5 Review and future challenges in snow avalanche risk analysis

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5.1 Background

Snow avalanches pose a major threat to alpine communities because they affect safety in villages and on traffic routes. Therefore, dealing with avalanche danger has a long tradition in Alpine countries. In most countries, avalanches contribute only to a small degree to the overall risk of a country. For Switzerland, for example, avalanche risk represents only 2% of all risks (BABS, 2003).

5.1.1 Snow avalanche formation, geomorphology and land use planning

Snow avalanches are a type of fast-moving mass movement. They can also contain rocks, soil, vegetation or ice. Avalanche size is classified according to its destructive power (McClung and Schaerer, 2006). A medium-sized slab avalanche may involve 10,000 m^3 of snow, equivalent to a mass of about 2,000 tons (snow density 200 kg/m^3). Avalanche speeds vary between 50 and 200 km/h for large dry snow avalanches, whereas wet slides are denser and slower (20–100 km/h). If the avalanche path is steep, dry snow avalanches generate a powder cloud.

There are different types of snow avalanches (Table 5.1), and in particular two types of release: loose snow avalanches and slab avalanches. Loose snow avalanches start from a point, in a relatively cohesionless surface layer of either dry or wet snow. Initial failure is analogous to the rotational slip of cohesionless sands or soil, but occurs within a small volume (<1 m^3) in comparison to much larger initiation volumes in soil slides. Snow slab avalanches involve the release of a cohesive slab over an extended plane of weakness, analogous to the planar failure of rock slopes rather than to the rotational failure of soil slopes. Depending on the type of avalanche (Table 5.1) the damage and required control process may vary significantly. In general, slab avalanches are most disastrous.

Most snow slab avalanches start naturally during or soon after snow storms. Failure is due to overloading and existing weakness in the snowpack. The existence of a weak layer below a cohesive slab layer is a prerequisite for a dry snow slab avalanche. Weak layers typically contain crystals originating from kinetic grain growth such as surface hoar or faceted crystals. Slab thickness is usually less than 1 m, typically about 0.5 m, but can reach several meters in the case of large disastrous avalanches. The observed ratio between width and thickness of the slab varies between 10 and 10^3, and is typically about 10^2. Snow avalanches start from terrain that favors snow accumulation and is steeper than about 30–45°. On terrain less than about 15° snow avalanches start to decelerate and finally stop.

Forest stands may hinder avalanche formation because redistributed snow from the crown prevents weak layer formation (Bründl *et al*., 1999; Bartelt and Stöckli, 2001) and stems in dense forests may stabilize the snowpack. However, if a snow avalanche starts above the timberline, the forest has only a marginal influence on the avalanche flow process.

Besides natural triggering by overloading or internal weakening of the snowpack, snow slab avalanches can also be triggered artificially – unlike most other rapid mass movements – by localized, rapid, near-surface loading by, for example, people (usually unintentionally) or intentionally by explosives used as part of avalanche control programs. Occasionally, snow avalanches have been triggered by large earthquakes (Stethem *et al*., 2003). In general, naturally released avalanches mainly threaten residents and infrastructure, whereas human-triggered avalanches are the main threat to recreationists.

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TABLE 5.1. *International snow avalanche classification*

Zone	Criterion	Characteristic and denomination	
Origin	Manner of starting	from a point ***Loose snow avalanche***	from a line ***Slab avalanche***
	Position of failure layer	within the snowpack ***Surface-layer avalanche***	on the ground ***Full-depth avalanche***
	Liquid water in snow	absent ***Dry-snow avalanche***	present ***Wet-snow avalanche***
Transition	Form of path	open slope ***Unconfined avalanche***	gully or channel ***Channelled avalanche***
	Form of movement	snowdust cloud ***Powder snow avalanche***	flowing along ground ***Flowing snow avalanche***
Deposition	Surface roughness of deposit	coarse ***Coarse deposit***	fine ***Fine deposit***
	Liquid water in deposit	absent ***Dry deposit***	present ***Wet deposit***
	Contamination of deposit	no apparent contamination ***Clean deposit***	rock debris, soil, branches, trees ***Contaminated deposit***

UNESCO, 1981

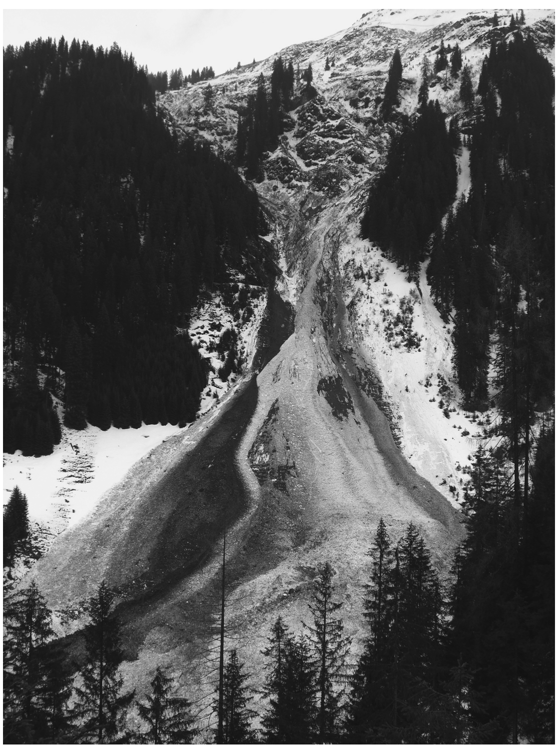


FIGURE 5.1. Grüenbödeli avalanche (Canton Grisons, Switzerland.) Note the results of the destructive forces and also the soil and rock mass transported by these snow avalanches. (Source: SLF.)

