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Avalanche Risk During Backcountry Skiing – An Analysis of Risk Factors

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Abstract. Skier-triggered avalanches are the main cause of avalanche accidents in backcountry skiing. The risk of accidents during backcountry skiing was analysed statistically and related to factors such as elevation level, aspect, stability rating and the time of the year. The analysis is based on a database about terrain usage and avalanche accidents from a large heli-skiing operator in Canada, which makes it possible to study the conditional probability of accidents given the recorded pattern of terrain usage. This study shows that the historical risk of accidentally triggering an avalanche greater than size 1 depends highly on the stability rating, with the highest risk occurring during "poor" stability. The risk is greater at high elevations, and it is lower during the late season than earlier on. Skier risk does not depend as much on aspect as may be indicated from avalanche data alone. However, it is relatively high in the N–NE–E sector. These factors are not independent of each other and therefore analyses of combined factors were also performed. Questionnaires and interviews were used to gain knowledge about the terrain selection of professional mountain guides. These results indicate that when selecting terrain, guides first look at the overall shape and size of the terrain, but avalanche history of terrain and inclination are also important factors. Finally, remarks in avalanche reports were analysed, and common human factors identified.

Key words: avalanche risk management, human triggered avalanches, risk analysis, avalanche risk, recreation, backcountry skiing, mountain guides, snow avalanches, Columbia Mountains, helicopter-skiing

1. Introduction

In recent decades, backcountry skiing and backcountry travelling in mountains during winter has become increasingly popular in Canada. The most important risk associated with this kind of travelling is snow avalanches and about half of the avalanche victims in Canada the last 20 years were backcountry skiers. In the period from 1998 to 2003, an average of 16 people per year, have lost their lives to avalanches (Jamieson and Geldsetzer, 1996; CAA, 2005).

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Avalanches occur naturally on rare occasions, typically for a total of a few hours each winter (McClung, 2000). It is estimated that for 85–90% of backcountry avalanche accidents, the avalanche is triggered by the victim or someone in the victim's party (e.g. Jamieson and Geldsetzer, 1996; Logan and Atkins, 1996; Tremper, 2001; McCammon, 2000; Schweizer and Lütschg, 2001). Human influences can therefore not be excluded when considering data on the triggering of avalanches. No avalanche occurrences in a certain area during a given period might simply reflect a low number of travellers rather than low risk. Information on where and when people travel in the backcountry is usually not available, and this is one of the obstacles when analysing risk due to human triggered avalanches.

The database used in this study contains information on the usage of defined ski runs within a helicopter skiing operation, as well as information on avalanches, which enables an analysis of the usage of certain terrain factors, stability ratings and time periods. Therefore, it is possible, perhaps for the first time, to analyse the risk associated with the different factors quantitatively.

Information about the terrain factors affecting terrain selection of professional mountain guides was collected via questionnaires and interviews.

Remarks in avalanche reports for avalanches involving human activity were analysed in order to identify some common human factors leading to the avalanche.

2. Avalanche and Usage Data

The database of Canadian Mountain Holidays (CMH) is called "Snowbase" and it contains good data on skier-triggered avalanches as well as information on the usage of CMH's defined ski runs.

CMH is the largest heli-skiing operator in the world, operating on more than 20,000 km^2 of land in the Cariboo, Monashee, Purcell and Selkirk mountain ranges of the Columbia mountains, British Columbia. Elevation ranges from 400 m in valley floors to approximately 3500 m above sea level. The snow climate is transitional with a strong maritime component (Hägeli and McClung, 2003).

The analysis in this section is based on data on all skier-triggered avalanches, greater than size 1 in *Snowbase* until April 2002, excluding skier controlled avalanches. The sizes are recorded according to the Canadian classification system (McClung and Schaerer, 1993) and by definition, a size 1 avalanche is relatively harmless to people and a size 2 avalanche could bury, injure, or kill a person. Here, this dataset is referred to as: "accidentally skier-triggered avalanches greater than size one". The total number of such avalanches is 345, and the majority (97%) are dry slab avalanches.

The usage data in the analysis are based on information from *Snowbase* on the daily usage of ski runs, until April 2002. A Geographical Information System (GIS) was used for the analysis. In British Columbia a regular grid DEM data set has been created with the grid spacing of 25 m. It is created from the 1:20,000 scale Terrain Resource Information Management (TRIM) Digital Elevation Model (Ministry of Sustainable Resource Management, 1996). The TRIM DEMs, along with polygons showing the defined ski runs, were used to define elevation levels and aspects for the individual ski runs. In total, 7 years of avalanche data and 4 years of usage data were analysed. The usage data consists of more than 20,000 skier days, when one skier day is defined as one run being used during one day.

For the purpose of the calculations in this paper, risk will be defined as following:

Risk: The probability of accidentally triggering an avalanche greater than size 1

This definition of risk reflects a kind of acceptability; it is suggested that it is always a mistake to accidentally trigger an avalanche greater than size 1, since a size 2 avalanche can bury, injure or kill a skier. The avalanches are recorded in half sizes, and in order to be slightly conservative, size 1.5 is included in the dataset.

The relative risk is analysed in terms of four different factors: (1) elevation level, (2) stability rating, (3) aspect, and (4) time of the year.

3. Analysis of individual risk factors

3.1. ELEVATION LEVELS

Elevation level can significantly affect avalanche risk. In the alpine elevation level there is no forest cover to prevent avalanches from starting. Also, formation of weak layers such as surface hoar is often dependent on forest cover and temperatures, and therefore, on elevation. Furthermore, precipitation and wind speed is often greater at higher elevations than lower down.

3.1.1. *The altitude of starting areas*

The three defined elevation levels in *Snowbase* are: alpine, treeline and sub-treeline. According to CMH guides (Colani Bezzola, personal communication, 2003) the elevations of these levels are approximately:

Alpine >2200 m a.s.l.
Treeline >1800 and ≤ 2200 m a.s.l.
Sub-treeline: ≤ 1800 m a.s.l.

In *Snowbase*, the maximum elevation in meters above sea level is given for the starting areas of the triggered avalanches. It is not an exact measurement and is usually recorded in 100 m increments.

3.1.2. *Usage of elevation levels*

The number of people that used a specific run on a given day, is recorded in *Snowbase*. In order to estimate the usage of elevation levels for this research, a digital elevation model (DEM) and GIS were used to define the elevation levels of the runs. If all or a part of a run lies above 2200 m a.s.l. it is assigned a checkmark for "alpine". For every day this run was used, the count 1 is added to the usage of "alpine", and correspondingly for the other two levels. One run can have a checkmark for one, two or all three elevation levels.

This is not an accurate measurement of usage of elevation levels, since the usage of a large run that lies completely in the alpine adds the same value to the usage of "alpine" as the usage of a run with only a small part in the alpine. We are, however, looking at thousands of runs in total, and about 45,000 user days (in this case: 1 user day = 1 elevation level of a run being used on 1 day) and therefore, this error should not affect one elevation level more than others. We have assumed that the errors mostly cancel out.

