QUANTITATIVE RISK REDUCTION METHOD (QRM), A DATA-DRIVEN AVALANCHE RISK ESTIMATOR

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ABSTRACT: Strategic methods are well established aids for planning backcountry ski tours. They typically combine the avalanche danger level and the slope angle to a "risk category". The broad application of these classical methods reduces the frequency of avalanche accidents. However, they can't represent the risk, because they are based exclusively on accident data and neglect the terrain usage by the skier community. In this paper we present the Quantitative Reduction Method (QRM), which allows the estimation of the relative avalanche risk on backcountry ski tours. The method is based upon data: Human involved avalanche accidents (1469), GPS tracks of backcountry ski tours (47'530 km) and avalanche conditions (taken from 4656 avalanche warning forecasts). First, we introduce two continuous indicators: the "Danger Indicator" (DI) to describe the danger predicted in the avalanche bulletin and the "Terrain Indicator" (TI) to describe the extent to which a certain point and its surroundings are typical avalanche terrain. Then, we compute pairs of DI and TI for both, the release areas of the avalanche accidents and discrete points along the GPS tracks. The latter gives information about the terrain usage by backcountry recreationists. For probabilistic interpretation we use Kernel Density Estimations (KDE). Dividing accident KDE by terrain usage KDE gives the QRM. At a first glance, the QRM resembles earlier strategic methods. However, the QRM shows, that in the orange and red zones the risk increases exponentially with the danger indicator and terrain indicator. On the other hand, the relative risk remains close to zero in the green zone. The new method is suitable for computer applications and separates unambiguously low risk zones from high risk zones. Approximately 50% of the avalanche accidents could be avoided, by abstaining from only 1.9% of route segments.

KEYWORDS: Reduction Method, Strategic Method, Avalanche Risk, Backcountry Skiing

1. INTRODUCTION

The first strategic methods, the "Elementary Reduction Method" and the "Professional Reduction method" got published in the nineties by Werner Munter (1997). In the following decades various graphical versions of strategic methods were introduced: "Stop-or-Go" in Austria (Larcher, 1999), "SnowCard" in Germany (Engler, 2001), "Graphical Reduction Method" in Switzerland (Harvey et al., 2016) and "Avaluator" in Canada (Haegeli et al., 2006). The latter is fundamentally different as it's based not only on the slope angle, but on a comprehensive terrain analysis according to the Avalanche Terrain Exposure Scale (Statham et al., 2006).

Typically, strategic methods derived more from expert knowledge than from scientific reasoning. Nevertheless, their broad application reduces the frequency of avalanche accidents. McCammon and Haegeli (2007) found prevention values of about 60% to 90%, for popular strategic methods.

Strategic methods combine information of different resolution and reliability. The information from the avalanche forecast is highly generalized and subject to uncertainty. In turn, the information about the terrain characteristics has a high resolution and a high precision. Russell & Norvig (2016) write in their standard work about artificial intelligence: "When making **decisions**, an agent needs to condition on **all** evidence it has observed". As long as strategic methods can prevent accidents there is no further issue in the data combination.

All methods except the Avaluator rely on the slope angle. Further, Stop-or-Go and Avaluator don't make systematic use of particularly affected aspects and elevations usually provided by avalanche forecasts.

Little is known about the terrain usage of backcountry skiers. Techel et al. (2015) analyzed summit reports of community sites and found that the community prefer easier destinations at higher avalanche danger. However summit reports can't be used to identify the characteristics of the explored terrain. Hendrikx & Johnson (2016) analyzed GPS tracks and found that backcountry skiers do generally not choose steeper slopes at lower danger levels.

Because all known strategic methods completely neglect the terrain usage of the skier community, they can't estimate the quantitative avalanche risk. Alone Pfeifer (2008) undertook a trial to vali-

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date the Elementary Reduction Method based on travel frequency assumptions.

McCammon & Haegeli (2005) stated, that for most recreationists and professionals traveling in avalanche terrain, the freedom of movement granted by a rule-based system is at least as important as its preventive value. Due to a lack of terrain usage data, it is not known what proportion of tours are undertaken outside the recommended zone. It therefore remains unclear to what extent the different strategic methods restrict the freedom of movement.

To tackle these problems, we have developed the data driven Quantitative Reduction Method (QRM). The new method computes the relative risk by relating the avalanche accidents to the total amount of backcountry skiing traffic. The QRM is a completely defined, continuous function and therefore also suitable for automatic computations.
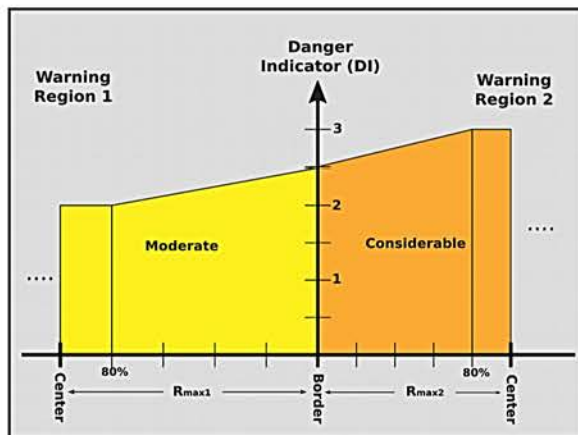

Fig. 1: Horizontal transition function

2. DATA AND METHODS

Danger and Terrain Indicator

We introduce two continuous indicators, both of them within a specific number range that allows any interim value. They expose trichotomy and transitivity but not proportionality.

Danger Indicator (DI)

The danger indicator is a decimal number in a closed interval [1..4] and describes the current avalanche danger. It is derived from the avalanche forecast, published the evening before the corresponding day. DI takes into account the discrete danger level and information about the particularly affected aspects and elevations (PAAE). The DI smooths out the discrete transitions between different warning regions, at elevation thresholds and at aspect alterations.

Statistical avalanche forecast analysis of Techel & Schweizer (2017b) suggest that even in the center of a warning region the danger levels of neighboring regions have an impact. Hence we assume the danger level applies to a center zone, that is located more then $0.8 * R_{max}$ away from all borders. R_{max} is the radius, of the biggest circle that fits into the warning region. Outside of the center zone we interpolate linearly with the neighboring region data (see Fig. 1). The data embraces the danger level as well as the particularly affected aspects and elevations (PAAE). The algorithm takes into account, that there can be more than one neighbor region.
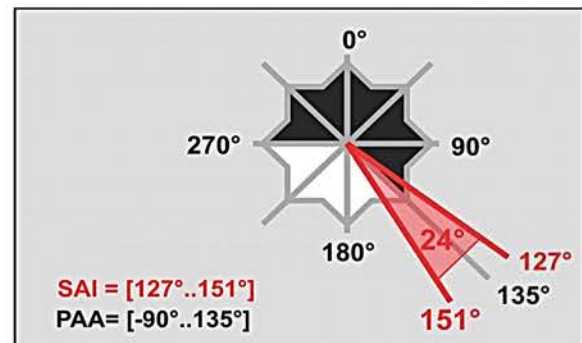

Fig. 2: Transition function over aspects

The Avalanche Bulletin Interpretation Guide (SLF, 2017) asserts: "*It has become customary in backcountry touring to assume the danger level to be one level lower on slopes outside the avalanche prone locations*". The magnitude "one level" got confirmed by snowpack analysis of the SLF (Schweizer et al, 2003). This rule of thumb is applied to design continuous transition functions in the affected zones:

1. Elevation: We introduce a continuous transition band of ± 100 m. For instance, if the avalanche forecast predicts "considerable" (3) above 2200 m, we use "moderate" (2) below 2100 m and considerable" (3) above 2300 m. In between the DI will be interpolated linearly.

2. Aspect: avalanche forecasts normally specify the particularly affected aspects (PAA) for each region. Moreover, every point in the terrain belongs to a slope that exhibits a slope aspect interval (SAI). The transition function computes the share of the SAI contained in the PAA. In the example of Fig. 2 a third of the SAI is contained within the PAA. If the danger level in the affected warning region is for instance 3, it will be downgraded about 0.33 to 2.67.

By superposition of the transition functions it becomes possible to assign to each point in the terrain a DI value.

Terrain Indicator (TI)

There is broad agreement, that the slope angle is the most relevant terrain parameter for avalanches. However, it's known that other terrain parameters like slope curvature, slope size and forestation are also relevant for avalanches (Vontobel, 2011).

We use the algorithm presented by Schmudlach & Köhler (2016) to assign a terrain indicator (TI) to each point in the terrain. Conceptually, this approach is similar to ATES (Statham et al., 2006), yet the approach focuses on human-triggered avalanches and neglects alpine difficulties.

The TI is a decimal number in the closed interval [0..1] and can be split into four classes (see Tbl. 1).

Tbl. 1:   Terrain indicator (TI)

Class	Description
0..0.25	No avalanche terrain.
0.25..0.5	Atypical avalanche terrain.
0.5..0.75	Typical avalanche terrain.
0.75..1	Very typical avalanche terrain.

The technical details of the algorithm can be studied in the mentioned paper. Yet, since 2016 some details of the algorithm were refined.

It is crucial to understand, that the TI of a specific point is always a function of the terrain properties of the environment around the point. The computations were made with the digital elevation model swissALTI3D (resolution 10 m) and the landcover swissTLM3D from Swisstopo.
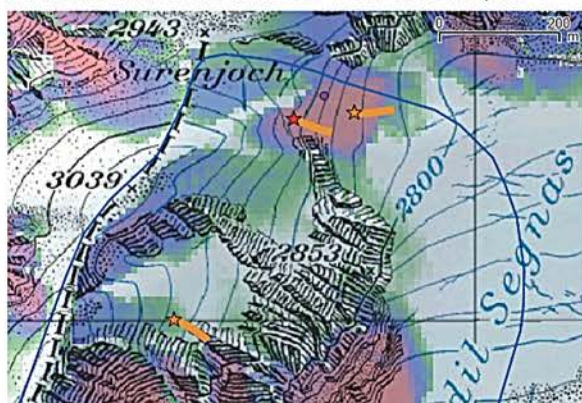

Fig. 3: Downhill trajectory of three accidents (orange) on a TI map (Base map: © Swisstopo)

Accidents

The accidents were taken from the winter reports of the SLF (SLF, 2002-2017). From 1695 accident reports 16% had fatal consequences and 26% had consequences with injured individuals. In contrast to accidents with no consequences, the accidents with consequences get systematically recorded by the SLF.

From the data set, we selected 1469 accidents that comply with three criteria:

1. Human-involved accident. Approximately 95% of human-involved accidents got triggered by humans (Techel & Schweizer, 2017a).

2. Data quality marked as reliable and accurate.

3. An avalanche forecast is available and includes the danger level.

Most of the accidents reports exhibit only an avalanche release point. The release point corresponds to the highest point on the release area and doesn't always represent the slope characteristics of the trigger point. Therefore, we assume a downhill trajectory of 60 m, corresponding to the length of a typical release area (see Fig. 3). Harvey et al. (2018) computed an average release area size of 2520 m² for 5225 small and medium-sized avalanches recorded in the region around Davos. Depending on the release area shape this area corresponds to a release area length between 40 m and 80 m.
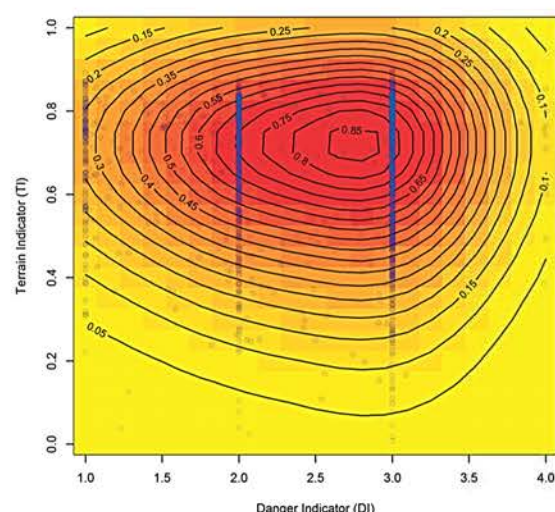

Fig. 4: Human involved accidents. Blue dots show the individual accidents, background colors and contour lines the accident density computed with KDE. Yellow means hardly any accidents, red indicates many accidents.

Subsequently 7 points in a distance of 10 m get distributed over the downhill trajectory. By averaging the TI/DI values from theses points we get the final TI/DI values of each accident. A test with 120 accidents (SLF, 2018) that exhibit a reported trigger point show, that the modeled TI/DI match reasonably the TI/DI at the reported trigger point (Median of TI error: 0.052).