Avalanche formation is usually, e.g. in avalanche control programs, assessed heuristically by weighing the so-called contributing factors: terrain, precipitation, wind, temperature and snow stratification, i.e. the complex interaction between terrain, snowpack and meteorological conditions are explored (Schweizer *et al*., 2003).

Objects in the deposition area are influenced by two major processes. First, the air pressure plume in front of a dry snow avalanche has a huge destructive power. Second, the snow in motion exerts high impact pressures on objects located in the run out path (Sovilla *et al*., 2008). The destructive forces of avalanches are also enforced by transported debris (Figure 5.1). While in motion, entrained rock particles of up to boulder size or large woody debris can cause major destruction (e.g. SLF, 2000).

As a consequence of the above, large snow avalanches are high energy processes that contribute to the shaping of environments with steep topography. Material picked up on run-over areas may be transported over tens of meters as reported e.g. from Iceland (Decaulne and Saemundsson, 2006). For example, large rocks in valley floors often do not correspond to rock fall processes but have rather been transported by snow avalanches (Kristjansdottir, 1997).

From a geomorphic perspective, a specific characteristic of every snow avalanche is, however, that the deposited snow melts every spring. Although the geomorphic forming effectiveness of a single snow avalanche might not be large, large full-depth wet snow avalanches (after

UNESCO, 1981) occurring every spring can considerably contribute to material transport (Ward, 1985; Becht, 1995) and can influence the vegetation cover in tracks by generally reducing tree growth, size and density (Kulakowski *et al.*, 2006; Rixen *et al.*, 2007). However, there is still a lack of knowledge in determining the role of snow avalanches in the coupled geomorphic process chains.

Changing land use is of major importance for avalanche risk. Examples are deforestation, changes in agricultural practices (e.g. grass cuts), and especially the development of infrastructure and settlements (Fuchs and Bründl, 2005). Land use planning is an important part of avalanche risk management and different types of maps indicating hazard or even risk do exist. Based on local, regional and national legislative conditions, these maps have either indicative character with no executive power and related requirements (typical scale 1:25,000) or they are compulsory for any future land use development plan (e.g. for Canada refer to Jamieson and Stethem, 2002). Hazard zone maps on the scale 1:10,000 to 1:5,000, which are mandatory for land use planning in many European countries, such as Austria, France and Switzerland, depict highly endangered areas and less endangered areas indicating where building is allowed and where not. For particular regions, risk maps have been developed (e.g. Arnalds *et al.*, 2004) showing the risk level for specific areas. Based on such risk maps, acceptable risk levels have been developed in close cooperation with affected social actors (Bell *et al.* 2006). According to the requirements of sustainable development, it would be highly advisable to consider snow avalanche hazard – and even risk – maps as a compulsory part of land use planning for every mountain region in the world.

5.1.2 General methodological framework of risk management

Risk management denotes a general framework, which aims at assessing, reducing and controlling the risks from different sources. An integrated part of risk management is the risk concept, which addresses the following basic questions (Kaplan and Garrick, 1981; Haimes, 2004):

- "What might happen?" (risk analysis);
- "What is allowed to happen?" (risk evaluation);
- "What needs to be done?" (planning and evaluation of mitigation measures).

The terms "risk analysis" and "risk evaluation" are often summarized within the term "risk assessment" (Crozier and Glade, 2005). The increasingly widespread use of this concept in different disciplines such as finance and health management, engineering and technology, biodiversity, nuclear technology or terrorism prevention has been proven to support decision-making in complex systems (Hatfield and Hipel, 2002) and has therefore become a routine procedure (Klinke and Renn, 2002) in the planning and realization of projects involving risks.

Risk management stresses the integration of risks from different fields into a systematic integrated approach. Based on existing guidelines (e.g. AS/NZS, 2004) this demand has recently been outlined in the new ISO Standard 31000 (ISO, 2008). This standard follows the argument that risk management can only be effective if it is a part of all management functions and decisions (Figure 5.2).

A risk analysis consists of four parts (Bründl *et al.*, 2009). The goal of a *hazard analysis* is to determine the scenarios that have to be taken into account in a risk analysis. Basic data are indications of the process in the terrain, topographic maps, aerial photographs and satellite images, which allow one to create a geomorphologic map of the phenomena in the area under analysis. The analysis of event register data or historical chronicles allows assuming possible scenarios. The intensity, defined as the physical impact of a process, is determined by modelling the process. The results of a hazard analysis are visualized by intensity maps.

In the *exposure analysis*, exposed persons and assets are determined regarding their location number, type, value and probability of exposure.

In the *consequence analysis*, the results of hazard and exposure analysis are combined and the damage or loss in case of events in the regarded scenarios is calculated. Finally, the *risk is calculated* as a product of the frequency of the given scenarios with the calculated damage of these scenarios. The risk is expressed as individual risk to single persons and/or societal or collective risk to assets and persons in the area under investigation. The individual risk is defined as the probability per year that a single person affected by the given scenarios will die. The societal risk is expressed as expected damage per year in monetary values per year or fatalities per year.

The hazard analysis is the fundamental part of a risk analysis. Investigations on the sensitivity of factors in the risk equation suggest that assumptions on the frequency and the physical impact of the considered process have the most significant influence on the calculated risk (Schaub, 2008). Therefore, in the following section an overview on recent trends in hazard analysis is given.

5.2 Review and recent trends in hazard analysis

Large snow avalanches are rare events and the prediction of disastrous avalanche events involves great uncertainty

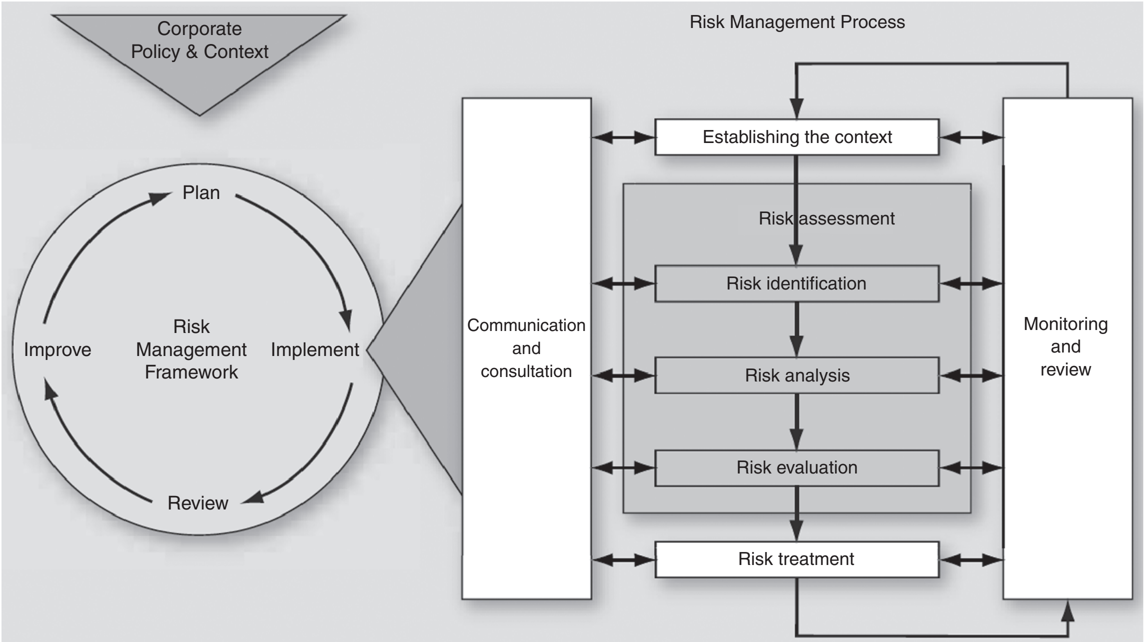


FIGURE 5.2. The systematic approach to risk management of ISO 31000. (Jaecklin, 2007.)

(Schweizer, 2008). Therefore, snow avalanche hazard analysis relies on defining hazard scenarios rather than well-described design events. Central to any snow avalanche hazard analysis is the definition of *hazard scenarios*. Scenario planning requires obtaining historical information (inventories of past events or case studies) and hands-on terrain information to develop an idea of what has and therefore what could happen at a particular site. In the end, the definition of an appropriate hazard scenario determines the quality of the entire hazard analysis since it tries to include how different factors (climatic conditions, release locations, wind blown snow, terrain, snow cover erosion, secondary releases, vegetation, etc.) can combine and lead to complex, historically unforeseen and therefore surprising and critical situations. Simple experience coupled with historical information are the primary resources that experts have at their disposal to define a reasonable hazard scenario.

Computer models can sometimes “support experience” if they can correctly simulate documented events. This provides the hazard expert with some confidence that the consequences of an undocumented situation can be predicted, or at least provide results that are thought provoking, causing the expert to modify his scenario. For example, the weight of different factors (e.g. location of starting zones or the inclusion of secondary release zones) may shift because of simulation results. Thus, the interplay between the computer model and the experience of the hazard expert is rather complex. On one hand, an expert will only employ a computer model if it provides results that are “beyond” his experience; while, on the other hand, results that do not agree with experience are simply not trustworthy. The difference between these two cases is extremely small and is always resolved in the end by the judgement of the expert (not the computer model). Computer models that continually supply the expected result are confidence building but in the end superfluous. The decision whether a model “expands” the expert’s experience, and is therefore useful because it has some predictive quality, or is simply used to satisfy the demands of the government authorities, who would prefer some “objective” calculation (and therefore non-expert, subjective analysis), is central to the future of risk analysis.

The application of computer models by hazard experts therefore has several fundamental consequences for avalanche and natural hazards engineering. First, computer models must contain enough detail (factors) to allow experts to test scenarios and, conversely, experts must have increasing knowledge of the numerical solution procedures at the core of the simulation programs. Model input must be flexible (and extremely user-friendly); solution algorithms robust, quick and stable. How the simulation results are affected by the mathematical approximation of terrain (slope averaging, grid spacing, smoothing of macro-sized roughness, etc.) must be known since these parameters influence whether or not the expert trusts the model results. The depiction of simulation results in the form of maps and three-dimensional visualizations is essential since the mass of numerical results provided by computer programs must be easily and quickly displayed and interpreted in a form experts can use.

However, at the very core of the expert–computer simulation problem is the "right" model physics. The model physics is *phenomenologically* right if the model provides the right answers – say run out distances or flow velocities – using flow parameters that have no direct experimental basis. The flow parameters have been determined over many years from model case studies, carried out under given assumptions (e.g. terrain averaging, no snow entrainment). The expert accepts these parameters because they do not transgress his experience and are, furthermore, usually recommended by the government authorities. A well-defined set of phenomenological model parameters is valuable since this set allows an expert to go "beyond" his experience. The phenomenological parameters are, however, always somewhat mysterious and intangible and therefore, in the end, uncertain. An expert will gladly use them, but is at the same time always troubled by them.

The model physics is *physically* right if the model provides the right answers using avalanche flow parameters that are experimentally based; that is, obtained from measurements, first with the material snow and second at the real scale. Such measurements in natural hazard science are unique (Sovilla *et al*., 2006, 2007; Kern *et al*., 2009). Clearly, physically correct models are needed for the future of avalanche science, but it should be stressed that physically correct models cause many problems:

(1) They disrupt the continuity of calculation procedures for hazard analyses. Authorities simply do not want to introduce new sets of parameters every few years since this will cause confusion in practice (perhaps with expensive re-reviews or even costly litigation). This means that new models must be carefully introduced – if at all – only after extensive testing and calibration. The lifetime of the model must be guaranteed to ensure some continuity – with the past as well as many years into the future. It is incorrect to suggest that older, phenomenological models are wrong because they have no experimental foundation. They are wrong only when they produce the wrong results – and this is not the case with well-known avalanche dynamics models such as the Voellmy–Salm model (Salm, 1993; Bartelt *et al*., 1999).

(2) Physically "right" models usually require too exact a definition of release and entrainment conditions as well as terrain geometry. Whereas the older phenomenological models are generous and robust (since they provide the right answers under simplifying assumptions), physical models are rigid and less generous. For example, the Voellmy–Salm model could be used well without snow entrainment. Physical models will require the specification of snow cover and entrainment rates. The hazard expert might be grateful that an additional factor in his hazard scenario can be included in the hazard analysis, or the hazard expert might feel simply overwhelmed by the required detail of the problem. In the end the analysis could be less certain and more confusing – even though a physical model has been employed.

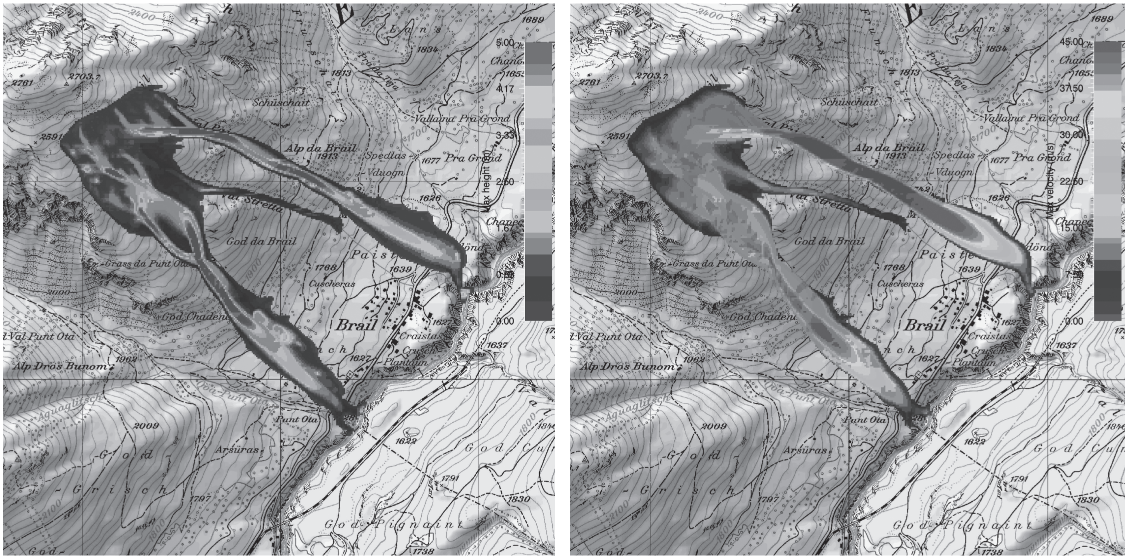
These considerations regarding the judgement of experts and the role of computer models have led to the development of the computer model RAMMS (Christen *et al*., 2007). The program RAMMS is especially designed to aid experts in making judgements in the hazard analysis process and represents an important development in avalanche risk assessment:

(1) The program uses three-dimensional digital terrain models (in Switzerland for certain examples up to a 2 m resolution) to model complex mountain terrain. Many important questions in snow avalanche hazard analysis are related to avalanche motion on real terrain, such as multi-channel flows, channel widening and slope deviations in the run out zone.