Results. Let:

E_i = Elevation level (i = alpine, treeline, sub-treeline)
A_s = Accidentally skier-triggered avalanche greater than size 1

Then:

$P(E_i|A_s)$ is the probability of a given elevation level, given a skier-triggered avalanche greater than size 1, that is the fraction of avalanches that fell in the given elevation level.
$P(E_i)$ is the fraction of time spent in an elevation level, during skiing.

In Figure 1, $P(E_i|A_s)$ is compared to $P(E_i)$: the elevation levels of avalanches are compared to the usage of elevation levels.

For a binomial random variable representing the number of successes in n trials where the probability of success in each trial is π, the confidence interval for π at a level of confidence $1 - \alpha$ is:

$$p - z_{\alpha/2}\sqrt{(p(1-p)/n)} \leq \pi \leq p + z_{\alpha/2}\sqrt{(p(1-p)/n)}$$

or

$$p \pm z_{\alpha/2}\sqrt{(p(1-p)/n)} \qquad (1)$$

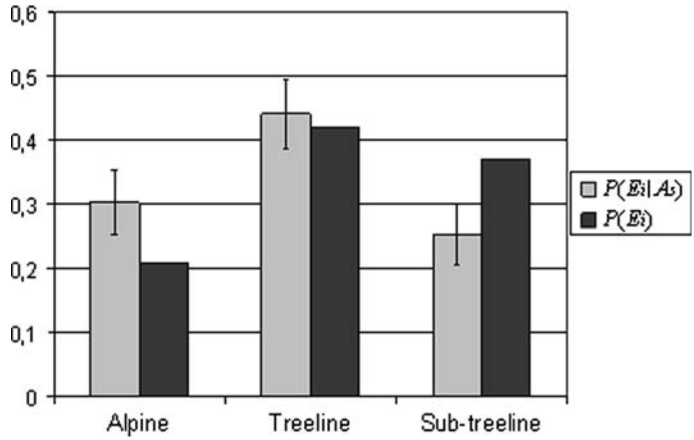

Figure 1. Comparison of the elevation level of avalanches [$P(E_i|A_s)$] with 95% confidence interval and usage of elevation levels [$P(E_i)$].

where p is the sample proportion of successes in n trials and $z_{\alpha/2}$ is the value of the standard normal distribution with an upper-tail probability of $\alpha/2$ (Barber, 1988).

For the trinomial distribution, the confidence intervals for the probabilities of the three outcomes are:

$$p_i \pm z_{\alpha/2}\sqrt{(p_i(1-p_i)/n)}, \quad i = 1, 2, 3 \tag{2}$$

There are no confidence intervals displayed for the usage data, since the sample is about 45,000 user days (1 user day = 1 elevation level of a run being used on 1 day) and thus, the uncertainty is negligible.

Figure 1 shows that more avalanches fell in the treeline than in other elevation levels, or almost 45% of the avalanches. About 30% fell in the alpine and 25% in the sub-treeline. However, the alpine part of runs were used only about 21% of the time, while the treeline sector was used about 42% of the time and the sub-treeline sector about 37% of the time.

One way to look at the historical risk it is to use Bayes' Rule (Press, 1989):

$$P(E_i|A) = \frac{P(E_i)P(A|E_i)}{\sum_{i=1}^{3} P(E_i)P(A|E_i)} \tag{4}$$

When E_i is three elevation levels: $i = 1,2$ or 3: they are mutually exclusive.

Alternatively, as the denominator is constant

$$P(E_i|A) \propto P(E_i)P(A|E_i) \tag{5}$$

The likelihood is defined as (Edwards, 1992):

$$L(E_i|A) \propto P(A|E_i) \quad (6)$$

Consequently Bayes' rule becomes:

$$P(E_i|A) \propto P(E_i)L(E_i|A) \quad (7)$$

In words:

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior} \quad (8)$$

Or:

$$\text{Likelihood} \propto \text{Posterior/Prior}$$

In our case, likelihood represents the proportional, historical risk of accidentally triggering an avalanche greater than size 1 in the different elevation bands. Results for the elevation bands are shown in Figure 2. The historical risk or likelihood of triggering an avalanche greater than size 1 is more than two times higher in the alpine than sub-treeline, and the risk in the treeline is approximately in between. Within the 95% confidence level for the avalanche data, the difference is statistically significant. Thus, the historical risk or likelihood increases on average with higher elevation levels.

3.2. STABILITY RATINGS

3.2.1. *Stability ratings when avalanches fell*

The guides of each operation area at CMH, rate the stability of the snowpack every morning and afternoon. The five stability ratings are: very

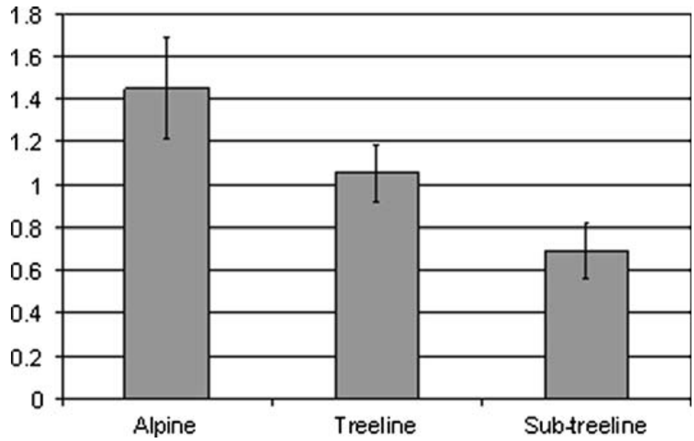

Figure 2. The relative risk or likelihood in the different elevation levels: $P(E_i|A_s)/P(E_i)$. Confidence limits are derived from $P(E_i|A_s)$.

poor, poor, fair, good and very good. The rating is given for the three different elevation levels: alpine, treeline and sub-treeline. Thus, in order to define under which stability rating an avalanches fell, the elevation of the starting areas has to be taken into account. For example, an avalanche within the alpine starting area fell under the stability rating given in the guides' morning meeting for the alpine region that day.

Here, the stability ratings "good" and "very good" are combined into one group: G/VG and the same applies to the stability ratings "poor" and "very poor". The stability rating "fair" is treated separately. The reason is that the stability ratings "very good" and "very poor" are used relatively seldom (less than 2% of the time), and the combination of the groups simplifies the analysis and results.

3.2.2. *Usage of stability ratings*

The stability rating is given for the three different elevation levels daily. For example, if a stability rating is "fair" in the alpine on a given day, then for each run used that day, which is partly or fully in the alpine, the count 1 (1 user day = 1 elevation level in 1 run being used for 1 day) is added to the usage of the stability rating "fair". The accuracy of the measurements is affected by the same errors as for the analysis of the usage of elevation levels.

Results. Let:

S_i = Stability rating $\quad (i$ = VP/P, F, G/VG)

Then:

$P(S_i|A_s)$ (posterior) is the probability of a stability rating, given a skier-triggered avalanche greater than size 1.
$P(S_i)$ (prior) is the fraction of time a stability rating is used.