As soon as TI/DI are estimated for each accident, they can be plotted on Fig. 4. Kernel density estimation (KDE) allows the estimation of the accident density (yellow to red). The x-bandwidth of the kernel was chosen by enlarging it until the initially separated peaks at DI=2 and DI=3 merge. The y-bandwidth was chosen proportionally.

Terrain usage

In order to reflect the relative avalanche risk, accident data have to be related to the terrain usage of the skier community.

We used GPS tracks collected by mountain web sites (www.skitourenguru.ch, www.gipfelbuch.ch) and individuals. The data was filtered and processed as follows:

1. All GPS tracks other than backcountry ski tours were eliminated.

2. All GPS tracks without time stamps or missing avalanche forecast were eliminated.

3. A specially designed algorithm detected and removed GPS spikes.

4. All GPS tracks that follow for more than 70% a street, way or path were eliminated. It's unlikely, that such tracks effectively were recorded during a backcountry ski tour.
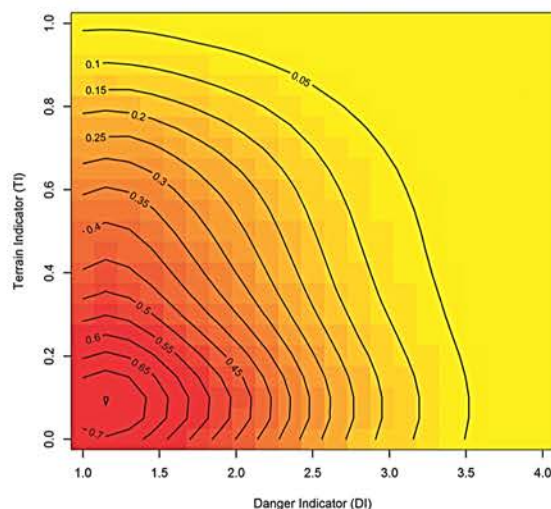

Fig. 5: Terrain usage of the backcountry skier community. The values are computed from GPS tracks with KDE. Yellow indicates hardly any traffic, red indicates heavy traffic.

After the data processing line segments with the total length 47'530 km left over. Applying the same KDE as for the accidents, the terrain usage could be computed (see Fig. 5).

3. RESULTS

Accidents

Fig. 4 shows the avalanche density as a function of the avalanche danger (Danger Indicator, DI) and the terrain (Terrain Indicator, TI). As expected we find most accidents between moderate/considerable (DI=2.8) and in (very) typical avalanche terrain (TI=0.75). The next chapter will give an explanation for the lack of accidents in the upper right corner.

Terrain usage

Fig. 5 shows that the backcountry skier community moves mostly through terrain with low avalanche exposure (TI < 0.4). This is partly due to the fact that even demanding tours often pass over long distances through uncritical terrain. Moreover the activity usually takes place at lower danger levels (DI < 1.5). Partly that's due to the downgrading of the DI outside the particularly affected aspects and elevations (PAAE) indicated in the avalanche forecast.

The lack of accidents in the upper right corner of Fig. 4 is due to the absence of backcountry skier traffic at high DI/TI. Little traffic mean few accidents.
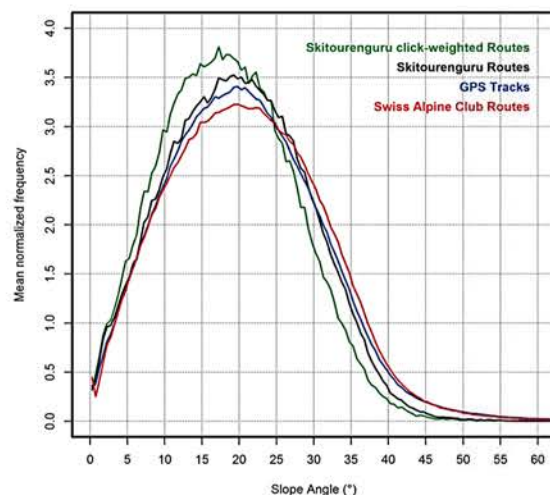

Fig. 6: Slope angle histograms of the GPS tracks (blue) and other route collections.