(2) Both phenomenological models (Voellmy–Salm) and experimentally based physical models (Bartelt–Buser) are included in the program package. (For more information concerning the Bartelt–Buser model, see Bartelt *et al*., 2006; Buser and Bartelt, 2009). This allows experts to exploit the advantages of both models and ensures model continuity. The comparison between well-calibrated phenomenological model results and more physically based models can be helpful in many situations, especially where the expert is uncertain.

Snow cover erosion and entrainment process models are included that allow a realistic representation of the avalanche mass balance (Sovilla *et al*., 2007).

(3) The program system contains sophisticated output features that allow the results to be interpreted. Two-dimensional maps (Figure 5.3) as well as three-dimensional representations can be chosen by the user. Other useful features include the import of measured, historical avalanche data, or aerial photos that can be overlaid on the simulation results. This too helps the interpretation of the simulation results. The simulation results can likewise be easily exported to GIS systems.



(a) (b)

FIGURE 5.3. Calculations of an avalanche, which occurred in 1968 near Brail, canton of Grisons, Switzerland. (a) Calculated maximum flow heights. (b) Calculated maximum flow velocities. The simulations were validated with the original observations. The avalanche crossed the road before and after the village of Brail.

5.3 Methods of risk analysis

5.3.1 Definition of risk

The term risk is defined as “a measure of the probability and severity of loss to the elements at risk, usually expressed for a unit area, object, or activity, over a specified period of time” (e.g. Crozier and Glade, 2005). Generally expressed in a mathematical equation, this definition can be written as (e.g. Fuchs *et al.*, 2007; Bründl *et al.*, 2009):

$$R_{ij} = p_j \cdot p_{ij} \cdot A_i \cdot V_{ij} \tag{5.1}$$

with R_{ij} as the risk to an object i in scenario j, p_j as the frequency of a scenario j, p_{ij} as the probability that an object i is present while scenario j is occurring, A_i as the value of an object or the number of exposed persons, and V_{ij} as the vulnerability of an object i in a scenario j. The frequency of a scenario can be approximated as the difference of the exceedance probability of two adjacent scenarios, e.g. $p_{10} = 0.1 - 0.033 = 0.067$ for a 10-year scenario (Bründl *et al.*, 2009; for an approximation from hazard maps see Rheinberger *et al.*, 2009). The total risk R for an area under investigation, e.g. for part of a village, is the sum of all risks to individual objects and the risks in all considered scenarios according to:

$$R = \sum_j \sum_i R_{ij} \tag{5.2}$$

Equation (5.1) shows that there are several factors that influence the risk. On the one hand there are probabilities that an event happens and that an object is affected, on the other hand there are values at risk and their characteristics. In the following section these factors are briefly described.

5.3.2 Factors for calculation of risk

For estimating potential damage, the type, the number, the value and the vulnerability of the *elements at risk* that depended on the process intensity have to be assessed. The type of elements considered and the level of detail depends on the scope of the risk analysis (Bell and Glade, 2004) and the target scale. A characterization of each specific element at risk is often connected to an extensive data collection. Therefore, it must be decided whether each single object should be recorded or whether objects could be grouped in object classes. Elements at risk are either at fixed locations (e.g. buildings, power stations, etc.) or they are mobile (e.g. trains or cars). The value of these objects can be expressed in monetary units representing the recovery values. Special attention has to be given to persons at risk and their presence in or outside structures.

It is common to assess elements at risk only in their present form. It depends on the goal of the assessment whether an expected increase in the damage potential should be regarded or not. However, incorporating future variability bears uncertainty and should be carefully indicated.

An important factor for the estimation of risk is vulnerability. Although this term is always related to the consequences of a natural disaster or an event, it is defined in different ways, as shown in literature (e.g. Cutter, 1996; Weichselgartner, 2001; Birkmann, 2006, Fuchs *et al.*, 2007). The definitions range from the social science perspective to those from engineering science. Thus, vulnerability is measured on a metric scale (as monetary units), or on an ordinal scale based on social values or perceptions and evaluations. From a natural science perspective, Uzielli *et al*. (2008) define vulnerability as a product of intensity during scenario j and the susceptibility of object i. Generally, vulnerability is considered as a function of a given intensity of a process, expressing the expected degree of loss for an element at risk (Varnes, 1984; Fell, 1994). The value ranges generally from 0 (no damage) to 1 (complete destruction).

The assessment of these "technical" vulnerability values involves the evaluation of several different parameters and factors such as building materials and techniques, state of maintenance, and the presence of protection structures (Fell, 1994; Fell and Hartford, 1997) in relation to the potential physical impact of a process (Fuchs *et al.*, 2007). For risk analyses at the regional scale it might be appropriate to work with average values. For detailed local investigations it may be necessary to determine the vulnerability of an object individually by considering relevant characteristics (e.g. windows at the upslope side of buildings, local structural protection, etc., Holub and Fuchs, 2008).

The determination of vulnerability values for snow avalanche risk assessment is based on empirical data, but in some cases also on expert knowledge. Wilhelm (1997), Jónasson *et al*. (1999) and Barbolini *et al*. (2004a, b) suggested vulnerability functions based on empirical data and Borter (1999), Borter and Bart (1999), Bell and Glade (2004) and Kraus *et al*. (2006) propose average vulnerability values for buildings and exposed persons. Vulnerability curves can be distinguished with respect to the elements at risk, and also with respect to the avalanche type. Powder snow avalanches are characterized by higher flow depths than dense flow avalanches; consequently, whole buildings are affected and damage is distributed over the entire building. Vice versa, damage is located only at the lower floor levels if dense flow avalanches occur. An overview of the available vulnerability relations for snow avalanches is provided in Table 5.2.

Related to people, vulnerability is denoted as mortality rate λ, defined as the conditional probability that a person is killed given that the object in which the person is present is affected and damaged. The value ranges between 0 (no fatality) and 1 (all exposed and affected persons are killed).

TABLE 5.2. *Overview of available vulnerability relations for snow avalanches*

Vulnerability	Buildings		DA	Wilhelm (1997)
			PA	Barbolini *et al.* (2004a)
	People	Inside buildings	DA	Jónasson *et al.* (1999); Keylock and Barbolini (2001); Barbolini *et al.* (2004b)
			PA	Barbolini *et al.* (2004b)
		Outside buildings	DA	Barbolini *et al.* (2004b)
			PA	–

DA, dense flow avalanche; PA, powder avalanche
Cappabianca, 2008

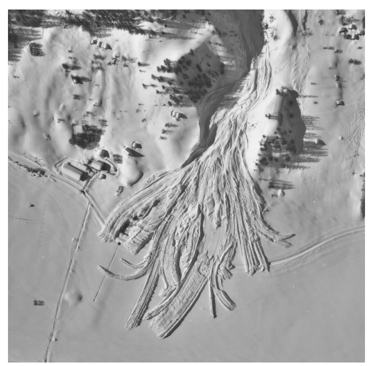


FIGURE 5.4. Run out area of an avalanche in Ulrichen, Switzerland (note the houses on the left side of the image as scale). The run out area is in most cases only partially affected by the deposition. This effect is considered in risk analysis by integrating a spatial occurrence probability. (Source: Federal Office for Topography, coordination unit for aerial photography.)

Observations of avalanche events show that single events in most cases do not cover the whole potential run out area (Figure 5.4). Therefore, the probability whether an object is hit or not is the conditional probability of the occurrence affected by the morphology of the terrain in the run out area, denoted as *spatial occurrence probability*. This conditional probability can be estimated by deriving an empirical probability based on past events using, for example, event trees for illustration. The other approach is to assume mean values for the spatial occurrence probability by analyzing past events for the run out location under investigation. Values in use in practice in Switzerland range from $p(e) = 0.10$ for a 30-year scenario, $p(e) = 0.50$ for a 100-year scenario, to $p(e) = 0.80$ for an extreme scenario with a return period of 300 years (BAFU, 2008).

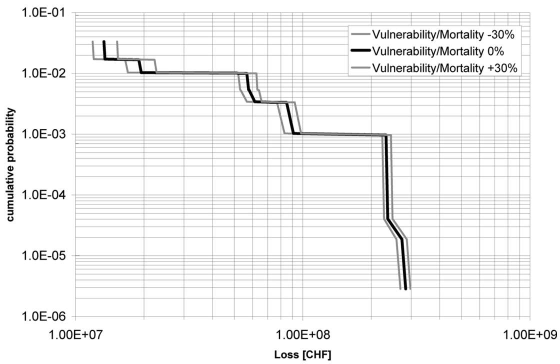


FIGURE 5.5. Example of a FN-diagram with an upper and a lower boundary reflecting the uncertainty of the factors vulnerability of buildings and mortality rate of persons in buildings (Bründl, 2008.)

5.3.3 Calculation and presentation of risk

The risk due to avalanches can be presented as societal or collective risk or individual risk. The *societal risk* is calculated by linking the frequency of scenarios with the consequence of the scenarios. The result is expressed as monetary units per year or number of fatalities per year. However, according to Kaplan and Garrick (1981) the societal risk cannot be expressed only as a single number. Therefore, the risk is usually presented with an FN-diagram (Figure 5.5). The area below the curve represents the societal risk given the assumed loss. The graph shows at what probability a certain damage is exceeded.

The *individual risk* is an indicator of how much risk a single, identifiable person has to bear as a consequence of the assumed scenarios. The total societal risk allows no statement of whether the risk for an individual person is above or below an accepted risk level. Fewer people with a high individual risk can result in the same societal risk as many people with a low individual risk. It is standard in risk assessment to calculate both the societal and the individual risk.

The calculation of risk in practice is based on the actual conditions, i.e. number and value of existing objects and persons, land use etc. However, land use is not constant over time. If factors in the risk equation are changing, it will have direct consequences on the risk.

5.4 Change in avalanche risk, influence of different risk factors

"The world is not static, and we discover new threats daily." This statement was made by Susan Cutter (2003, p. 4) to describe a world view, that seems sometimes to have been forgotten in risk research concerning natural hazards. Beside this insensitivity to a dynamic perspective, natural hazards can no longer be seen as single, isolated events. Risk research requires an integrative approach to explain the interactions among natural and social systems. According to Cutter (2003) it requires a new way of viewing the world, one that integrates perspectives of science and social science and furthermore incorporates the dynamic (temporal and spatial) dimension.

A fundamental characteristic of risk resulting from natural hazards is the connectivity between the natural system (or geosystem, governing the physical part of the process) and the social system (including values at risk and vulnerability). Both systems are subject to continuous changes in space and time. Due to changes in the social system (such as varying risk awareness and acceptance, changing economic conditions or mobility behavior) new demands on the geosystems are entailed, resulting in, for example, different use of natural resources or engineering structures. This may produce the intended response of the geosystem due to changing process conditions, and additional unintended feedbacks, both of which in turn induce a reaction in the social system. If the run out area could be reduced to a specific magnitude, new development areas could be assigned in areas supposed to be safe.

The same development can be seen vice versa. Higher snow avalanche activity may give rise to a response of the social system, which may change the environmental settings for snow avalanches. Due to the dynamics of the geosystem and the social system, new interaction emerges and therefore enhanced connectivity can develop. Increasing connectivity is likely to induce higher complexity (Hufschmidt *et al*., 2005). Complex systems imply two fundamental conditions: (1) the system consists of multiple interactive components and (2) these interactions give rise to emergent forms and properties, which are not reducible to the sum of the individual components of observed system. The geosystem, in our case snow avalanches, as well as the social system can be considered from this perspective as well as the interaction between these systems. Hence, rising losses related to natural hazard processes can not be solely connected either to the changes of the natural processes or to the development of the damage potential and the vulnerability. These losses are the result of increasing complexity. Thus, increasing knowledge about one part, such as the understanding of the hazard processes, elements at risk or vulnerability, without analyzing the interaction between these components and their dynamics does not help in finding useful management strategies to reduce risk.

The above-described concept differs from approaches used in science and practice. Risk analyses applied to natural hazards are in general static approaches (Jónasson *et al.*, 1999; Keylock *et al.*, 1999; Gächter and Bart, 2002; Bell and Glade, 2004) neglecting past risk levels and the history of evolution to the current situation under consideration as well as possible future risk levels. However, risk related to natural hazards is subject to temporal changes since the risk-influencing factors are variable over time, each factor with an individual evolution (Fuchs and Keiler, 2006). Therefore, identifying temporal changes of natural risk, as well as the underlying processes, contributes to an improved understanding of today's risk levels.

In the following, an overview of results of a study with the focus on temporal changes of snow avalanche risk between 1950 and 2000 (Keiler *et al.*, 2006) is presented. First, a brief description of the general change in avalanche activity, elements at risk and vulnerability since the 1950s in the Eastern Alps is given. In the second part, the evolution of risk is illustrated focusing on a few avalanche paths in the municipality of Galtür (Austria).

In the twentieth century, natural avalanche activity seems to have been neither significantly increasing nor decreasing, although the variability of events makes an exact statement difficult (Bader and Kunz, 1998; Schneebeli *et al.*, 1998; Laternser and Schneebeli, 2002, 2003). Thus, it can be assumed that changes in the natural processes are due to the construction of permanent mitigation measures in the release areas or run out areas of avalanche tracks. In Switzerland, about 1 billion euros has been invested for this purpose since 1950 (SLF, 2000). In the Galtur study, snow avalanches were simulated by the 3D model SAMOS (Sailer *et al.*, 2002; Sampl and Zwinger, 2004) considering the Austrian design event with a 150-year recurrence interval. Furthermore, the construction of supporting structures in the release area over time and their influence on processes area and occurring impacts were modelled (Keiler *et al.*, 2006).

In contrast to the snow avalanche activity, societies in the Alps have undergone considerable socio-economic changes since the mid twentieth century. This development reflects a shift from farming-based activities towards a tourism and leisure-time orientated economy (Bätzing, 1993). Contemporaneously, settlements and the population increased significantly in the Eastern Alps. A similar trend is outlined for the damage potential in Keiler (2004), Fuchs and Bründl (2005) and Keiler *et al.* (2005). Therefore, areas suitable for land development are relatively scarce in the Inner Alpine valleys, e.g. in Austria, only about 20% of the whole area is appropriate for development activities (BEV, 2004). The change in number and size of buildings is a good example to illustrate this development. For the long-term risk assessment, monetary values of buildings were calculated using the volume of the buildings and average prices per cubic meter for new buildings, as used by insurance companies. Furthermore, details of the function and construction types were analyzed (Keiler, 2004; Keiler *et al.* 2006).

Regarding vulnerability approaches related to snow avalanches, it has to be stated that there is a lack of studies in general as well as on temporal changes of vulnerability in both natural science and social science. Changes in the construction method of buildings have a huge influence on vulnerability to the impact of snow avalanches. Therefore, the vulnerability functions for different construction methods related to snow avalanche pressure were used in this study, as outlined in Wilhelm (1997).

The following results (calculated using Formula (5.1)) show the changes of avalanche risk, expressed as the potential monetary loss of buildings resulting from the occurrence of the defined design event. This risk scenario illustrates the real-time change of the possible loss, taking into account changes of all three risk-influencing factors: (1) the shifts in the values at risk, (2) the varying vulnerability of buildings and (3) the construction of supporting structures.

In a comparison between 1950 and 2000, the development of risk of the three studied avalanche tracks differs considerably (see Figure 5.6). The risk related to the Großtal West and East avalanches doubled and nearly doubled, respectively. One of the avalanche tracks shows a steady increase, whereas the other one is characterized by a slight increase and decrease during this 50-year period. In contrast, the risk associated with the Gidisrinner avalanche in 2000 was just below the risk for the year 1950. Furthermore, the risk evolution of this avalanche path is shaped by the strongest increase and reduction of risk. Summing up the possible losses of all three avalanche tracks, the risk increased considerably until the 1980s, followed by a short period of

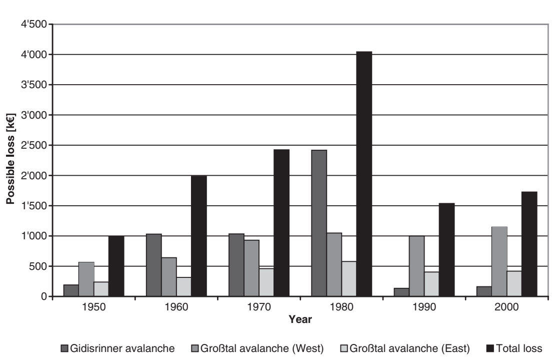


FIGURE 5.6. Development of the possible loss from 1950 to 2000 for the Gidisrinner and the Großtal avalanche (West and East). The black columns denote the total loss.

reduction due to mitigation measures, and then rose slightly in the last decade.

Considering that the development of the values at risk for all three avalanche tracks shows an increase of a factor of five between 1950 and 2000 (Keiler *et al.*, 2006), no general trend could be determined for the calculated risk. Analyzing the different influencing factors and their interaction, this development is caused by different aspects. These aspects were the spatial distribution of the exposed objects, the values at risk, the occurring impact pressures and the related vulnerability of the objects, the effectiveness of the mitigation measures regarding both the extent of the run out zone and the reduction of the pressure as well as legal regulations. Small changes of one of these aspects can cause considerable differences in the resulting risk. These findings are consistent with recent studies in the Swiss Alps (Fuchs *et al.*, 2004). The increase in risk can therefore not solely be attributed either to an overall increase in values at risk as suggested in different studies (White *et al.*, 2001; Barbolini *et al.*, 2002), or to a decrease in run out distance due to the construction of technical mitigation (Ammann, 2001); rather these losses are simultaneously a result of increasing complexity caused by changes of the geosystem, the social system, and the connectivity between these systems.

5.5 Conclusions: where to go from here; future challenges

Challenges for future work on snow avalanche risk assessment relate to different aspects. For avalanche formation and for defining the release conditions, the monitoring of snow accumulation and the modelling of both snowpack properties and stability will be major areas of research. Besides direct field measurements, which continue to be important as ground truth and for model verification, also applications of remote sensing technologies (e.g. Prokop, 2008; Schaffhauser *et al.*, 2008) and modelling of the energy fluxes between atmosphere, snowpack and soil in complex alpine terrain (Lehning *et al.*, 2008) are needed to improve hazard scenarios.

In hazard analysis the continuous improvement of snow avalanche models is essential since it is an important basis for risk assessment. Models that are able to accurately reconstruct the behavior of avalanches in three-dimensional terrain will be used in the near future. Real-scale experimental investigations of avalanches have placed the prediction of impact pressures (Sovilla *et al.*, 2007) and extreme avalanche friction parameters (Buser and Bartelt, 2009) on a better foundation. Thus, it will be possible to formulate more realistic hazard scenarios and to better simulate mitigation methods such as dams. However, the definition of initial conditions, solution parameters and grid resolution will also become more difficult. More than ever, practical experience will be required to interpret model results. Therefore, the development of other model approaches should not be forgotten (e.g. statistical run out modelling by Delparte *et al.* (2008)). In numerous regions of the world, very simple model applications are the only way to assess snow avalanche hazard.

Improved risk analyses in the future are also related to more realistic assumptions on the vulnerability of people and objects or the spatial distribution of avalanche deposits in the run out zone. Monitoring of damage-causing events and analyzing the dynamic interactions between process and objects is an issue that holds not only for snow avalanches but also for the assessment of other gravitational processes such as debris flow, rock fall or landslide.

Risk management for natural hazards includes an integrated use of different types of measures: technical (e.g. snow supporting structures), biological (e.g. protection forest), organizational (e.g. closure of roads or evacuation of buildings) and land use planning. Developing innovative methods and tools for optimization of the scarce financial resources for planning of measures is a field for future work (e.g. Cappabianca *et al.*, 2008; Bründl *et al.*, 2009).

In countries where the safety level is lower, the establishment of an observation and measurement network, the transmission of data, the building up of warning services adapted to local or regional conditions and the education of local or regional avalanche experts are key issues. Additionally, the coping capacity and the resilience of the potentially affected society have to be strengthened.

Snow avalanche hazard and risk has also to be framed within principle geomorphic hazard and risk assessments. Although the demand for a multi-hazard risk assessment has been conceptually addressed (e.g. Glade and von Elverfeldt, 2005) only minor work has been carried out in trying to link different geomorphic hazard assessments (e.g. Fuchs *et al.*, 2001).

A major issue for the future is how changes in society (e.g. tourist resort development) and environment (e.g. climate change) cause temporal and spatial changes in avalanche risk. This also includes the changing consequences of snow avalanches due to suburban development on alluvial fans in valley floors or by expansion of lifeline networks. Even without changing snow avalanche activity, snow avalanche risk might change purely because of changes in land use. Dealing with these challenges will remain a central task for many countries in order to allow sustainable development of mountain regions in the future.

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