Natural Hazards and Earth System Sciences (2004) 4: 263–275
SRef-ID: 1684-9981/nhess/2004-4-263

Natural Hazards
and Earth
System Sciences

Development of avalanche risk between 1950 and 2000 in the Municipality of Davos, Switzerland

S. Fuchs[1], **M. Bründl**[1], **and J. Stötter**[2]

[1]WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2]Department of Geography, University of Innsbruck, Austria

Received: 30 September 2003 – Revised: 10 December 2003 – Accepted: 12 December 2003 – Published: 16 April 2004

Part of Special Issue “Multidisciplinary approaches in natural hazards”

Abstract. In recent years, risk assessment has become increasingly important for the protection of settlements against natural hazards because the public authorities have to economise their budgets and therefore to legitimate their investments. To quantify risk, information is needed on both, recurrence intervals of the potentially damaging natural processes and on the associated damage potential. In the past, high efforts were undertaken to assess the former, while the latter was almost ignored. The aim of this study was to determine the development of the avalanche risk in the inhabited areas of the municipality of Davos, canton of Grisons, Switzerland, for the period between 1950 and 2000. The extent of avalanche prone areas was quantified using the numerical avalanche model AVAL-1D and the current legal hazard maps. The damage potential was quantified by the number and reinstatement values of buildings and by the number of persons per building. It has been demonstrated that, contrary to the frequently expressed statement that the vulnerability of communities has increased, the risk for this settlement in fact decreased substantially. This can mainly be attributed to the realisation of mitigation measures, such as defence structures in avalanche starting zones. The only exception regarding the development of risk was in the category of residential buildings, were an increase in risk was already detectable at medium recurrence intervals. This is remarkable because methods of land use planning, such as hazard mapping, are intended to protect residential buildings from the impact of hazardous processes. However, general statements referring to a larger area (region, country) might be difficult to make, since small-scale disparities have a very important influence on the diversification of risk and risk management. Furthermore, it has to be emphasized that the results are highly dependent on the assumptions made in this study.

1 Introduction

Avalanches pose a threat to settlements and infrastructure in Alpine environments. In addition to flooding events and landslides, avalanches repeatedly cause serious damage in inhabited areas, even though this damage is usually on a smaller scale. Overall, damage resulting from avalanches is decreasing, in contrast to the damage caused world-wide by other natural hazards (Burton et al., 1993; Munich Re, 2002; United Nations, 2002). However, avalanches can pose a high level of threat locally, because Alpine settlements are concentrated in confined areas. This intensive utilisation is because many Alpine areas cannot be utilised in an economic sense. In the canton of Grisons, a typical central-alpine mountain area, non-productive areas amount to 44% of the whole territory (Ritzmann-Blickenstorfer, 1996). In recent years, possible climate-induced changes in areas of natural environment have been investigated systematically, particularly changes in magnitude and frequency of hazardous events (e.g. Schneebeli et al., 1998). However, until now little work has been done to assess changes that have occurred in the Alpine man-made environment since the end of the 19th century, and to ascertain whether susceptibility to intensified processes has increased. One way of approaching this question is to investigate changes in the risk of natural hazards in settlement areas, because changes in risk in settlements result from changes in natural environment on the one hand and changes in man-made environment on the other hand.

In Switzerland, about EUR 1 billion has been invested in technical avalanche mitigation measures since 1950 (SLF, 2000). This figure does not include money spent on protection forests. It represents an average investment of EUR 20 million per year. However, the extensive damage that occurred during the avalanche winter of 1998/1999 in Switzerland, when 1350 avalanches were released, amounted to over EUR 500 million, consisting of EUR 300 million for direct property damage and around EUR 200 million for indirect damages (Noethiger et al., 2002). The extent of this

---

Correspondence to: S. Fuchs
(fuchs@slf.ch)

damage corresponds to approximately 25 years of investment in mitigation measures, without taking into account expenses for regular support payments, maintenance and accruals.

In connection with the losses sustained, it is repeatedly postulated that the risk has increased gradually during the past decades, mainly because of modified demands on the part of the population with regard to infrastructure, mobility and communication (see e.g. Ammann, 2001; Barbolini et al., 2002). Until now, this qualitative statement has not been quantified for Alpine settlements. However, Wilhelm (1997a) is concluding in his investigation relating to the cost-effectiveness of avalanche protection measures in the Swiss Alps, that an increased risk cannot be inferred from the development of losses in recent years.

The aim of the present work is to present a conceptual attempt to determine the development of risk resulting from natural hazards in inhabited areas. The investigation area is the municipality of Davos, Switzerland, in which the development of the avalanche risk is described for the years between 1950 and 2000. The investigation aims to make a contribution towards a well founded statement concerning the development of risk arising from natural hazard processes. A method highlighting remaining temporal and spatial risk for assets and persons is presented. Within the framework of disaster prevention, this paper contributes to an improvement in the integrated risk management process.

2 Methods

2.1 Risk concept

The methodological concept used for this work is based on a procedure to quantify the development of risk for natural hazard processes over different time intervals, using publicly obtainable data. The procedure for avalanche risk is presented, and the investigated time interval is 1950 to 2000.

In the area of natural hazards, risks are defined as a function of probability of occurrence of defined events and the corresponding extent of damage. The basic formulation of this function is the product formula, which can be adjusted, according to the specific requirements, to take account of additional components like reduction factors (Wilhelm, 1997a) or vulnerability factors (e.g. Varnes, 1984; Morgan et al., 1992; Cutter, 1996), see Eq. (1).

$$R_{i,j} = p_{Si} \cdot A_{Oj} \cdot p_{Oj,Si} \cdot v_{Oj,Si} \tag{1}$$

$R_{i,j}$ is the risk, dependent on scenario i and object j; p_{Si} is the probability of scenario i; A_{Oj} is the value of object j; $p_{Oj,Si}$ is the probability of exposure of object j to scenario i and $v_{Oj,Si}$ is the vulnerability of object j, dependent on scenario i.

This is a very technical perspective. Particularly from the socio-scientific perspective, it has to be noted that risk has a wider meaning than the product of recurrence interval and extent of damage (Kates, 1971; Kates and Kasperson, 1983; Renn, 1995; Cutter, 1996; Slovic, 1999). Nevertheless, this basic formulation is well established in the area of engineering science (Varnes, 1984; Fell, 1994; Hollenstein, 1997; Borter, 1999).

The recurrence interval of an avalanche event depends on two parameters: changes in the natural avalanche activity on the one hand and changes due to the realisation of mitigation measures on the other hand. As investigations in the Swiss Alps have shown, the natural avalanche activity appears to be constant, at least for the period under consideration between 1950 and 2000 (Laternser and Schneebeli, 2002), although it has been pointed out that the variability of events makes an accurate statement difficult. This is why changes in the extent of accumulation areas are dependent only on the realisation of technical mitigation measures and on diversification in protection forests with regard to species and age. For the year 1950, the spatial extension of the process areas is represented using the one-dimensional avalanche model AVAL-1D (Christen et al., 2002a), while the lateral extension is retrieved by querying the event cadaster of former events. For the year 2000, the legally valid hazard maps are used.

2.2 Avalanche modelling

AVAL-1D is a one-dimensional avalanche dynamics program that predicts runout distances, flow velocities and impact pressure of both flowing and powder snow avalanches. Calibrated depth-average continuum models are used to track the motion of the avalanches from initiation to runout. AVAL-1D consists of two computational modules for dense flow avalanches and powder snow avalanches. These modules solve the governing equations of mass, energy and momentum balance using a finite difference scheme (Christen et al., 2002a).

The dense flow simulation model employs a "Voellmy-fluid" flow law. This law assumes that the shear strains in the flow body are small and that the flow resistance, given by a dry-Coulomb type friction (μ) and a velocity squared friction (ξ), is concentrated at the base of the avalanche. The magnitude of these two friction parameters is based on extensive model calibration (Bartelt et al., 1999) as well as observed field events.

The powder snow simulation follows Norem's description of powder flow avalanche formation and structure (Norem, 1995). The model consists of a suspension layer and a saltation layer, mass and momentum exchange between those two layers being determined by particle settling, turbulent diffusion against the concentration gradient, and aerodynamic shear forces (Christen et al., 2002a). The net erosion or deposition rate is a function of the kinetic energy of the impacting forces. More details about the model and its validation are described in Issler (1998) and Förster (2000).

The avalanche calculations as well as the selection of the friction parameters μ and ξ followed the guidelines given in the manual (Christen et al., 2002b). The fracture depths were obtained applying extreme value statistics by Gumbel on the possible maximum new snow height within three days. The input parameters were calibrated on the basis of the current

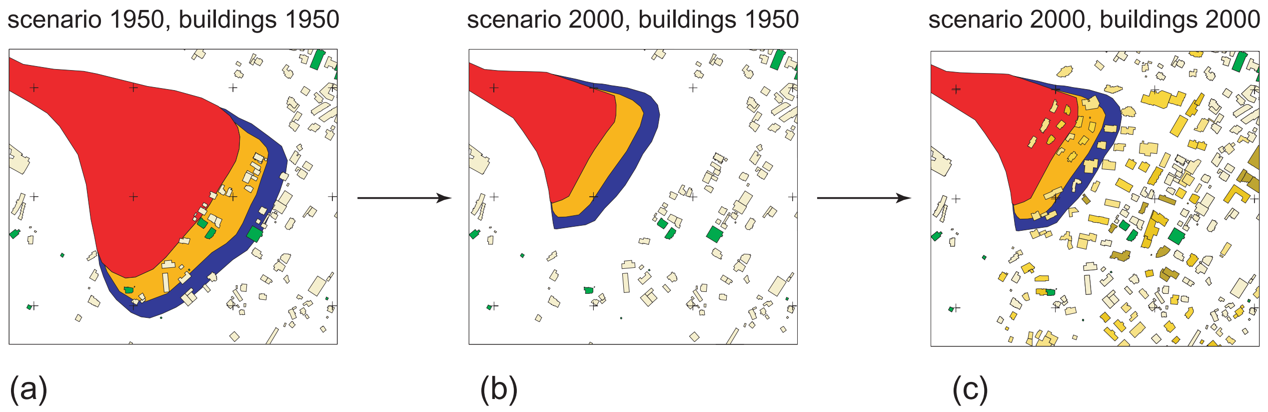

Fig. 1. Illustration of the procedure when investigating the temporal development of the risk. The analysis is based on a 30-year (red), a 100-year (brown) and a 300-year (blue) avalanche event. The extent of the accumulation areas in the year 1950 with the appropriate number of buildings is presented in Fig. 1a. Figure 1b shows the locations of buildings existing in 1950 in the context of the accumulation areas of the year 2000, resulting from the realisation of mitigation measures. In Fig. 1c, the current building location map is presented for the year 2000 with the corresponding avalanche scenario.

hazard maps. The following assumptions were made for the determination of the run-out zones:

- The release areas of the avalanches under investigation were included as a whole in the calculation, partial triggering was not assumed.
- Since in the model AVAL-1D the parameter ξ is regarded as being dependent on the friction coefficient μ, the stock of wood in the transit zone was considered using the smallest possible value for the friction parameter ξ. A value of 400 [m/s^2] was shown to reproduce the real conditions very accurately (SLF, 1999).
- Buildings within the accumulation area were not considered as defenses to retard avalanches, because their effect is not precisely quantifiable. Thus, there were examples where an avalanche destroyed a building situated perpendicular to the avalanche axis (e.g. in the hamlet of Valzur, Paznaun valley, Austria, in February 1999), but there were cases where such a building was able to stop such an avalanche completely (e.g. in the village of Airolo, Tessin, Switzerland, February 1951). An important factor according for such differences in vulnerability is the structure of these buildings. Simple wooden chalets or brick buildings have only little resistance to avalanche impacts, while reinforced concrete buildings can resist medium to strong pressure intensities and retard the avalanche flux. However, investigations based on the structure of buildings require a totally different approach and a much larger measuring scale than the one used in this investigation.
- In this investigation, it was assumed that all mitigation measures are 100% efficient, even though, during the avalanche winter of 1998/1999 for example, some avalanches appeared to have started within existing defence structures (SLF, 2000).

2.3 Calculation of damage potential

The extent of damage is a direct consequence of the damage potential in the accumulation area of the particular scenarios (see Fig. 1). The damage potential results from the number of potentially affected buildings and their insured reinstatement values, as provided by the mandatory building insurance (GVA building insurance company of Grisons). Since these values have been adjusted to take account of inflation, the insured sum for the year 1950 can be compared directly to the sum for the year 2000.

The number of endangered persons can be calculated on the basis of the number of domiciles. Statistics indicated 3.6 persons per unit in the year 1950 and 2.4 per unit in the year 2000 (Ritzmann-Blickenstorfer, 1996; BfS, 2001). The number of persons in hotels, guest houses and clinics was quantified using the existing number of beds, multiplied by the degree of utilisation. To account for the employees working in hotels and clinics facilities the number of beds was increased by 20% (Davos Tourist Board, 2002, pers. comm.) and 70% (BfS, 2002), respectively. The availability of such data eliminates the need for costly and time consuming field work and means that the procedure can be adapted to other areas of investigation.

In this paper, the vulnerability of buildings and persons is considered in terms of probable maximum loss (PML). From an actuarial point of view, this is the largest potentially possibly assumable loss. This means that the total accumulation area revealed was considered when calculating the values at risk and that buildings located therein influence the risk calculation with their entire reinstatement value and their entire number of attendant persons. Thus, the risk – in absolute values – was overestimated compared to the effective existent risk. Since the current work represents a relative comparison of different system states, the methodology used is considered to be acceptable. Furthermore, the

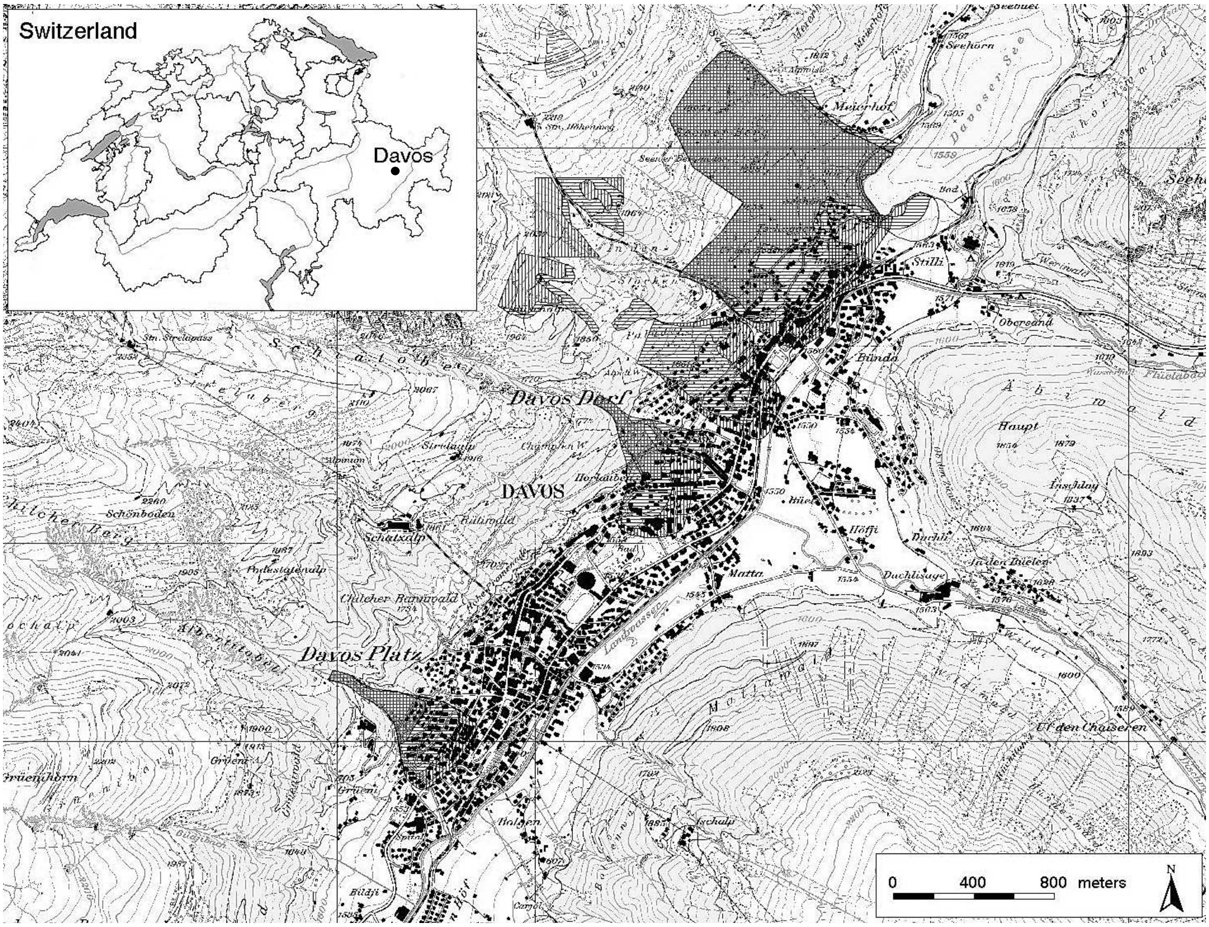

Fig. 2. The municipality of Davos, covering totally 254 km^2, is located in the eastern part of Switzerland. The investigation area included those areas of the city centre that are affected by avalanches, indicated in grey raster graphics. The cross hatch represents the 30-year scenario, the lined hatch the 300-year scenario and the continuous line the outer line of powder snow avalanches. Reproduced with permission of SWISSTOPO (BA035092).

large uncertainties in the vulnerability term, which are not yet completely known, could be ignored (e.g. Cutter, 1996; Wilhelm, 1997b; Jónasson et al., 1999; Keylock et al., 1999; Keylock and Barbolini, 2001).

2.4 Calculation and comparison of risk

The principal approach is the following: the cumulative risk for the settlement area resulting from accumulation areas and damage potential in the year 1950 was compared to the situation in the year 2000. Initially, the damage potential for the year 1950 was quantified (Fig. 1a). In a second step, the damage potential relating to the year 1950 was recalculated on the basis of the reduced accumulation areas applicable in 2000 (Fig. 1b). This represents the theoretical development of damage potential between the years 1950 and 2000 as it would have been without new buildings, but with the mitigation measures realised in that period. In a third step, the process areas of the year 2000 were intersected with the effective damage potential in the year 2000 (Fig. 1c). This is the development of risk, resulting from the reduction in the accumulation areas on the one hand and the aggregation and expansion of buildings on the other hand. This procedure is theoretically applicable to any arbitrary time interval and provides, as a result, the development of risk over time.

In order to make a fundamental statement concerning the development of risk, scenarios for an avalanche event with a 30-year, a 100-year and a 300-year recurrence interval were calculated. The specifications of the avalanche scenario concerned were intersected with the affected inhabited area using a GIS. Subsequently, the development of risk over time could be quantified, and specific risk peaks could be depicted. The results constitute a source of information to aid decision making, measurement planning and developing methods of risk communication.

2.5 Investigation area

The investigation area is located in the municipality of Davos, Grisons, Switzerland (see Fig. 2). Davos is a typical Alpine holiday region with about 13 000 permanent inhabitants during summertime and up to 60 000 people in winter time. The residential area of Davos is located between 1500 and 1900 m asl, which illustrates the susceptibility of this area to avalanche damage. Between 1950 and 2000, 66 avalanche events are documented within the municipal area, causing damage to a total of 171 buildings. Thirty of these events occurred in the winter of 1951, damaging 64 buildings, and 24 occurred in the winter of 1968 and damaged 85 buildings. Altogether, 21 persons went missing during these events. For the analysis of risk, only areas of the city centre of Davos that are susceptible to avalanche events were investigated, which amounts to only about 10% of the whole building inventory within the municipality. The avalanche paths under investigation also pose a threat to the main road in town and the railway line towards the Albula valley, which is of particular importance for the tourism industry. In total, the centre of Davos is affected by four avalanche paths.

3 Results

The development of value and number of buildings affected in the avalanche scenarios with 30-, 100- and 300-year recurrence intervals is presented in the following sections for the years 1950 and 2000. Additionally, the analysis of the number of persons affected by these scenarios is shown. The results are presented in their entirety on the one hand, and in part on the other hand, with divisions into certain building categories to highlight certain risk peaks.

3.1 Variations in the damage potential of buildings

A summary of changes in the damage potential (value and number) of buildings is shown in Table 1 and, in graphic form, in Figs. 3a and 3b.

Inside the areas affected by an event with a recurrence interval of 30 years, there were 83 buildings, with a total replacement value of approximately EUR 107.6 million in the year 1950. After the construction of mitigation measures, the areas affected by the process were reduced; and the scenario threatened only six buildings, with a total replacement value of EUR 3.7 million. When buildings constructed or extended by the year 2000 were added, a total of 33 buildings, with a total replacement value of EUR 19.3 million, were located within this area. This is nearly 40% of the buildings originally present in the status before defense structures were constructed. The insured value amounted to 18% of the endangered value in the year 1950. This development indicates that although an increase in the threat to the number of buildings from originally 7.2% to 39.6% was recorded, relatively expensive buildings have been protected, because the insured value increased from 3.4% of the initial value to only 17.8%. This is in direct relation to the legally binding land-use plan, allowing only low floor space indices higher up the slope.

A similar trend can be observed in the areas affected by a 100-year avalanche event. In 1950, in the status without defense structures, 127 buildings, with a total replacement value of EUR 173.5 million, were inside the endangered areas. When the implementation of mitigation measures in the starting zones was taken into account, nearly 90% of the originally existent buildings were protected, leaving just 15 buildings exposed, with a total replacement value of EUR 12.5 million. The addition of buildings constructed or extended by the year 2000 resulted in a total of 91 buildings, with a total replacement value of EUR 75.2 million, being located in the endangered area. This corresponds to 71.7% in number and 43.3% in assets of the initial value in the year 1950. Once again, the relatively expensive buildings are oriented towards the valley-side of the accumulation areas.

In the year 1950, a total of 161 buildings, with an insured value of EUR 239.4 million, were located inside the area affected by an 300-year avalanche. With the implementation of mitigation measures, this number was reduced to 28 buildings, with a total replacement value of EUR 20.2 million. In the year 2000, owing to the increase in the construction of new buildings, a total of 125 buildings, with an aggregated value of EUR 121.7 million, were located inside the endangered area, corresponding to 77.6% and 50.9% of the initial value in the year 1950, respectively.

Accordingly, the risk has undergone a change, as shown in Table 1, because the factor for the vulnerability was set to the value of 1, and thus the PML was calculated. The risk reduction for the 30-year recurrence interval amounted to 60.4% concerning the number of endangered buildings and 82.1% concerning their insured value. The risk reduction for a 100-year recurrence interval amounted to barely 30% concerning the number of endangered buildings and 56.7% concerning the corresponding value. The risk for a 300-year recurrence interval was reduced by about 22.4% with regard to the number of buildings and 49.1% with regard to the respective value.

The rarer an event is, the higher the risk in the year 2000 is compared to the initial state in the year 1950. This indicates that there has been an aggregation of the building development, which is thinning out towards the avalanche path.

In the following section, the results are presented for different categories of buildings. The buildings in Davos were separated into six categories, in an effort to represent the existent damage potential in the best possible way. These categories are: residential buildings, commercial buildings, hotels and guest houses, agricultural buildings, special-risk-buildings (churches, hospitals and public administration buildings) and other buildings. The analysis for the years 1950 and 2000 according to the number of buildings is presented in Table 1 and Fig. 3a. For comparison, on the right x-axis of Fig. 3a the total sum of all buildings within each scenario is presented.

As mainly commercial buildings and accommodation facilities were protected by mitigation measures, there was no noticeable increase in the risk. In the zone relating to the 30-year scenario, there was no remaining risk in the year 2000. The 100-year scenario affected only one building

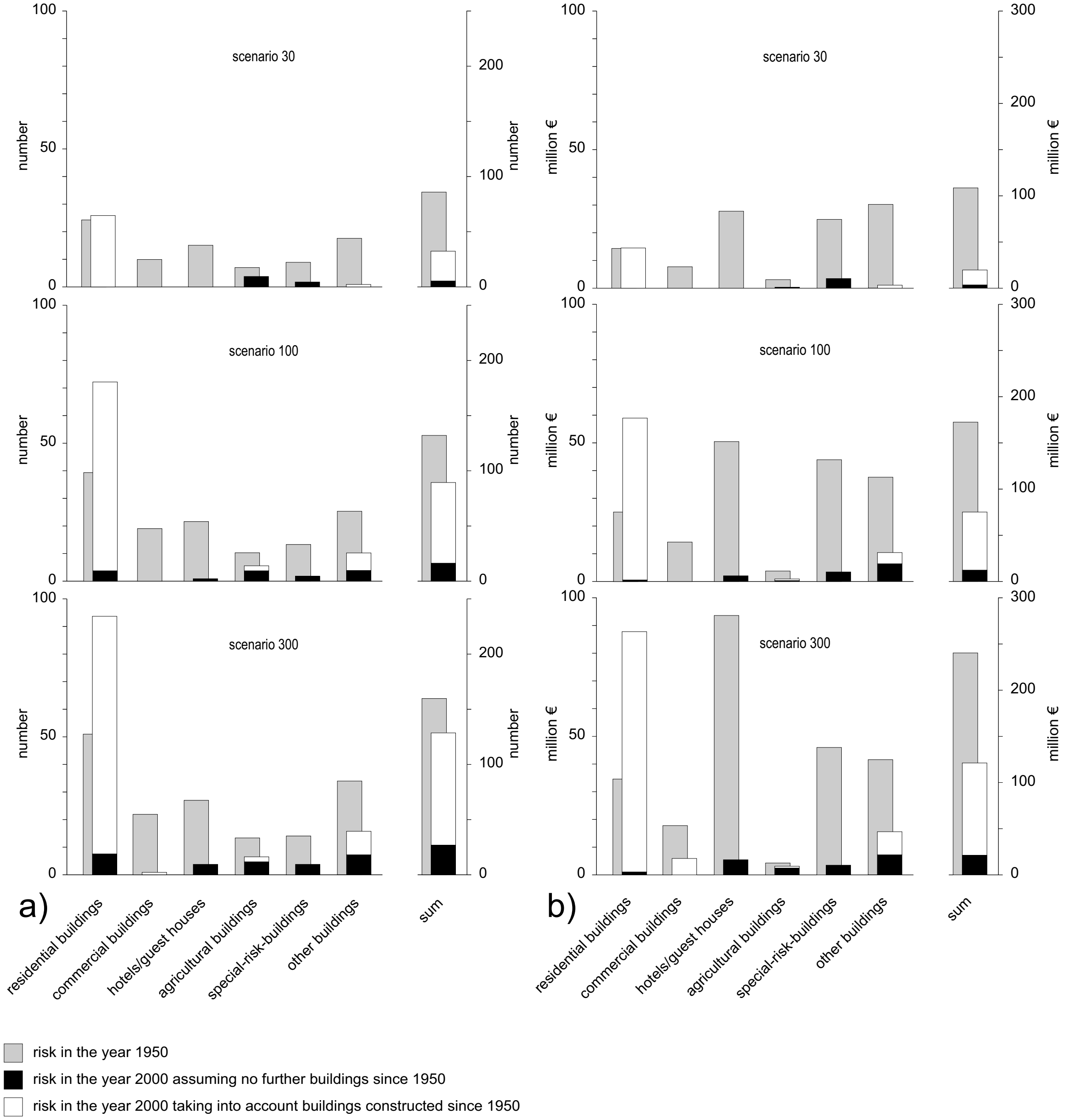

Fig. 3. **(a)** Number of buildings involved in each scenario, subdivided into residential buildings, commercial buildings, accommodation facilities (hotels and guest houses), agricultural buildings and extraneous risks (special-risk-buildings). The left (primary) ordinate illustrates the number of buildings in each category, and the right (secondary) ordinate illustrates the sum of all buildings affected by the scenario. **(b)** Insured value of the buildings affected in each scenario, subdivided into residential buildings, commercial buildings, accommodation facilities (hotels and guest houses), agricultural buildings and extraneous risks (special-risk-buildings). The left (primary) ordinate illustrates the value of buildings for each category, and the right (secondary) ordinate illustrates the sum of all values affected by the scenario.

Table 1. Number (N) and insured value (in kEUR) of the buildings affected by the scenarios (30-, 100- and 300-year avalanche), annual change in the risk and change in the total risk versus the initial risk. The results for a starting scenario in the year 1950 (starting 1950) and for a scenario in the year 2000 (mitigation 2000) taking into account mitigation measures are illustrated. Additionally, the existent buildings of the mitigation scenario (mitigation 2000) are subdivided into buildings built before 1950 (mitigation $\leq$1950) and buildings built after 1950 (mitigation $\geq$1951).

recurrence interval	scenario	residential buildings		commercial buildings		hotels/guest houses		agricultural buildings		special-risk-buildings		other buildings		sum					
		N	k€	N	k€	N	k€	N	k€	N	k€	N	k€	N	risk/year (N)	% of starting scenario	k€	risk/year (€)	% of starting scenario
30	starting (1950)	24	14 313	10	7 806	15	27 808	7	2 926	9	24 727	18	30 058	83	2.8	100.0	107 638	3 587 933	100.0
	mitigation (≤ 1950)	-	-	-	-	-	-	4	260	2	3 450	-	-	6	0.2	7.2	3 710	123 667	3.4
	mitigation (≥ 1951)	26	14 471	-	-	-	-	-	-	-	-	1	1 127	27	-	-	15 598	-	-
	mitigation (2000)	26	14 471	-	-	-	-	4	260	2	3 450	1	1 127	33	1.1	39.6	19 308	643 600	17.8
100	starting (1950)	39	25 198	19	13 366	21	50 542	10	3 956	13	43 493	25	37 013	127	1.27	100.0	173 568	1 735 680	100.0
	mitigation (≤ 1950)	4	523	-	-	1	1 994	4	260	2	3 450	4	6 285	15	0.15	11.8	12 512	125 120	7.2
	mitigation (≥ 1951)	67	58 332	-	-	-	-	2	611	-	-	7	3 784	76	-	-	62 727	-	-
	mitigation (2000)	71	58 855	-	-	1	1 994	6	871	2	3 450	11	10 069	91	0.91	71.7	75 239	752 390	43.3
300	starting (1950)	51	34 980	22	17 594	27	93 768	13	4 589	14	46 833	34	41 668	161	0.537	100.0	239 432	798 107	100.0
	mitigation (≤ 1950)	8	1 138	-	-	4	5 633	5	2 676	4	3 450	7	7 299	28	0.093	17.4	20 196	67 320	8.4
	mitigation (≥ 1951)	85	86 718	1	5 902	-	-	2	611	-	-	9	8 329	97	-	-	101 560	-	-
	mitigation (2000)	93	87 856	1	5 902	4	5 633	7	3 287	4	3 450	16	15 628	125	0.417	77.6	121 756	405 853	50.9

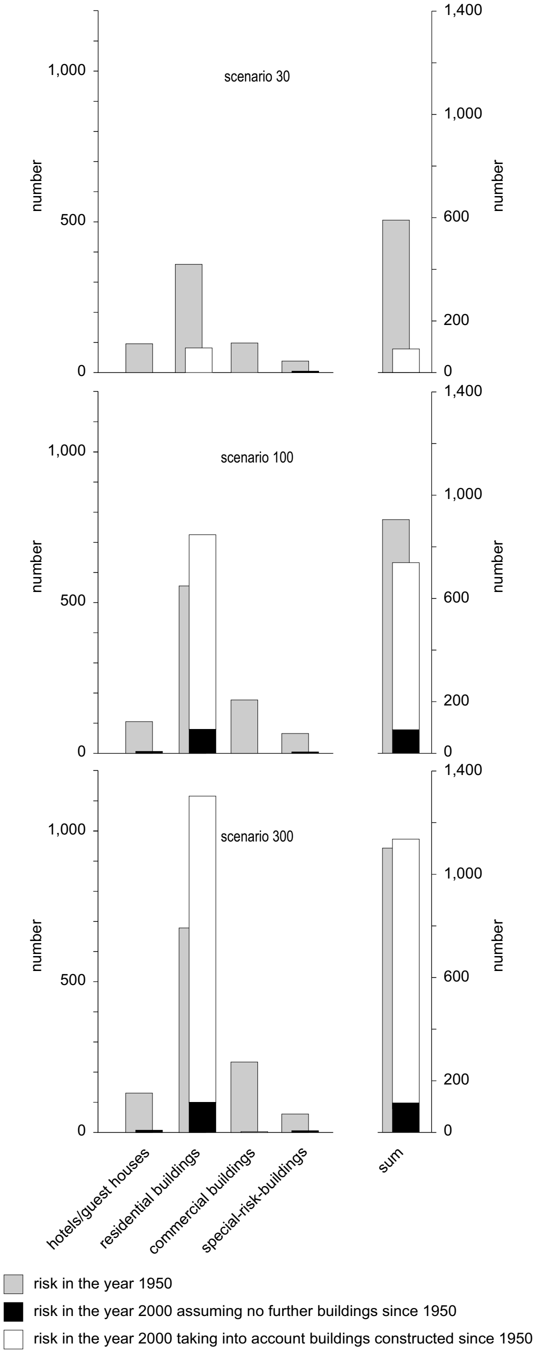

Fig. 4. Number of persons affected per scenario. On the left (primary) ordinate, the number of persons is subdivided into different building categories (accommodation facilities (hotels and guest houses without number of beds and employees), residential buildings, commercial buildings and extraneous risks (special-risk-buildings)). On the right (secondary) ordinate, the total sum of all affected persons is illustrated.

in the year 2000. The 300-year scenario affected fourbuildings in the category of the hotels and guest houses, all of which had been erected before 1950, and one commercial building that was erected after 1950. The risk for agricultural buildings amounted to 40% of the initial risk in the year 1950, which can be ascribed to new buildings on the one hand and to the relatively exposed position of individual haystacks and alp buildings on the other hand. Within the category of special risks, there were two buildings in each of the 30-year and the 100-year scenarios, and a total of four buildings in the area affected by the 300-year scenario.

There is a problematical development relating to the category of residential buildings. In the scenario of an avalanche with a 30-year recurrence interval, the initial risk in the year 1950 is just exceeded. In the year 2000, two additional buildings were situated in the endangered areas compared with the year 1950 with its expanded process areas. Regarding the 100- and 300-year scenarios, the initial risk in the year 1950 had increased in both cases by 82%.

The analysis of the corresponding insured values for each scenario is presented in Table 1 and Fig. 3b. For comparison, on the secondary x-axis of Fig. 3b the total values of all buildings within every scenario is shown. The development of the financial risk runs more or less in analogy to that of the number of buildings. It is remarkable that in the year 2000 the risk for residential buildings within the 30-year scenario was slightly exceeded, while within the 100- and 300-year scenarios it more than doubled (2.3 times and 2.5 times). Since in the case of insurance claims, from an economic point of view, the financial loss to be compensated for by the insurance is much more important than the real number of damaged buildings, the development of the risk is remarkable. In contrast, the value exposure of accommodation facilities and buildings in the special risks category decreased significantly during the same period. The erection of one relatively expensive commercial building in the area affected by a 300-year avalanche event was noticeable, corresponding to approximately one third of the total initial risk (33.5%).

3.2 Permanent residential population in buildings

The number of the resident population affected by the different avalanche scenarios is presented in Table 2 and Fig. 4. The buildings were split into the categories described above, whereas agricultural buildings and other buildings are missing due to the fact that they do not contain any living space.

In the year 1950, 591 people resided inside the area affected by a 30-year avalanche. In the year 2000, after the implementation of mitigation measures and the consequent reduction in the accumulation areas, 87 residents remained. The risk reduction for the 30-year scenario amounted to 85.3%, which was the highest risk reduction, when compared to the other scenarios. In the hotel and guest houses category and the commercial buildings category, the risk reduction amounted to 100%. In the residential buildings category, it amounted to only 77%, and in that of the special risks to 90%.

Inside the area affected by a 100-year avalanche event, 903 persons were resident in the year 1950. In the year 2000, there were only 738, which is a decrease of 18.3%. If there had not been an aggregation and extension of the building

Table 2. Absolute number and relative change in the resident population of the buildings affected by the scenarios (30-, 100- and 300-year avalanche), subdivided into the different building categories: accommodation facilities (hotels and guest houses, without number of beds and employees), residential buildings, commercial buildings and extraneous risks (special risks). In addition to the scenarios 1950 (starting 1950) and 2000 (mitigation 2000), the number of persons resident in those buildings in the scenario 2000 that were built before 1950 (mitigation 1950) is illustrated.

scenario	category of building	starting (1950)	mitigation (1950)	mitigation (2000)	risk reduction 1950 → 2000 [%]
30	hotels/guest houses	94	0	0	−100.0
	residential buildings	356	0	82	−77.0
	commercial buildings	98	0	0	−100.0
	special risks	43	5	5	−88.4
	$\sum$	591	0	87	−85.3
100	hotels/guest houses	108	10	10	−90.7
	residential buildings	554	77	723	+30.5
	commercial buildings	176	0	0	−100.0
	special risks	65	5	5	−92.3
	$\sum$	903	92	738	−18.3
300	hotels/guest houses	133	12	12	−91.0
	residential buildings	673	96	1116	+65.8
	commercial buildings	227	0	2	−99.1
	special risks	65	7	7	−89.2
	$\sum$	1098	115	1137	+3.6

development between the years 1950 and 2000, the number of persons would have been reduced to 92, which would cause a theoretical risk reduction of 89.9%. This clearly demonstrates the increase in damage potential due to the development of the settlement topology. Within the hotel and guest houses category and the special risks category, the risk was reduced by more than 90%. In the residential buildings category, an increase in risk of 30.5% was detectable. This development corresponds to that of the number of buildings, though the latter increased even more. This is a clear evidence that nowadays there are fewer residents per building than in the year 1950.

Inside the area of a 300-year avalanche event, 1098 persons resided in the year 1950. In the year 2000, there were 1137 persons, which was an increase in risk of 3.6%. In the commercial buildings category, the decline in risk was almost 100%. Within the hotel and guest houses category, there is, once again, a risk reduction of about 90%, as is the case in the special risks category, while in the category relating to residential buildings, there is an increase in risk of about 65.8%. This development correlates, once again, with that of the number of buildings.

It is apparent that with the extension of the scenarios from 30 years to 300 years and the consequent extension of the potential accumulation areas, the total risk reduction is decreasing. From this, it can be deduced that the building structure becomes sparse in direction towards the transit areas. Furthermore, the typical local mixed structure of development is increasingly superseded by smaller accommodation units. In contrast, the (statistically) relatively rare event of a 300-year avalanche shows a very high damage potential nowadays, despite the realisation of mitigation measures and the consequent reduction in the accumulation areas. According to the method applied in this study the damage potential of residential areas seems to be also very high.

Regarding the absolute number of persons in residential buildings for the year 2000, the risk associated with one 300-year event was 14 times higher than the risk related to one 30-year event. This means that the risk associated with the 300-year event is almost 1.4 times higher than the risk related to one 30-year event, which fits ten times into a 300-year event. For the 100-year event, this relationship is more unfavourable: here, the risk is 2.7 times higher than that of a 30-year event, based on an observation period of 100 years. From this, it can be concluded that the risk associated with the 100-year event is the most unfavourable, followed by that of the 300-year event. For the 30-year event, a relatively low risk can be detected, although 2.7 persons are still endangered on average per year. Considering fatality rates of 46% inside buildings (Wilhelm, 1997a), this means 1.2 demises per year; for the 300-year scenario, this value amounts to 1.7 persons. The scenario for the 100-year recurrence interval leads to 3.4 demises per year. Considering those values, it is obvious that temporary preventive measures, such as evacuations, play a key role in the reduction of the risk. At this point it has to be emphasised that,

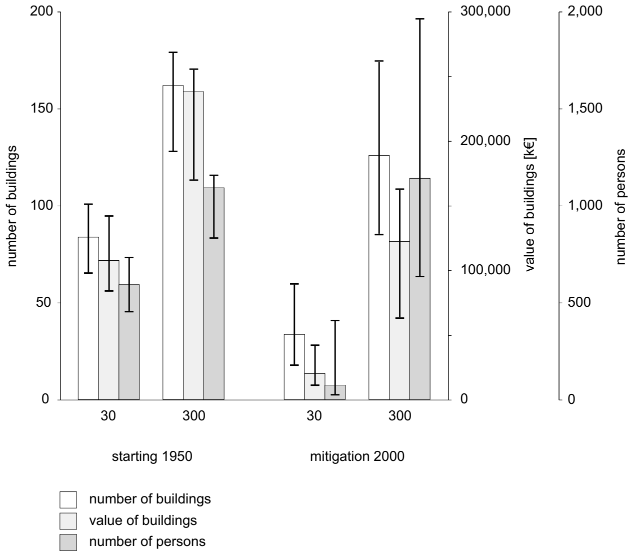

Fig. 5. Illustration of the range of the 30- and 300-year scenarios of all buildings according to the error bars on the basis of a 95% confidence interval for the avalanche runout length taking into account a variation of ±20 m (30 years) and ±30 m (300 years). A decrease in potential damage is detectable comparing the scenarios starting 1950 and mitigation 2000. The error increased remarkably in the rare event of the scenario mitigation 2000, which can be ascribed to the development of buildings within the avalanche prone areas until the year 2000.

because of the methodology used in the study, these values tend to be on the high side. This is due to the exclusion of reduction factors from the risk formula. Generally, the fatality rate of 46% for people buried in buildings also seems to be relatively high. However, this value is generated from the database of destructive avalanches at the SLF Davos, when searching for the average risk to a person of being killed during an avalanche event that buries and damages a building. However, as already mentioned in Sect. 2.5, 21 persons were killed during the investigation period, which corresponds to an average fatality rate of 0.42 per annum.

3.3 Error bars

The modelling of avalanche scenarios is affected by uncertainties, which can be divided into two groups: those resulting from model parameters and those resulting from the input parameters used.

Regarding the input parameters of the models, the uncertainties are linked, in particular, to the adequate choice of the values for the friction parameters μ and ξ, although a specific combination of these parameters is found to be more suitable than others (see Christen et al., 2002b). Models are always subjective formations of the cognition of an objective reality (Ninck, 1994). Thus, a model is an attempt to describe a system, and is consequently only one possible reproduction of this system. Since the relationships within a system are very complex, they cannot be described completely. Therefore, only those characteristics of a system that are thought to be relevant to the problem are extracted. This leads to an accentuation of certain characteristics and a rejection of others (Körner, 1980).

Fracture depth and release area are the important input parameters in avalanche modelling. In fact, both variables are measurable, but the determination of the possible extent of the release area, and the average fracture depth as a function of the recurrence probability of a certain snow height are still afflicted with uncertainties (Barbolini et al., 2002). To obtain information concerning the snow height, the application of the extreme value statistics by Gumbel to the possible maximum new snow height within three days is normally recommended to extrapolate rare snowfall events (Burkard and Salm, 1992). However, as the measurements of the observation stations for snow data date back only 70 years as the most, the extrapolation of rare events can be faulty. Further sources of error are the inadequate consideration of possible snowdrift when defining the fracture depth, and the correction factor for the altitude, which is required in order to estimate the local precipitation height (Barbolini et al., 2002).

In the present treatise, the range resulting from those uncertainties within the avalanche accumulation areas is used following the suggestions in Barbolini et al. (2002) on the basis of a 95% confidence interval. The 30-year event is calculated, as an example, on the basis of a variation in the accumulation length of ±20 m, and the 300-year event is calculated on the basis of ±30 m. Thus, substantial ranges occur in both the existent insured values inside the hazard area and the number of persons present therein (see Fig. 5 for a summary of all scenarios and Fig. 6 for the residential buildings).

It is remarkable that the mean variation within the area of the starting scenario (1950) is less than that in the area of the mitigation scenario (2000). