pressures and avalanche frequency whereas the Swiss standard gives higher weighting to impact pressures meaning acceptable impact pressures at a given return period are slightly higher than for the Canadian standard.

The new Austrian standard (Höller and Schaffhauser, 2001) is more conservative than the Canadian standard in that for the same return period allowable impact pressures are less than for the Canadian standard. The theoretical basis for the Canadian standard is equal (proportional) weighting of impact pressure and avalanche frequency in risk determination. The basis of Swiss and Austrian proposals is largely ad-hoc conditioned by experience.

APPENDIX D: BAYESIAN APPROACH FOR MAPPING AND OTHER APPLICATIONS AND RELATION TO CANADIAN AVALANCHE SIZE CLASSIFICATION

The probable consequences in the risk definition and the expected damage in the engineering
definition contain a conditional probability of the form: $P_B(X_i|A)$ where X_i is an attribute representing destructive potential (one of a set of mutually exclusive attributes) and A represents data about avalanche occurrence with some defined characteristics. As written, this conditional probability may be regarded as the Posterior Probability in Bayes Rule. Bayes Rule states (e.g. Press, 1989) : Posterior Probability α Prior Probability x Likelihood. The Prior Probability (hereafter called the Prior) represents more general information about consequences which is usually not specific to the site in question (information obtained from generally about the problem perhaps collected from other sites). The Prior may be regarded as constructed from mostly distributional data. The Likelihood represents usually represents information specific to the site in question and is mostly constructed from singular data. Formally, Bayes rule can be expressed: $P_B(X_i|A) \alpha P_B(X_i) L_B(X_i|A)$ where the Prior is represented as $P_B(X_i)$ and the Likelihood is represented as $L_B(X_i|A)$. If no information is incorporated in the analysis which is site specific then the Posterior is represented as the Prior. This is very common in avalanche mapping. However, if site specific information is included in the analysis or as judgmental input, then the Posterior will be essentially updated using Bayes Rule as above.

As an example, consider the case described above for avalanche hazards on roads. The Posterior Probability may be represented as: $P_C(S_i|A_j \cap E_j)$. In applications, this would require data representing the distribution of avalanche sizes for path j when the road is open. In practice, there would not normally be enough data to perform such calculations. Instead, one might substitute the distribution of avalanche sizes which reach the road when the road is open for the general avalanche area and this would be represented by the Prior: $P_C(S_i)$ which may suffice for order of magnitude estimates. Expected damage would then be estimated by $P_C(S_i)V_C(S_i)$ where $V_C(S_i)$ represents a vulnerability (loss) vector expressed as fraction of loss for avalanche sizes i = 1-5.

In many avalanche mapping applications there will not be enough information (or data) to expand the Posterior (conditional probability) in probable consequences so that the Prior is substituted for the Posterior. However, the power of Bayesian approaches is to provide a formalism for which judgmental information can be included which is what avalanche mappers do: the Prior is updated with site specific information by including the Likelihood: $L_B(X_i|A)$ which contains the site specific information provide the Posterior. The Likelihood of a specific attribute, (for example, partial destruction of a building) given an avalanche with site specific characteristics is provided by experience, field observations and judgmental reasoning. Bayesian statistics are usually not calculated per sé but the Posterior is estimated from past experience and evidence at the site. Pearl (1988) gives the formalism for Bayesian updating as more information is added. This is a formalism which can be followed when adding information sequentially. For example, using Geographic Information Systems (GIS) to make avalanche risk maps by adding information sequentially should follow this strategy and expert systems could be constructed using this framework.

Input of judgmental information, as described above, is usually more difficult than information determined by theoretical models. It requires a knowledge of geoscience and engineering principles conditioned by experience as well as the basis for models, their limitations and appreciation for uncertainty. The power of a Bayesian framework is that judgmental information and information from deterministic or statistical models can be combined in many ways and this is what avalanche mappers do. In most cases, the Prior is updated with site specific information judgmentally to obtain the Posterior without explicit, formal mathematical procedures. However, mastery of geoscience and engineering principles with appreciation for uncertainty and experience is needed for proper input to mapping and other applications.

8. ACKNOWLEDGEMENTS

The work in this paper was supported by Canadian Mountain Holidays, the Natural Sciences and Engineering Research Council of Canada and the National Search and Rescue Secretariat of Canada. I am grateful for all the support.

9. REFERENCES

Bartelt, P., B. Salm and U. Gruber. 1999. Calculating dense-snow avalanche runout using a Voellmy-fluid model with active/passive longitudinal straining, *J. Glac*. 45(150: 242-254.

Borstad, C.P. and D.M. McClung. 2008. Sensitivity analyses in snow avalanche dynamics modeling , implications and modeling extreme events, submitted to: *Can. Geotech. J.*

Canadian Avalanche Association. 2002, Guidelines for snow avalanche risk determination in Canada , D.M. McClung, C. Stethem, P. Schaerer (Eds), *Canadian Avalanche Association,* Revelstoke, B.C., 23 pp.

Cave, P.W. 1992. Hazard acceptability thresholds for development approvals by local government, in : Proc. Of the Geologic Hazards '91 Workshop, Feb. 20-21, 1992, *B.C. Geol. Survey Branch, Open File* 1992-15: 15-21.

de Quervain. M.R. 1975. Lawinendynamik als grunlage fuer die ausscheidung von lawinen zonen. In: *Proc. of Inrepraevent.* Vol. 2: 247 -267.