To estimate a possible bias of the crowd sourced GPS tracks, we compare them with different route collections (see Fig. 6). For the Skitourenguru Routes and for the Swiss Alpine Club Routes we suppose, that the routes get traveled evenly:

1. Swiss Alpine Club Network (red): For two reasons the data set has a bias towards steep terrain. First, the network has a high generalization level and therefore often crosses extremely steep

terrain. Second, steep routes are less often traveled then flat routes.

2. Click-weighted Skitourenguru Routes (green): The data set has a bias towards flat terrain as easy going routes receive the majority of clicks.

3. Skitourenguru Routes (black): Diverging effects make it difficult to attribute a bias.

All four data collections exhibit a similar slope angle histogram (see Fig. 6). The GPS track collection lies between the green line (bias towards flat terrain) and the red line (bias towards steep terrain). Hence it's unlikely that the GPS track collection has a strong bias. However, this plausibility check can't totally exclude a data bias of the GPS track collection.
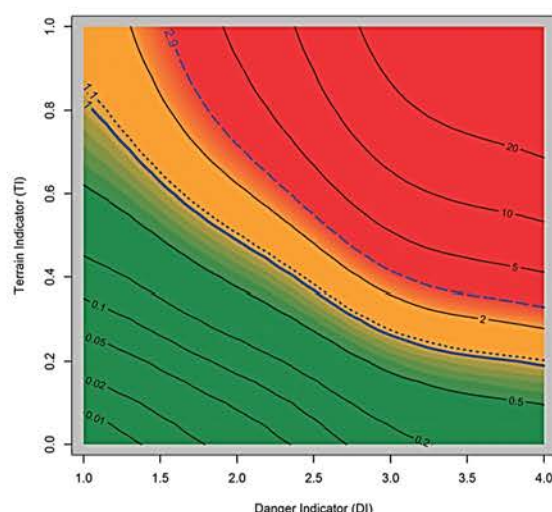

Fig. 7: Quantitative Reduction Method (QRM): Relative avalanche risk as a function of the avalanche danger (Danger Indicator, DI) and the terrain (Terrain Indicator, TI).

Quantitative Reduction Method (QRM)

The density functions of Fig. 4 and Fig. 5 were computed over a 20 x 20 matrix. For each matrix cell, the relative risk (RR) is computed by dividing the accident density (AD) by the terrain usage (TU). The normalization factor 0.0678 ensures that the average relative risk corresponds to RR=1 (blue, continuous line in Fig. 7):

$$RR_{IJ} = 0.0678 * AD_{IJ} / TU_{IJ}.$$

The resulting QRM is shown in Fig. 7. The contour lines reflect the relative avalanche risk. The term "risk" refers to the probability to cause a human-involved accident which ends up in the database of the SLF.

The QRM indicates three zones: green (low risk), orange (elevated risk) and red (high risk). The thresholds between these zones are given

in Tbl. 2. They have been set such that 60% of accidents are prevented if the community avoids the red zone and 80% if it avoids the orange and red zones. The chosen preventive effect is similar to that of previous strategic methods (McCammon & Haegeli, 2007). The values of RR_{orange} and RR_{red} were computed with the contour lines of the QRM (Fig. 7) and the terrain usage (Fig. 5). Route segments prohibited by the QRM were substituted by representatively selected permitted route segments.

The contour lines of the QRM also enable risk comparisons. A backcountry skier moving close to the red zone is exposed to a threefold risk, compared to a backcountry skier moving at the transition from green to orange.

Tbl. 2: Targeted accident prevention values and thresholds for the relative risk in the QRM.

Restriction	Targeted accident prevention value	Thresholds for the relative risk
Avoiding red zone.	60%	$RR_{red} = 2.9$ (blue dashed line)
Avoiding orange and red zone.	80%	$RR_{orange} = 1.1$ (blue dotted line)

4. DISCUSSION

Safety comes at a price. We can only reduce the risk with a strategic method, if we refrain from crossing specific terrain at specific avalanche conditions. The aim is to reduce risk as much as possible with as little restrictions as possible. Fig. 8 shows the performance curve of the QRM: Percentage of remaining accidents in function of the percentage of abstinence. If the backcountry community renounces to 1.9% of the "most risky route segments", 50% of the accidents could be prevented.

