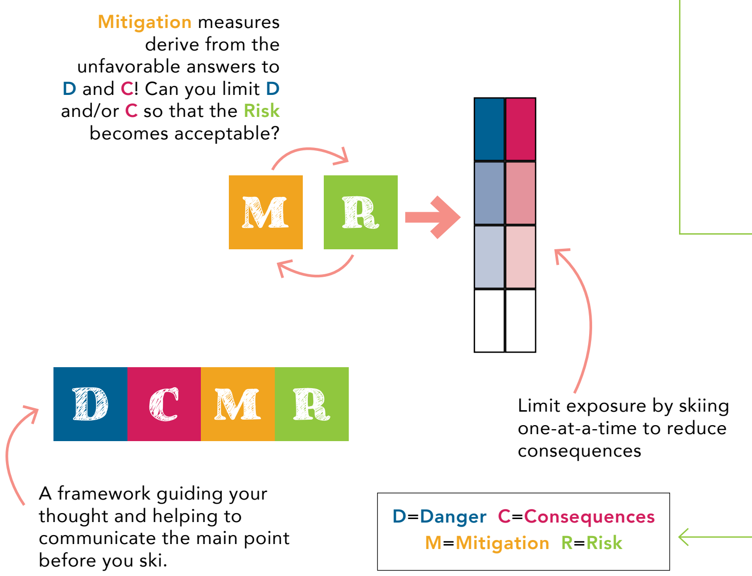

An Intuitive Path to D×C–M=R

Avalanche Risk Management

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Since the old days, humans have been dealing with natural hazards in the mountains. It's no surprise that nowadays different approaches for risk management exist. In this article we present one approach that we find intuitive to assess avalanche risk. It is a path that many of us already take when we're traveling the backcountry, so all we're doing here is putting it together and trying to explain why. We'll see that our approach does not lie far from current research.

TWO PERSPECTIVES ON AVALANCHE DANGER

The starting point for most decisions we take when it comes to avalanche danger assessment is the avalanche forecast—but forecasters and skiers usually have different view angles. Skiers are typically focused at the scale of one or a few slopes, while avalanche forecasters look at the problem at a regional scale. Maybe these two different views, or what we would call a scale mismatch, are at the root of the confusion we sometimes run into?

Forecasters typically discuss: "What are the chances that we'll see skiers triggering avalanches today?" With Considerable danger, human-triggering is typical. So, on a sunny day in the forecast region the answer could be: "Skier triggering is likely." Indeed, researchers found that on average two to three avalanches are released daily in a Swiss forecast region, which has several 100 km2 (*Figure 1*).

Forecasters look at what happens in a region. Skiers may rather ask: "Will the slope avalanche?" A Considerable danger, however, doesn't mean the answer is "likely." If this was the case, there would be no snow left on the slopes after one day of skier traffic. The probability of triggering an avalanche on a slope described in the forecast region will be on the order of 1:1000*—even with Considerable avalanche danger. So, the chance that a particular slope comes down is way different from the chance of seeing avalanches in the region. Avalanches remain rare events. Even if you're hard at it, you won't trigger more than a handful or so of avalanches—unless you're talented.

Now the question arises: How the avalanche forecast can be useful for our risk assessment? Well, the danger level does not describe the individual slope since the scale of the forecast is not slope specific—they're two different pairs of boots. Still, the forecast is a multi-tool and may help us in different ways as it offers more than a number 1 through 5.

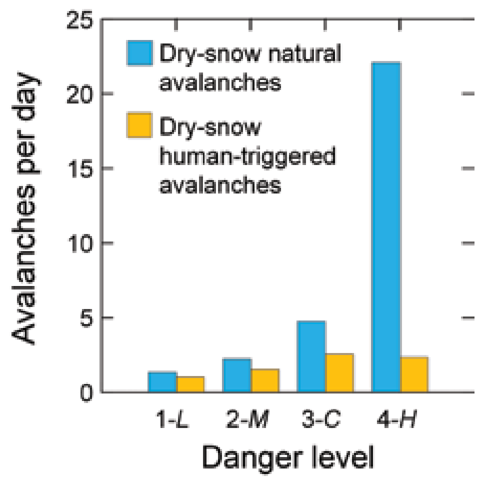


Figure 1: Thanks to 21 years of observations, we can compare the frequency of avalanches with the danger level in a forecast region (Schweizer et al., 2020). More than 4000 avalanches were counted over these years in the region of Davos. The number of natural avalanches clearly increases with increasing danger level. On days with "high" danger many natural avalanches were observed. This increase is also seen in human-triggered avalanches—even though less pronounced, as we stay away from more terrain the higher the danger is.