Dent, J.D., K.J. Burrell, D.S. Schmidt, M.Y. Louge, E.E. Adams and T.G. Jazbutis. 1998. Density, velocity and friction measurements in a dry-snow avalanche. *Ann. Glaciol.* 26: 247 -252.

Einstein, H.H. 1988. Special lecture: landslide risk assessment. In : *Proc. Of the 5th Intll Symp. on Landslides*, Lausanne, Switzerland: 1075-1090.

Gubler, H., H. Miller, G. Klausegger and U. Suter. 1986. Messungen an fleisslawinen, *Eidg. Inst. fuer Schnee und Lawinenforsch. Internal Report 41*, Davos, Switzerland, 71 pp.

Hoeller, P. and H. Schaffhauser. 2001. The avalanches of Galtuer and Valzur in Feb. 1999. In : *Proc. International Snow Science Workshop*, Oct. 1- 6, 2000, Big Sky Montana: 514-518.

Keylock, C.J., D.M. McClung and M. Magnússon. 1999. Avalanche risk mapping by simulation, *J. Glac*. 45(150): 303-314.

LaChapelle, E.R. 1966. Encounter probabilities for avalanche danger. *U.S.D.A. Forest Service, Alta Avalanche Study Center, Misc. Report* 10, 10 pp.

McClung, D.M. 1990. A model for scaling avalanche speeds. *J. Glac*. 36(123): 188-198.

McClung, D.M. 1999. The encounter probability for mountain slope hazards, *Can. Geot. J*. 36(6): 1195-1196.

McClung, D.M. 2001. Superelevation of flowing avalanches around curved channel bends, *J. Geophys. Res*. 106(B8): 16489-16498.

McClung, D.M. 2000. Extreme avalanche runout in space and time, *Can. Geotech. J.* 37: 161 -170.

McClung, D.M. 2002 (a) The elements of applied avalanche forecasting part I: the human issues, *Natural Hazards* 26(2): 111 -129.

McClung, D.M. 2002(b) The elements of applied avalanche forecasting part II: the physical issues and the rules of applied avalanche forecasting, *Natural Hazards* 26(2): 131-146.

McClung, D.M. 2005. Risk-based definitions of zones for land-use planning in snow avalanche terrain, *Can. Geotech. J.* 42: 1030 – 1038.

McClung, D.M. and P.A. Schaerer. 1985. Characteristics of flowing snow and avalanche impact pressures, *Ann. Glaciol*. 6: 9-14.

McClung, D.M. and A.I. Mears. 1991. Extreme value prediction of snow avalanche runout, *Cold Reg. Sci. and Tech.* 19: 163-175.

McClung, D.M. and A.I. Mears. 1995. Dry-flowing avalanche run-up and run-out. *J. Glac*. 41(138): 359-372.

McClung, D.M. and F. Navin. 2001. Linear risk maps for avalanches on highways. Unpublished paper.

McClung, D.M. and P.A. Schaerer. 1981. Snow avalanche size classification. In *Proceedings of Avalanche Workshop, Canadian Avalanche Committee (Eds)*, Associate Committee on Geotech. Res. Technical Memo. 133, Ottawa: National Research Council of Canada, 12-27.

McClung, David and Peter Schaerer .2006. The avalanche handbook, *The Mountaineers Books*, Seattle, WA, USA, 342 pp.

McCormick, Norman J. 1981. Reliability and risk analysis, *Academic Press*, N.Y. 446 pp.

Mears, A.I. 1992. Snow-avalanche hazard analysis for land-use planning and engineering, *Colorado Geol. Surv. Bulletin* 49, Denver, 54 pp.

Morgan, G.C. 1990. Quantification of landslide risks from slope hazards, Preprint: Landslide hazard in the Canadian Cordillera, *Geol. Surv. Of Canada*, 17 pp.

Pearl, J. 1988. Probabilistic reasoning in intelligent systems: networks of plausible inference, *Morgan Kaufmann Publishers*, San Mateo, CA, 522 pp.

Platzer, K., P. Bartelt, and M. Kern. 2007. Measurements of dense snow avalanche basal to normal stress ratios (S/N). *Geophys. Res. Lett*. L070501, doi:10.1029/2006GL028670.

Salm, B. 1993. Flow, flow transition and runout distances of flowing avalanches, *Ann. Glaciol*. 18: 221-226.

Salm, B. 1997. Principles of avalanche hazard mapping in Switzerland , In: *Snow Engineering: Recent Advances , Izumi, Nakamura and Sack (eds), Balkema*, Rotterdam: 531 - 538.

Salm,B., A. Burkhard and H.U. Gubler. 1990. Berechnung von fleisslawinen. Eine Anteleitung fuer Praktiker mit Beipielen, *Mitteillungen des Eidg. Insts. fuer Schnee und Lawinenforsch.* 47, Davos, Switzzerland, 37 pp.

Sovilla, B., P. Burlando and P. Bartelt. 2006. Field experiments and numerical modeling of mass entrainment in snow avalanches, *J. Geophys. Res*. 111, F03007, doi:10.1029/2005JF000391.

Switzerland. 1984. Richtlinien zur Beruecksichtigung der Lawinengefar beiraumwirksamen Taetigkeiten. Besamt fuer Forstwesen, *EISLF, EDMZ, Bern* , 34 pp.

Varnes, D.J. 1984. Landslide hazard zonation: a review of princiles and practice. Natural Hazards 3, *UNESCO*, 63 pp.

Voellmy, A. 1955. Über die zerstoerungskraft von lawinen, *Schweiz. Bautzg*. 73(12); 159-162, 73(15), 212-215; 73(19), 282-285.