A 3D-View of the QRM shows, that the QRM distinguishes sharply between zones with low risk and zones with elevated or high risk. The QRM shows that both, the terrain and the information from the avalanche bulletin have a decisive influence on the avalanche risk. That is remarkable in light of the quality of the available data, such as the rough danger levels and the unknown hit rate of the avalanche bulletin.

The abstinence necessary for a certain risk reduction is the central quality criterion and should therefore be used to compare the performance of different strategic methods. McCammon & Haegeli (2007) computed prevention values for some popular strategic methods, but did not confront these values to the price, in form of abstinence, that has to be paid. As long as performance curves are not available for popular

strategic methods, it is not possible to compare them.

It is known that avalanche accident databases have a strong bias towards serious accidents (Jamieson & Jones, 2015) and also towards higher danger levels. The latter since at higher danger levels avalanche accidents have more often serious consequences (Techel & Zweifel, 2013). This bias towards serious consequences is certainly desirable for our purpose since the QRM is primarily intended to prevent serious accidents.

The future will produce a flow of new data (accidents, GPS tracks and avalanche forecasts). The data must be used to continuously update the QRM. This will further improve the method. However, in view of the already large data basis, it is unlikely further data will change the principal shape of the QRM.
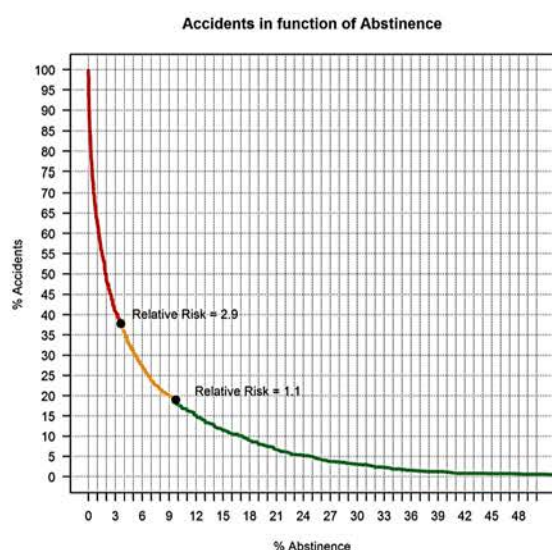

Fig. 8: Performance of the QRM: Remaining accidents in function of abstinence.

5. CONCLUSIONS

We presented the Quantitative Reduction Method (QRM), a data-driven avalanche risk estimator for backcountry touring. In contrast to former strategic methods, the QRM exhibits quantitative risk relations. At first glance, the QRM resembles earlier strategic methods. However the QRM shows, that in the orange and red zones the relative risk increases exponentially with Danger Indicator (DI) and Terrain Indicator (TI).

On the other hand the relative risk remains close to zero in the green zone.

Even though the avalanche forecast is subject to high spatial generalization and uncertainty, the danger indicator and the terrain indicator together predict the probability of avalanche accidents. Like any other strategic method, the QRM will never replace on-site avalanche assessment and each individual's responsibility. Strategic methods should be taken into account in all situations where the data basis is restricted to the avalanche forecast and the terrain. While this applies particularly to the planning phase of a backcountry ski tour, it is also pertinent to some on-site situations that do not support an integral avalanche assessment.

The QRM shown in Fig. 7 is valid for the Central Alps, and the TI computed according to Schmudlach & Köhler (2016). The algorithm can easily be used for every other, consistent avalanche terrain classification scheme, e.g. the approach of Harvey et al. (2018). It should be noted that different terrain classifications lead to different contour lines in the QRM and to different performance curves (see Fig. 8).

Existing strategic methods proved to be challenging for recreationists. Compared to former strategic methods the QRM adds complexity. Therefore, it is particularly suitable for computer applications. Unlike manual application, it will be possible to estimate the statistical avalanche risk not only of individual route cruxes, but of entire routes.

The results of the QRM can be improved if future avalanche bulletins provide enhanced machine-readable data, e.g. an expected avalanche danger not rounded to integers. Furthermore, there might be some potential by improving the algorithm that computes the most likely trigger point given an avalanche release point.

REFERENCES

Engler, M., 2001: SnowCard & Faktorencheck. Berg&Steigen, 4/2001.

Haegeli, P., McCammon, I., Jamieson, B., Israelson, C. Statham, G., 2006: The Avaluator. A Canadian rule-based avalanche decision support tool for amateur recreationists. Proceedings of the International Snow Science Workshop, Telluride. pp. 254-263.

Harvey, S., Rhyner, H., Dürr, L., Schweizer, J., Henny. H. M., 2016: Caution Avalanches! Kern-Ausbildungsteam Lawinenprävention Schneesport, Switzerland.

Harvey, S., Schmudlach, G., Bühler, Y., Dürr L., Stoffel A., Christen, M., 2018: Avalanche terrain maps for backcountry skiing in Switzerland, Proceedings of the International Snow Science Workshop, Innsbruck.

Hendrikx, J., Johnson, J., 2016: Understanding global crowd sourcing data to examine travel behavior in avalanche terrain. Proceedings of the International Snow Science Workshop, Breckenridge, Colorado.

Jamieson B., Jones A., 2015. The Effect of Under-Reporting of Non-Fatal Involvements in Snow Avalanches on Vulnerability. 12th International Conference on Applications of Statistics and Probability in Civil Engineering, Vancouver.

Larcher, M., 1999: Stop or Go – Entscheidungsstrategie für Tourengeher. Berg&Steigen, 4/1999.

McCammon, I., Haegeli, P., 2007. An evaluation of rule-based decision tools for travel in avalanche terrain, Cold Regions Science and Technology, 47, 193-206.

McCammon, I., Haegeli, P., 2005: Description and evaluation of existing European decision-making support schemes for recreational backcountry travelers. Report for Canadian Avalanche Association, NIF Project: Avalanche Decision Framework for Amateur Winter Recreationists.

Munter, W., 1997: 3x3 Lawinen. Entscheiden in kritischen Situationen. Pohl & Schellhammer, Garmisch-Partenkirchen. pp. 120-129.

Pfeifer, C., 2008: On probabilities of avalanches triggered by alpine skiers. Nat. Hazards, Vol. 48, pp. 425–438.

Russel, S., Norvig, P., 2016: Artificial Intelligence. Pearson, Harlow, pp. 485.

Schmudlach, G., Köhler, J., 2016: Method for an automatized avalanche terrain classification. Proceedings of the International Snow Science Workshop, Breckenridge.

Schweizer, J., Kronholm, K., Wiesinger, T., 2003: Verification of regional snowpack stability and avalanche danger. Cold Regions Science and Technology, Vol. 37, pp. 278.

SLF, 2017: Avalanche Bulletin Interpretation Guide. SLF, Davos, pp. 34-35.

SLF, 2002-2017: Schnee und Lawinen in den Schweizer Alpen. Unfallberichte. SLF, Davos / WSL, Birmensdorf

SLF, 2018: Data request „Historical Avalanche Forecasts", Avalanche forecasts 2001-2013. 1. Jan. 2018.

SLF, 2018: Data request „Damage Database", 167 accidents with reported trigger points. 8. Mai 2018.

Statham, G., McMahon, B., Tomm, I., 2006. The Avalanche Terrain Exposure Scale. Proceedings of the International Snow Science Workshop, Telluride, pp. 491-497.

Techel, F., Zweifel, B., Winkler K., 2015: Analysis of avalanche risk factors in backcountry terrain based on usage frequency and accident data in Switzerland. Nat. Hazards Earth Syst. Sci., Vol. 15. pp. 1985-1987.

Techel, F., Schweizer, J., 2017a: Lawinenunfälle Schweizer Alpen. Berg&Steigen, 1/2017.

Techel, F., Schweizer, J., 2017b: On using local avalanche danger level estimates for regional forecast verification. Cold Regions Science and Technology, Vol. 144, pp. 52-62.

Techel, F., Zweifel, B., 2013. Recreational avalanche accidents in Switzerland: Trends and patterns with an emphasis on burial, rescue methods and avalanche danger. Proceedings of the International Snow Science Workshop, Grenoble, pp. 1106-1112.

Vontobel, I., 2011: Geländeanalysen von Unfalllawinen. Geographisches Institut der Universität Zürich, Zürich.