$P(S_i|A_s)$ is compared to $P(S_i)$ in Figure 3, showing that more than half of the avalanches fell under the stability rating "fair" and almost 30% under "very poor" or "poor" (VP/P) stability ratings. However, the stability rating "fair" (F) was used almost half of the time, while VP/P were used only 8% of the time. Thus, the historical risk or likelihood under VP/P stability ratings is higher than under "fair" stability rating.

The likelihood is calculated as:

$$L(S_i|A_s) \propto P(S_i|A_s)/P(S_i)$$

The results are displayed in Figure 4, which shows that the probability of triggering an avalanche greater than size 1, under the stability rating "poor" or "very poor" is about 3.5 times higher than under "fair"

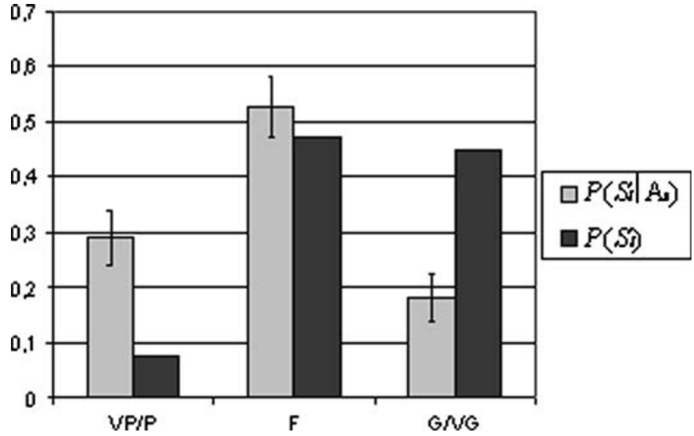

Figure 3. Comparison of the stability ratings under which avalanches fell [$P(S_i|A_s)$] and usage of stability ratings [$P(S_i)$].

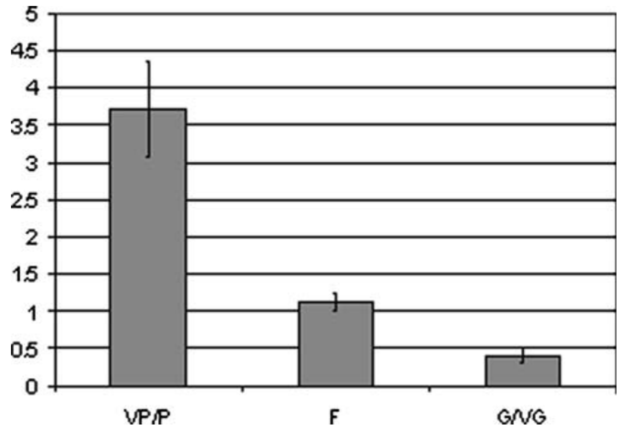

Figure 4. The likelihood under different stability ratings: $P(S_i|A_s)/P(S_i)$.

stability rating. The risk under "fair" is more than two times higher than under "good" or "very good" stability ratings.

3.3. ASPECT

Because of solar radiation and wind-drifted snow, the strength and thickness of the snowcover and distribution of weak layers can vary with the aspect.

3.3.1. *Aspect of avalanches*

The starting areas are recorded with eight different aspects: N, NE, E, etc. The recorded aspect is often an estimation of the guide, rather than an accurate measurement.

3.3.2. *Usage of aspects*

With the help of DEMs and GIS, each run is assigned a main aspect. If a run with the main aspect "North" is used for one day, the count 1 (1 user day) is added the usage of "North". This is not an accurate measurement of the usage of aspects since within each run, starting areas with variable aspects may be found. However, we assume the errors are random so that they cancel out due to the high number of runs and user days.

Results. Let:

AS_i = Aspect of starting areas $(i$ = N, NE, E, SE, S, SW, W, NW)

Then:

$P(AS_i|A_s)$ (posterior) is the probability of an aspect of starting area, given an accidentally skier-triggered avalanche greater than size 1.
$P(AS_i)$ (prior) is the fraction of time each aspect is used.

Figures 5 and 6 show that most avalanches fell in northern, northeastern and eastern aspects, which are the lee and shady aspects. These, along with northwest, are also the aspects that are most frequently used. However, the difference between avalanche occurrences and usage is greatest in north aspect, as 25% of the avalanches fell there, but it was only used about 17% of the time.

The uncertainty is relatively high when the data is divided to eight classes instead of three before, and it is relatively high in southern aspects because the number of avalanches is lower than in other aspects.

The likelihood is calculated as:

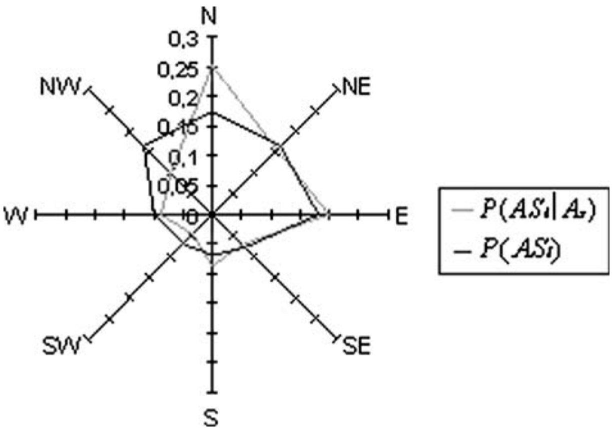

Figure 5. Comparison of aspect of avalanches $[P(AS_i|A_s)]$ and usage of aspects $[Pt|AS_i)]$.

$$L(AS_i|A_s) \propto P(AS_i|A_s)/P(AS_i)$$

The likelihood is on average greater in the main aspects; N, S, E and W than other aspects, which is at least partly due to inaccurate recording of aspect of avalanches. We suggest that in reality the likelihood is probably more evenly spread between aspects.

Figures 5–7 indicate that the risk of triggering avalanches greater than size 1 is not as dependent on the aspect as suggested by data on avalanche occurrences alone. On average, the risk is lower in the western (SW–W–NW) sector than other aspects. Figure 7 shows that, in terms of 180° sectors, the risk is generally slightly higher on east aspects than west aspects, but there is little difference between north and south aspects.

3.4. TIME OF THE YEAR

The characteristics of the snowcover change significantly from the early winter, to mid-winter and towards the spring. In co-operation with CMH guides (Colani Bezzola, personal communication, 2003), three time periods within the skiing season were defined:

(1) *Early winter*: December 1–January 31
(2) *Mid-winter*: February 1–March 15
(3) *Late season*: March 16–April 31.

Results. Let:

T_i = Time of the year,
(T_1 = Dec 1–Jan 31, T_2 = Feb 1–Mar 15, T_3 = Mar 16–Apr 31)

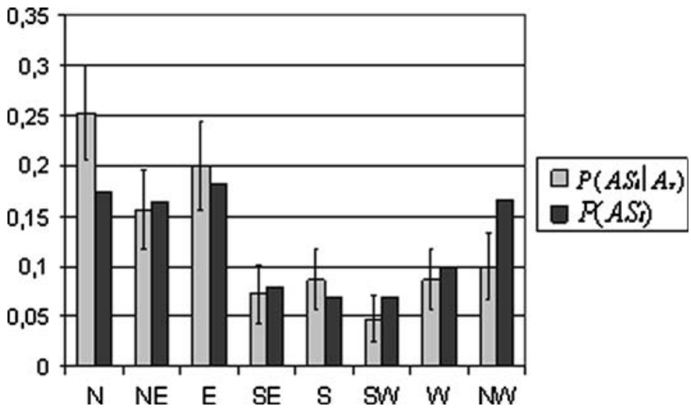

Figure 6. Comparison of aspect of avalanches [$P(AS_i|A_s)$] and usage of aspects [$P(AS_i)$].

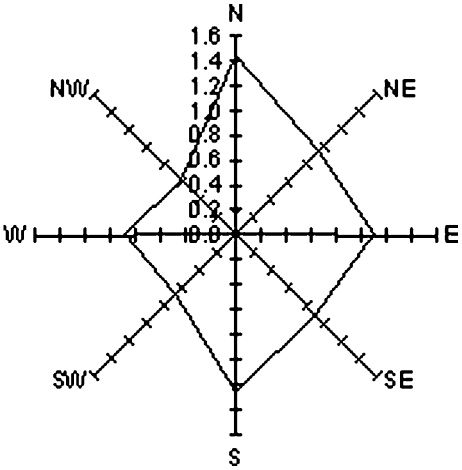

Figure 7. A radar plot of the likelihood in different aspects: $P(AS_i|A_s)/P(AS_i)$.

Then:

$P(T_i|A_s)$ (posterior) is the probability of a time period, given a skier-triggered avalanche greater than size 1.

$P(T_i)$ (prior) is the fraction of skiing that takes place in a given time period.

$P(T_i|A_s)$ is compared to $P(T_i)$ in Figure 8.

The likelihood is calculated as:

$$L(T_i|A_s) \propto P(T_i|A_s)/P(T_i)$$

The results are shown in Figure 9. The historical risk or likelihood during late season is only half of what it is during mid-winter. There are at least two possible reasons for that: (1) The snowpack is probably on average more stable during late season than earlier on due to fewer active persistent layers and fewer large storms. (2) During late season the instability is often due to solar radiation, which is a relatively manageable factor for professional guides. The difference between early winter and mid-winter is insignificant.

3.5. SUMMARY OF INDIVIDUAL FACTORS ANALYSES

In Table I, the individual factors from the risk analysis are listed with the factor associated with the highest likelihood first.

Table I shows that the historical risk or likelihood depends most on stability ratings of the factors analysed in this research. The highest risk overall was under VP/P stability ratings and the lowest risk under G/VG

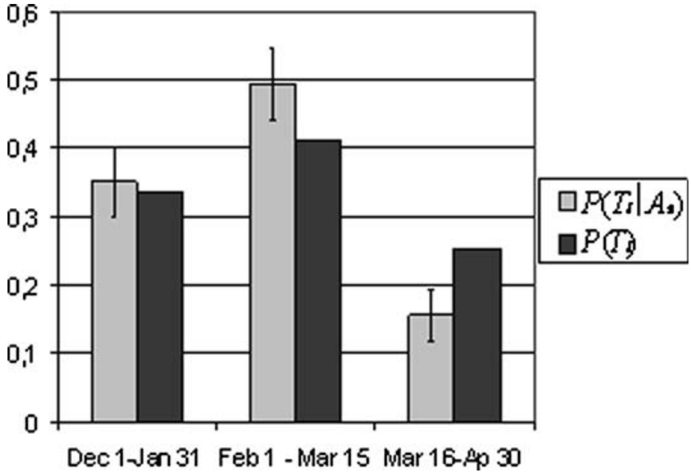

Figure 8. Comparison of the time periods when avalanches fell [$P(T_i|A_s)$] and the usage of time periods [$P(T_i)$].

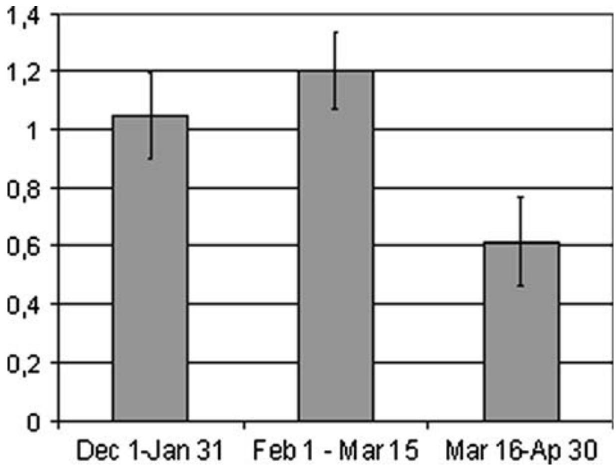

Figure 9. The likelihood during different time periods: $P(T_i|A_s)/P(T_i)$.

stability ratings. The difference between late season and the earlier time periods is also significant, while the difference between mid-winter and early winter is not. Thus, early winter and mid-winter can be combined to one class which has significantly higher risk than late season. The variation in likelihood with elevation levels is also significant. It is difficult to estimate the variation of likelihood with aspects. Here the aspects are combined to three groups, but when looked at in terms of 180° sectors there is not a significant difference between northern and southern aspects, but the risk is

Table I. Likelihood for individual factors.

Risk factor	Likelihood
VP/P stability	3.7
Alpine	1.4
N–NE–E	1.2
Mid-winter	1.2
F stability	1.1
Treeline	1.1
Early winter	1.0
SE–S–SW	0.9
Sub-treeline	0.7
W–NW	0.7
Late season	0.6
G/VG stability	0.4

somewhat higher in eastern aspects than western. However, the risk in north, northeast, and east aspects is higher than in other aspects. The significance of the analysed factors, in terms of historical risk, ranks as follows:

1. Stability ratings
2. Elevation levels
3. Time of the year (early and mid-winter vs. late season)
4. Aspect

4. Analysis of historical risk for combined conditions

The factors analysed in Section 3, cannot be assumed to be statistically independent. Therefore, it is necessary to analyse combined conditions directly from the database to estimate combinations of factors. The avalanche dataset is too small to permit an analysis of many combined factors, and, therefore, it is restricted here to two factors at the time. The statistical uncertainty still becomes high when looking at two factors combined, and the results in this section do not contain confidence intervals. Therefore, they only represent the historical risk in CMH from the time period spanned by the data, and do not have a predictive value.

4.1. ASPECT AND ELEVATION LEVELS

In Figures 10–12 the probability of aspects of avalanches is compared to the probability of usage of aspects, as a function of elevation level.

The likelihood in the different elevation levels and aspects is calculated as:

$$L(AS_i \cap E_i | A_s) \propto [P(AS_i \cap E_i | A_s)]/[P(AS_i \cap E_i)]$$

Figures 10–12 indicate that the usage of aspects is not much different between elevation levels; however, the aspect of avalanches in the alpine differ from the aspect of avalanches at lower elevations. In the alpine region, the likelihood or historical risk (Figure 13) is greatest in east aspects as well as southeast and south, while the likelihood is by far highest in north aspects in the treeline and sub-treeline regions. The reason for this is not clear. Perhaps, wind loading has a greater effect in the alpine, resulting in increased risk in eastern aspects. Solar radiation might also pose more risk in the alpine than lower down, due to the open terrain. Lower elevations are probably more prone to surface hoar formation, which might also be more persistent than in the alpine, due to lesser wind effect. That might result in greater risk in northern aspects at lower elevations.

4.2. STABILITY RATINGS AND THE TIME OF THE YEAR

Figure 14 shows that the stability rating, under which avalanches fell, is highly dependent on the time of the year. In early winter more than 40% of the avalanches fell under VP/P stability ratings while the ratio is less than 5% for late season. The ratio of avalanches falling under G/VG conditions is lowest in early winter (8%) and highest during the late season (40%). Figure 15 shows that the fraction of time VP/P stability ratings are used goes from 10% in early winter down to less than 5% in late season. "Fair" is the most used stability rating during early winter and mid-winter, while G/VG is the stability rating most often used during late season.

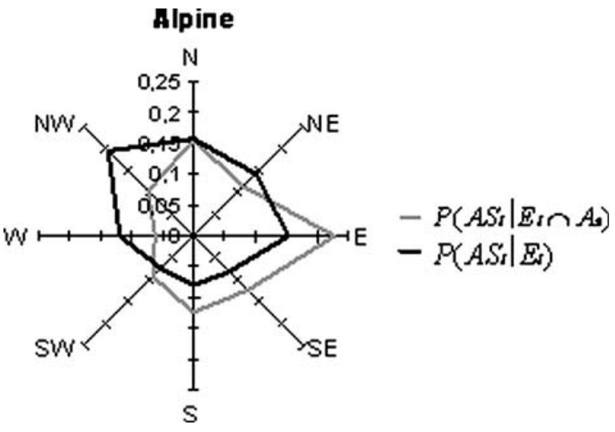

Figure 10. Alpine – Comparison of aspect of avalanches $[P(AS_i|E_i \cap A_s)]$ and the usage of aspects $[P(AS_i|E_i)]$.

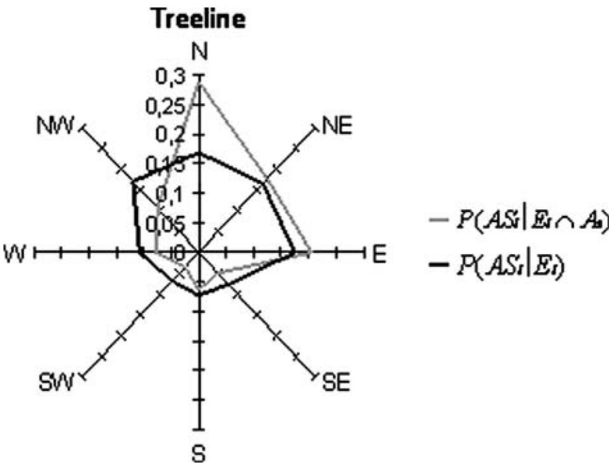

Figure 11. Treeline – Comparison of aspect of avalanches [$P(AS_i|E_i \cap A_s)$] and the usage of aspects [$P(AS_i|E_i)$].

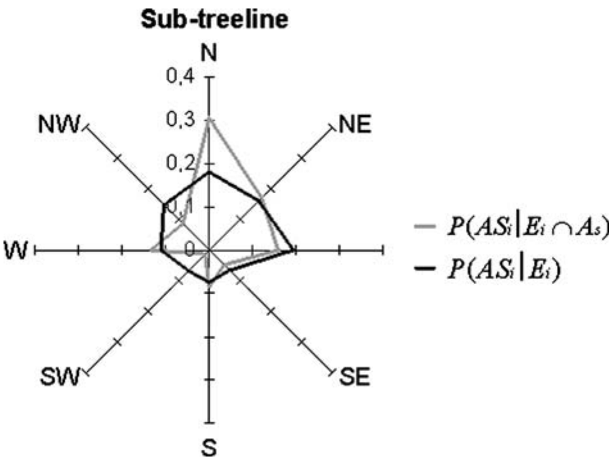

Figure 12. Sub-treeline – Comparison of probability of aspect of avalanches [$P(AS_i|E_i \cap A_s)$] and the probability of usage of aspects [$P(AS_i|E_i)$].

The likelihood during different time periods under different stability ratings is calculated as:

$$L(S_i \cap T_i|A_s) \propto [P(S_i \cap T_i|A_s)]/[P(S_i \cap T_i)]$$

The results are shown in Figure 16. The historical risk or likelihood is by far highest under VP/P stability ratings in early winter and mid-winter. The difference in likelihood between the stability ratings is even greater during early season than mid-winter, and the lowest risk when looking at

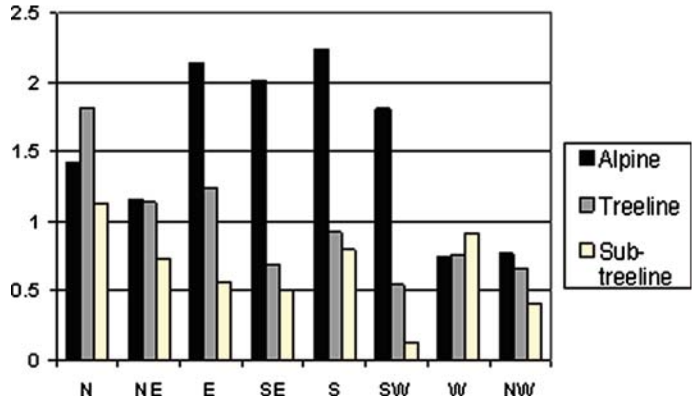

Figure 13. Likelihood in the different elevation levels and aspects: $[P(AS_i \cap E_i|A_s)]/[P(AS_i \cap E_i)]$.

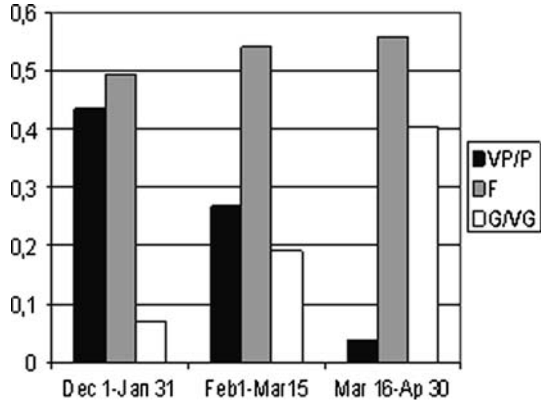

Figure 14. Stability ratings under which avalanches fell during different time periods: $P(S_i|T_i \cap A_s)$.

stability ratings and time of the year is during early winter under G/VG stability ratings. During late season the likelihood is highest under "fair" stability rating and very low under P/VP stability ratings compared to earlier in the season.

It should be noted that by definition, P/VP stability ratings are associated with natural avalanche activity. Those kinds of conditions are most often found during and after major snowfalls, which usually happen during early winter or mid-winter, rather than late in the season. The number of avalanches in the analysis is lower late in the season than earlier and, therefore, the statistical uncertainty is higher.

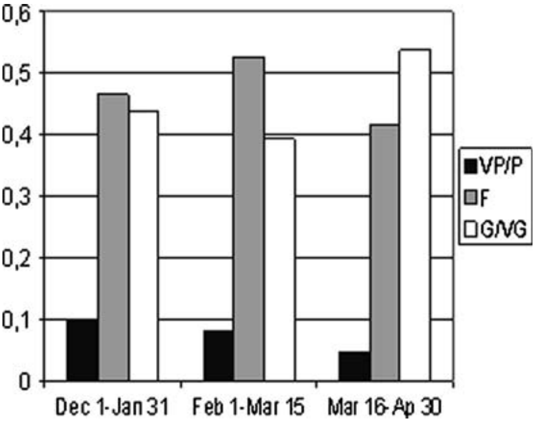

Figure 15. The usage of stability ratings during different time periods: $P(S_i|T_i)$.

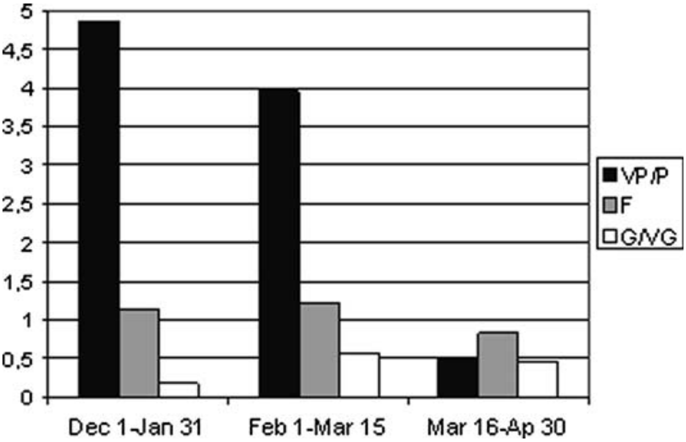

Figure 16. Likelihood during the different time periods under different stability ratings: $[P(S_i \cap T_i|A_s)]/[P(T_i \cap E_i)]$.

4.3. OTHER COMBINED FACTORS

Figures 17–20 show the likelihood associated with four more factor combinations.

Figure 17 indicates that the likelihood is high in the N–NE–E sector during all time periods. The likelihood is high in south aspects during mid-winter, but very low in south aspects during late season. This shows that the relatively high likelihood in southern aspects (refer to Figure 7) is not explained by spring events. The result might reflect the controllability of avalanche hazard due to solar radiation during late season, while it might be harder to manage during mid-winter when solar radiation is just starting to become a factor. Also, the southern aspects are used less often

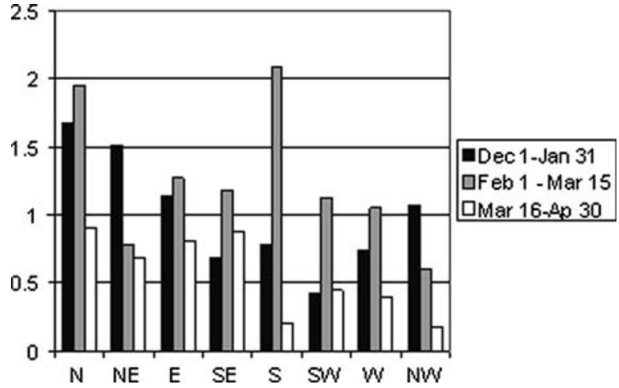

Figure 17. Likelihood in the different aspects at different time periods: $[P(AS_i \cap T_i|A_s)]/[P(AS_i \cap T_i)]$.

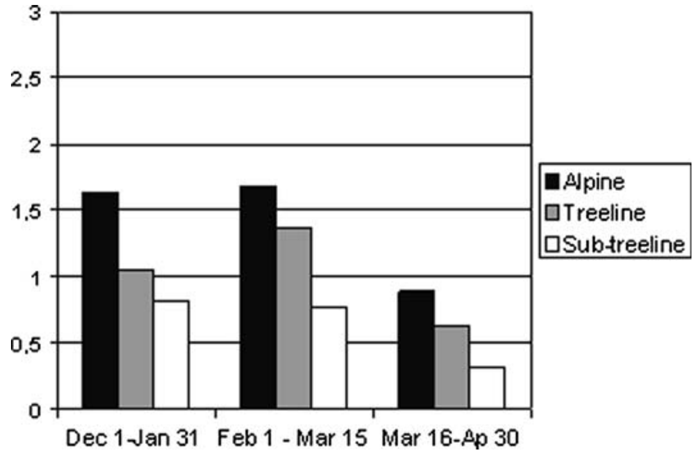

Figure 18. Likelihood in the different elevation levels at different time periods: $[P(E_i \cap T_i|A_s)]/[P(E_i \cap T_i)]$.

during mid-winter and late season than during early winter, probably due to poor skiing quality. Relatively few avalanches are reported in south aspects in total, and the statistical uncertainty is therefore high.

Figure 18 shows that the historical risk or likelihood is highest in the alpine sector and lowest in the sub-treeline sector during all three time periods. This may show the strong influence of forest cover as a factor to reduce the likelihood of triggering.

Figure 19 indicates that when the stability rating is VP/P, the likelihood is high in the NE aspect and quite low in south aspects. That may be so because the VP/P stability rating is associated with natural avalanche

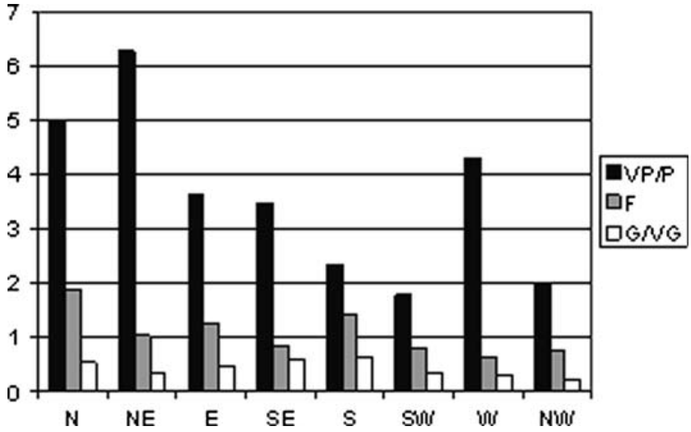

Figure 19. Likelihood in the different aspects under different stability ratings: $[P(AS_i \cap S_i|A_s)]/[P(AS_i \cap S_i)]$.

activity, which is most common during or right after snow storms. During a storm more snow is deposited on the lee side of the mountains, which is often the NE aspects in this case, and that may cause stability problems. The prevalence of avalanche occurrences on northerly aspects and human issues such as skiing quality may have significant influences. The likelihood is highest under VP/P stability ratings in all aspects and lowest under G/VG stability ratings.

Figure 20 shows that the likelihood is also highest under VP/P stability ratings in all elevation levels. In general the risk decreases with elevation except when the stability rating is VP/P, in which case the risk increases with decreasing elevation. The VP/P stability rating is rarely used sub-treeline, however, about 35% of the avalanches recorded there fell under those stability ratings.

4.4. SUMMARY

The individual factors associated with the highest relative risk are listed in descending order below, with the addition of under which combined conditions the risk is especially high.

1. Very poor and poor stability ratings

1.1. The likelihood is high during VP/P stability ratings in all aspects and elevation levels
1.2. The likelihood under VP/P stability ratings is high during *early and mid-winter*, while it is low during late season
1.3. VP/P stability ratings and the *N–NE–E* sector is especially associated with high historical risk

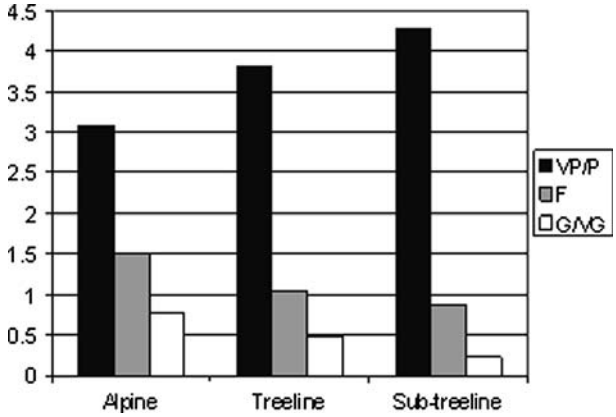

Figure 20. Likelihood in the different elevation levels under different stability ratings: $[P(S_i \cap E_i|A_s)]/[P(S_i \cap E_i)]$.

2. The alpine

2.1. The sector *E–SE–S–SW* in the alpine has high likelihood
2.2. The likelihood is high during *early winter and mid-winter* in the alpine

3. Early and mid-winter

3.1. As stated before the likelihood during early and mid-winter is very high under *VP*/*P* stability ratings, and it is highest in the *alpine*
3.2. *Southern aspects* are associated with high likelihood during *mid-winter* (Feb 1–Mar 15), while the sector *N-NE* has high likelihood during *early winter* (Dec 1–Jan 31)

4. N–NE–E

4.1. In addition to the factors mentioned above ("VP/P" stability ratings and "early winter"), the risk in the *treeline* is especially high in the N–NE–E sector
4.2. The likelihood during "*Fair*" stability ratings is also especially high in the N–NE–E sector

5. Remarks

There are some sources of uncertainty associated with the recording of data, and the methods used to estimate the usage of terrain, as described in this paper. The uncertainties should always be kept in mind while looking at the results of the analysis.

When analysing single factors, the statistical 95% confidence level is shown. The assumption is that the avalanches analysed are a random sample from a population. The population may be defined as future avalanches in CMH, and then the analysis would have a predictive function. However, the various factors affecting the avalanche risk are not constant over time. The snow and weather patterns may change over the years, and most importantly human behaviour is included, which is probably very dynamic. The confidence intervals are introduced only to give some ideas about statistical uncertainty in the calculations.

The factors analysed in Section 3 are not independent of each other, as shown in Section 4. However, the dataset is too small to analyse the combinations of more than two factors at the time. The analysis of two factor combinations is based on limited data and the confidence interval is not shown. Comparison of results should therefore be done with caution. However, it still gives valid information about the historical risk for the time period of the data.

The aspect data are used as they were recorded in the database, and not merged into fewer classes (except in the summary), even though that would simplify the calculations and decrease the statistical uncertainty. The reason for this is that the classification would not be straightforward. For example, by looking at the combined data, different classification seems appropriate for the different combinations.

The usage data reflect the decisions of heli-skiing guides. It is not clear how representative the data are for the usage of other groups, such as recreational skiers. The heli-skiing guides in CMH are professional guides, and most of them have long experience in managing avalanche risk in the backcountry. Another factor affecting the data is that helicopters facilitate the movement over land in heli-skiing operations, and it is e.g. sometimes possible to go directly from one low incline run to another, or from one north facing run to another. The data, however, gives some general indications; such as that all aspects are probably not used equally by backcountry skiers.

The avalanche data are affected by the risk management of guides from the time of the data. Therefore, the results of the risk analysis reflect the residual, historical risk after decisions had been made by guides. This will, however, always be the case with such data since they include a human factor.

Due to the complexity of human factors, it is not always possible to give highly accurate scientific explanations for the statistical results in the analysis. The results are not completely explained by physical reasoning on snow and weather since human behaviour has influences on the results.

6. Terrain selection of heli-skiing guides

6.1. DATA

During February, March, April and August, 2003, the first author spent a total of 19 days visiting 8 of the Canadian Mountain Holidays (CMH) heli-skiing operation areas in the Columbia Mountains in British Columbia, Canada. During these fieldtrips, the guides were asked to answer a questionnaire, which was completed by 40 guides. Loosely structured, in-depth interviews were conducted with 1 or 2 experienced guides in each area (10 in total), and the working day of guides was observed. A few findings from this research are described here.

6.2. RESULTS FROM QUESTIONNAIRE ON TERRAIN FACTORS

The guides were asked to rate the importance of four different terrain factors for the decision making process with relation to the stability rating, and whether the decisions are made during morning meetings or skiing. The four main factors were: (1) general shape of terrain, (2) inclination, (3) aspect and (4) elevation level.

According to the questionnaire, the *general shape of the terrain* is more important in the process of terrain selection than any of the other factors. This applies under all stability ratings and both during morning meetings and skiing. *Inclination* was rated the second most important terrain factor both during morning meetings and skiing. It was rated important under all stability ratings. However, the level of importance rose significantly between the stability rating "good" and "fair", while there was not a big difference in the importance of inclination between "fair" and "poor". Out of 40 guides, 22 said that they are constantly aware of the inclination of the terrain they are skiing, and 32 guides said that they first and foremost think about the shape of the terrain, rather than inclination directly.

The importance of *aspect* was on average rated number three out of the four terrain factors. Unlike inclination, the importance of aspect increased gradually between "good", "fair" and "poor" stability ratings. On average, the importance of aspect was rated slightly higher for the decision process during morning meetings, than during skiing.

The importance of *elevation levels* was on average ranked No. 4 out of the 4 factors. Elevation levels were rated more important than aspect in "fair" and "poor" stability ratings during skiing.

In summary, the ranking was as follows:

1. General terrain shape
2. Inclination
3. Aspect
4. Elevation levels

6.3. SOME RESULTS FROM INTERVIEWS ON TERRAIN FACTORS

Interviews and observations gave similar indications to the questionnaire; the shape of the terrain as well as the size of it, are the factors first considered by guides during terrain selection.

In general, the interviewed guides first think about potential consequences of something going wrong in an area. Therefore, the first concern was usually whether the terrain (size and shape) is capable of producing large avalanches. In such terrain, the decisions of guides might be different and more conservative than in terrain that is not considered capable of producing very large avalanches, such as broken or forested terrain. This applies, even when other conditions, such as inclination, aspect and snowpack characteristics, are equal. A large avalanche can put people at greater risk of death than a small one, and it also puts more people at risk. This dependence in the decision making on the size and shape of the terrain is an important part of avalanche risk management for backcountry skiing operations.

The interviews indicated that, in addition to the general shape of the terrain, the avalanche history of the terrain and inclination are the most important factors in terrain selection (in terms of avalanche risk). Aspect was not a big factor at the time of the interviews. Elevation was not often mentioned directly unless when discussing skiing quality. However, the presence or absence, and the type of the tree-cover was considered important, and that varies with elevation.

7. Analysis of remarks in notable avalanche records

7.1. DATA

If an avalanche is recorded as "notable" in *Snowbase*, the guide involved makes a special report. The reports often contain a short description of circumstances, e.g. on the terrain where the avalanche fell and human factors leading to the avalanche. In this study, we looked at all "notable" avalanches for which it was recorded that someone was caught. The total number of such avalanches is 189 in the time period from 1982 to 2002. The remarks were analysed in order to identify the most common factors mentioned in the remarks, in terms of human factors. Some of the results are presented in this section.

7.2. DECISIONS AND BEHAVIOUR

Below, some of the most common factors in terms of decisions and behaviour are listed.

In 41 reports it is stated that the run had been skied before, most often on the same day, but sometimes in the days before. In 22 reports it is commented that the run or line had been ski-cut or checked by a guide. The clients did not do what they were expected to do according to the remarks of 33 reports. The three most common explanations for that were: (1) the client intentionally did not follow instructions (2) the client could not follow the instruction, because he or she lost control of the skiing (3) the client did not respond in the intended way to a warning call. In 16 reports the avalanche was either triggered from a spot were skiers had regrouped or caught the skiers in the regrouping spot. The fall of a skier or a skier who had taken off skis after a fall may have triggered the avalanche according to 8 reports.

It should be noted that some factors are probably more likely than others to be mentioned in reports (for example client not following instructions). Therefore, such a summary is not necessarily a true representation of the most common factors; however it still gives some valuable information. Furthermore, in order to analyse it, the text in the remarks has to be broken into some *basic elements* or *factors*, and the result is always affected by the interpreter, and his or her motives.

7.3. STATISTICS ON TRIGGERS

In 89 reports it is mentioned *where the trigger was in the group*. Out of those 20% were triggered by the guide who is the first skier, 8% were triggered by a skier who had passed the guide or skied a different line, 42% were triggered by 2nd to 4th skier, 30% were triggered by one or more of the skiers behind the 4th skier. The average group size is 10 people, including guide. These statistics indicate that the probability of a guide triggering an avalanche is higher than for any other person in the group. One of the first four skiers in the group is on average more than two times more likely to trigger an avalanche than the skiers behind. However, about 1/3 of the avalanches were triggered by someone who came after the first four skiers, showing that the risk is not solely associated with the first skiers.

In 46% of the avalanches where someone was caught, more than one person was caught. For 125 reports, indications on whether one or more skiers triggered the avalanche are available. Out of those, 82 (66%) avalanches were probably triggered by only one skier, while 43 (34%) were probably triggered by more than one skier. In 137 of the reports, indications are given about whether the person who triggered the avalanche got caught, and in 87 (63%) of those avalanches the trigger was caught.

8. Conclusions

The risk analysis in this study shows the importance of considering usage when estimating avalanche risk in backcountry travelling. Since the greatest number of avalanches in CMH's database fell in the treeline sector, and under "fair" stability rating, one might assume that the avalanche risk is highest under these conditions. However, this study shows that when usage of elevation levels and stability ratings are taken into account, this is not the case. This study is probably the first to estimate the usage of terrain, and thus, give realistic indications about risk factors for avalanche triggering.

An important result is that the importance of aspect for avalanche risk in the backcountry may have been overestimated. The radar plot for the aspect of skier-triggered avalanches (see Figure 5) looks similar to plots in many other studies in N-America (e.g. Jamieson and Geldsetzer, 1996), with most avalanches falling in the N–NE–E sector. However, these may be the aspects most used, and the risk may therefore not be as dependent on aspects as indicated by avalanche data alone. Furthermore, the questionnaire in this research indicated that aspect is on average considered less important than the general shape of the terrain and inclination, and aspect was not considered important at the time of the interviews. Rule based methods (such as Werner Munter's (2003) Reduction Method), who are based on avalanche data without usage data, might thus overestimate the dependence of risk on aspects. Munter (2003) recognises that the lack of usage data is a serious problem for his risk analysis. Schweizer and Lütschg (2001) analysed human triggered avalanches in Switzerland. They calculated the probability of triggering in different aspects relative to the total distribution of aspects in a defined region. They found that the relative probability was highest in the lee and shady aspects N–NE–E. However, they admit that the risk cannot be calculated because the frequency of skiing is unknown. The lee and shady aspects may in fact be the most frequently used aspects in many areas, due to skiing quality.

The analyses of combined factors indicate that the risk factors are interrelated in a complicated way. These analyses support the view of mountain guides which was reflected in the questionnaire and interviews, that looking at individual factors such as elevation or aspect, without considering a larger context, is an oversimplification. Their decision-making on terrain selection is based on the size and shape of the terrain as a whole, as well as on snow conditions. Experienced guides may be able to base their decisions on a combination of different factors.

It is, however, important for people working in an avalanche prone environment to constantly pay attention to statistics on avalanches and avalanche risk, in order to find patterns that are not easily seen due to the abundance of data. This study, for example, shows that the historical risk in CMH of accidentally triggering an avalanche greater than size 1, is much higher under "very poor" and "poor" stability ratings than other stability ratings. The historical risk is also quite dependent on elevation levels. This was not reflected in the interviews and questionnaire results.

An analysis of remarks in reports on notable avalanches may also show patterns that are not easily recognised with the "bare eye". The high number of comments on the run being skied earlier may indicate that guides rely too much on previous skiing as an indicator of a safe slope. The fact, that in many cases the client was not located where the guide intended him or her to be, reflects the importance of group management.

The study of Schweizer and Lütschg (2001) from Switzerland showed that 95% of the skier-triggered avalanches analysed, were triggered by the first person or several persons. Our studies indicate that the first four persons in a group of the average size of 10 people are more likely than the others to trigger an avalanche. However, 1/3 of the avalanches were triggered by skiers behind the fourth skier.

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