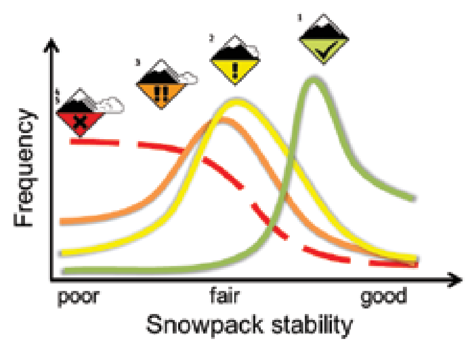


Figure 2: Sketch illustrating the frequency of snowpack stability with the different danger levels (Schweizer et al., 2003). The curves indicate for the different danger levels how likely it is that poor, fair or good stability will be encountered on a slope. The higher the stability the lower is the likelihood of triggering. Each graph relies on many expert observations including snow pits from a forecast region. During danger level "high" only limited data were available (dashed line).

THE MULTI-TOOL

When his friend asks: "where are we gonna go?" Karl pulls out his phone and looks at a colored map. Choosing to go in an orange region exposes them to a higher danger than a yellow region with level Moderate. The danger level is the big lever Karl pulls for the first choice they make before they go: Likelihood of avalanches, frequency of trigger locations, and avalanche size melt into our avalanche danger level.

The next decision, however, is about choosing a trip or looking at a particular descent. So, what about pulling the same lever again? Now we're talking about slopes and not about regions. So we pull up some data describing the distribution of snow stability of slopes in a region (*Figure 2*). Picking a slope from the frequency distribution of the danger level High we likely won't hit the stability class "good." If we choose randomly from the frequency distribution at danger level Low, we likely don't end up with poor stability. In other words, if danger levels are High or Low it is easy to keep poor and good stability apart.

This is no longer the case for Moderate and Considerable. The graphs have quite some overlap as frequency distributions look much alike. Let's get this right, Moderate danger does mean that fewer avalanches are expected in the region compared to a situation with Considerable danger. But when we look at a particular slope, we don't want to rely on the subtle difference that Considerable means every second and Moderate means every fourth or fifth slope has poor stability (*left tail of the graphs in Figure 2*). Besides, we can't locate those potential avalanche slopes within the hazard locations described in the forecast. Slope stability assessment is beyond the power of the number. When the danger level is Moderate or Considerable, which happens on about 80% of the days in winter, we need a different tool.

That's no big deal, because the forecast offers more than a number, as long as we take the time to dig into that forecast. Some forecasting services even describe the terrain where the avalanche problem is most present. In the end, the description of the avalanche problem helps us to focus and find complementary information in the field. Our behavior in the field eventually derives from the avalanche problem—rather than the danger level alone.

DANGER = RISK?

Well, that would only be true if the consequences were always the same. But climbers and skiers know better: we have a healthy respect for large slopes. In case of doubt, we hold back and choose the mellower run, even though we may be tempted by the big face.

Indicator	Reason	Limitations	Conclusion
Slope angle (1,2,3,4)	The steeper the slope the higher the likelihood of triggering.	• Remote triggering is possible also from low-angle terrain. • Natural avalanches can run out into low-angle terrain.	Consider all steep slopes along the intended route—depending on the type and spatial pattern of the avalanche problem.
Danger level (1,2,3,4)	Number of locations with poor snow stability and number of avalanches in the forecast region (>100 km2) increase with increasing danger level.	The danger level gives a poor estimate of the likelihood of triggering at a slope. With High danger unstable slopes are clearly more common than stable slopes, and with Low danger stable slopes are more common than unstable slopes. But Moderate and Considerable don't discriminate well between unstable and stable slopes and are the most common levels: about 80% of the season.	• Use to select region or mountain range you plan to travel. Limited relevance for trip selection within an area. Clearly, there are trips that don't go well with most situations of Considerable danger, but finally it comes down to the type of avalanche problem and its spatial pattern. Not useful for slope evaluation, as stability distributions overlap too much.
Combination of slope angle and danger level (1,2,3,4)	With increasing slope angle, the likelihood of triggering increases. With increasing danger level, the number of locations with poor snow stability increases and so does the probability for avalanches in the region. Slopes with lower slope angle required to balance higher danger level.	Regional danger level (>100 km2) and local slope angle (1 km2) refer to different scales. Combining both parameters could work, but the danger level is a poor indicator for the likelihood of triggering at the slope. Locations with poor snow stability increase significantly with the danger level. The influence of the slope angle on stability is more subtle. Balancing the danger level with slope angle i.e., to ski less steep terrain, does not work.	Consider all potential avalanche slopes, no matter what the danger level is. Avalanches may release from 30° slopes and skier triggered avalanches have similar sizes.
Hazard locations (1,2,4)	The described avalanche danger is prominent at the hazard locations (aspects/elevation band in forecast).	Descriptions merely based on aspects and elevation band cannot always nail down the hazard locations, e.g. persistent weak layers can remain prone to triggering where the snowpack is shallow.	• Hazard locations may indicate the crux slopes of the trip. • Need to double check hazard locations with local observations.
Group size (4)	Likelihood of human-triggering depends on the additional load. Release is more common if we gather or climb nose to tail.	Locations where a single person can trigger an avalanche almost always exist, even if they're sparse and human-triggering is rare.	Traveling in small groups does not reduce the chances of triggering. It comes down to our behavior as even with Low danger a single person may be sufficient to trigger in isolated locations.

Table 1: Indicators for the likelihood of triggering that are used in trip planning methods
(1 SnowCard, 2 Graphical Reduction Method, 3 Stop or Go, 4 Classic Reduction Method).

While in daily life danger and risk may get muddled up, science wants to keep them apart.

Risk means the combination of danger and the consequences. In other words, risk summarizes the likelihood of avalanche release and the consequences of being caught. Climbers and skiers are trying all the time to keep dangers and consequences between the fences: We spread out while we climb (to reduce the likelihood of triggering) or ski one by one from one safe spot to another (to limit the exposure and hence, the consequences). If chances to trigger are zero, the risk is zero and there's no need for mitigation. The higher the likelihood of triggering, the lower the consequences we want to see and the more effective our mitigation strategy needs to be.

We have not always drawn this clear line between the danger or the chances for avalanches in a region and the risk or the individual chances for injury at the slope scale. Many trip planning methods developed in the 1990s missed this distinction; they combine indicators for the likelihood of triggering (*Table 1*). The idea is clear and aims at reducing the number of accidents by omitting terrain where the danger is higher on average. As it is common for straightforward approaches in complex worlds, this comes at a price. Here is one example. Remote triggering of dangerously large avalanches can be an issue even at danger level Moderate if a persistent weak layer poses an avalanche problem. Sure, if the danger level is Moderate only few locations exist where triggering is possible, but consequences would be severe due to avalanche size and the risk is not low.

We can use the indicators described in Table 1 for trip planning to get a rough danger estimate for the intended slope or route. However, if we use the indicators not only for trip planning, but also for slope evaluation, the limitations shown in Table 1 set us on the wrong path. Undoubtedly, the indicators contain valuable information, but usually on larger scale, and only concerning the danger and not the risk. Hence, they can be used to describe danger as long as we're lacking local information—that is before the trip, at home.

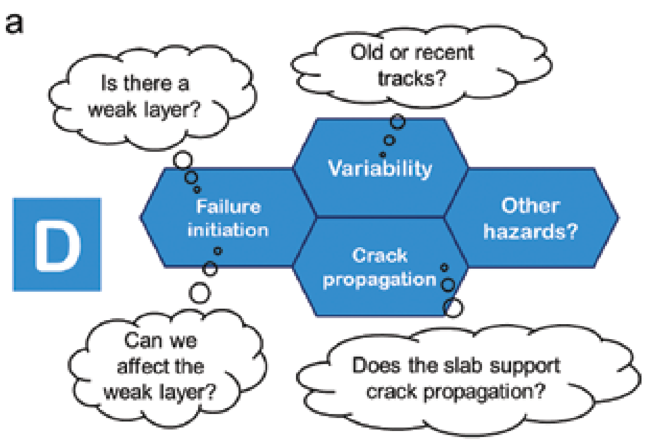
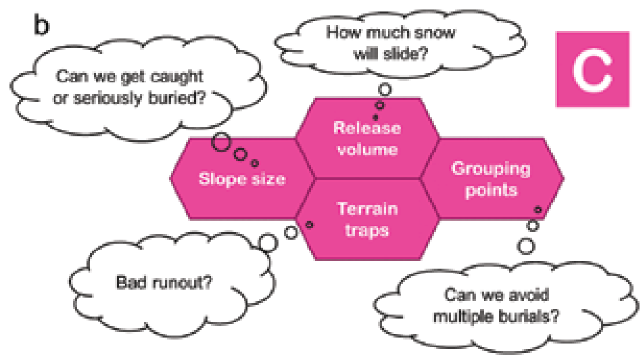


Figure 3: DCMR combines elements describing danger and consequences to conclude on the risk we are exposed to. Four key words each trigger questions concerning (a) the danger and (b) the consequences. Appropriate mitigation measures derive from the unfavorable answers to the eight questions.

CONSEQUENCES FIRST!

Just because it's often easier, we start with the consequences. Climbers often ask themselves intuitively, "what's above?" and "what's below?" In other words, if the slope came down what would be next? Here are four keywords that should trigger the questions that follow:

- *Slope size:* Is the slope rather large? Would release mean serious burial? It may depend on where you ski or climb the slope.
- *Release volume:* How much snow is going to move? Release width and possible crown thickness? Larger slides tend to be more harmful.
- *Terrain traps:* Are there terrain traps that increase the consequences of being caught? Cliffs, trees, rocks in the runout? Gullies or unfavorably shaped runout terrain?



- *Safe spots:* Can we avoid multiple burials? Is only one person exposed at a time? Is the group near to help in case of a burial?

Unfavorable answers give clues for what's at stake—how serious the consequences would be, if we triggered an avalanche (*Figure 3b*).

DANGER

Estimating the danger is typically the harder part, as we're dealing with a question that has no simple straightforward answer: "Will the slope release?" In fact, there is no black or white—all we can do is look at the odds. "Is triggering a likely or a rather unlikely scenario here?" As we're lacking reliable indicators, any method involves considerable uncertainty and hence has to be conservative by nature. This yields a high number of false alarms—even though in hindsight it seems that its application could have prevented many accidents. That's the nature of rare events.

To come up with a reasonable estimate of the odds, we need solid information regarding the key indicators. Research can't do our job (yet), but it can give us directions in the decision process. The likelihood of releasing an avalanche depends on a number of fracture processes that chase each other. If we initiate a failure in a weak layer, a crack may form that can propagate—possibly across the entire slope if weak layer and slab properties sustain self-propagation. Failure initiation and crack propagation can be both observed in field experiments and modeled in computer simulations. The models teach us what it takes that snow layer fails and a crack starts to run. A comparison of observed signs of instability and indicators of snow instability shows that for a slope to be unstable it takes both the propensity for failure initiation and for crack propagation. (*Figure 4*).

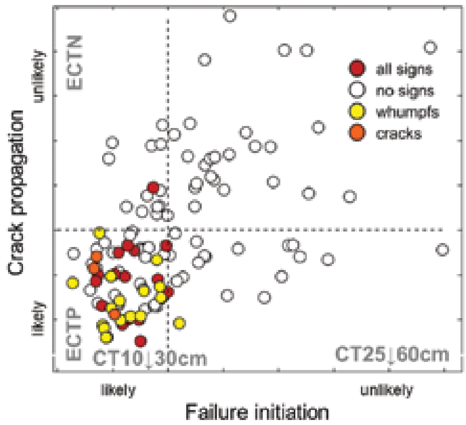


Figure 4: Likelihood of failure initiation and crack propagation describe the release probability at one point on a slope. In 37 of 60 days signs of instability, such as recent avalanches, whumpfs or shooting cracks, were observed in slopes (color filled circles). Signs of instability were observed only if both criteria yielded low values (dashed lines) indicating that failure initiation and crack propagation were "likely." Signs of instability do not always reveal the instability and hence, some white circles remain in the lower left corner. For illustration, examples of snow stability tests are given in gray (Reuter and Schweizer, 2018).

To make it short, we want to know if a weak layer is present that we can affect. Once we fail the weak layer, the snowpack may support the propagation of the crack—or not. The weight and the layering of the slab determine the amount of energy that is available to drive the crack against the weak layer's resistance. Once the crack is running you may think it's too late. But still, spatial variations in weak layer and/or slab properties can stop the shooting crack—imagine surface hoar crystals have flipped before the storm and the "healthy" weak layer ends. Fracture models have identified the described requirements for slab avalanche release and here we try to make the link with field measurements that eventually allow us to develop a method. We wrap it into four keywords that are supposed to trigger the questions that follow:

Figure 5: "Hang on—this roll looks weird..." We've seen snow blowing across ridges yesterday that has released avalanches naturally. Today the wind is less strong, but whatever the weak layer was, I believe it may still be triggered. The weak layer may be deep now, but to the sides the slab on the picture is shallower (Minus). Recent wind slabs always propagate well (Minus). No tracks. No idea whether the surface was smooth or very rough before the storm (Minus). The probability for release is rather high with three unfavorable answers to our four questions. The consequences look rather mellow, but we're not keen. When we reach the foot of the slope where the slab is shallower...

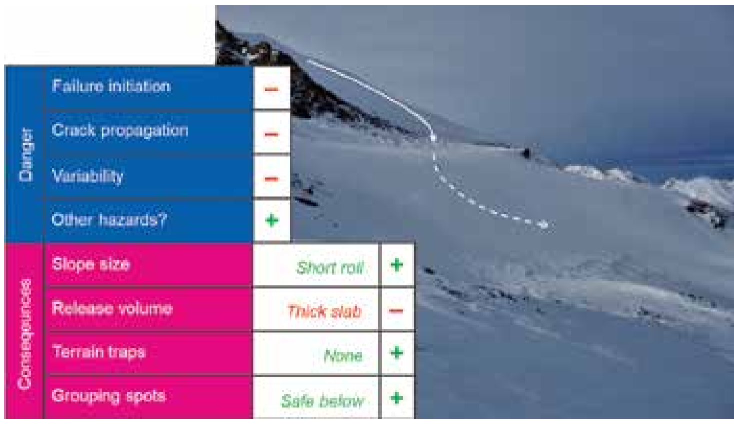


Figure 6: ...the sound of a whip. We hurry away. But the slab does not move our way. Despite the short slope the thick crown fed the slab with substantial volume. We take home that looking at slope size only is not sufficient. We'll be good and ask all four questions.

- *Failure initiation:* How likely is failure initiation? Are there weak layers? Can we affect them along the intended route or at grouping spots?
- *Crack propagation:* How likely is crack propagation? Do slab and weak layer support crack propagation?
- *Variability:* Has the slope been skied much? Skiing is a stability test and triggering is less likely on tracked slopes. Skier traffic increases variability that can help stop crack formation later on. Persistent weak layers can remain sensitive to triggering despite skier traffic.
- *Other hazards:* Is the group threatened by other hazards? Natural release? Falling seracs? Crevasses? Other people who may trigger an avalanche above us?

Having estimated the **Danger** and anticipated the **Consequences** (*Figure 3*) we can now think about suitable **Mitigation** which may help us lower the **Risk** to an acceptable level. The method **DCMR** brings together the key elements for risk management in avalanche terrain and is guided by latest research. There is a good chance that we learn something new when we discuss the risk along these lines with our backcountry partners. *Figures 5 and 6 tell a short story.*

SUMMARY

Danger is not risk. Forecasters refer to regions not to slopes. No surprises here. Obviously, this is not rocket science. We have just presented a method for framing up the important questions—based on our present understanding of avalanche formation. We tried to explain why we ask these questions and how to filter the relevant pieces of information.

The danger level highlights the differences between mountain ranges. In the next steps, when we look at trips or slopes, we need to link local data to forecast avalanche problems and check out where the avalanche problem type is present in the terrain. Picking up the words from the forecast sets our focus in the terrain—what to look out for.

The workflow DCMR supports us during all stages. By answering the four questions about the likelihood of releasing an avalanche and the consequences of being caught, we eventually estimate our individual risk on a particular slope. And this is exactly what we'd like to know eventually before we ski or climb the slope.

The questions on snow instability are hard to answer because the topic is complex, but also because often we just don't know enough. Data on the snowpack are not easy to obtain, particularly at hazardous locations. If we're lacking knowledge we'd better hold back. So, let's think about alternatives when we plan a trip, and maybe we'll find the missing pieces that complete the puzzle outdoors. ⬢

The concept DCMR was presented at ISSW 2018 and CSAW 2020. A workbook for professionals and interested recreationists is currently being tested by some of you. Thank you, we'll keep you posted.

FIGURES FROM:

Reuter, B. and Schweizer, J., 2018: Describing snow instability by failure initiation, crack propagation, and slab tensile support, Geophysical Research Letters 45(14): 7019-7027.

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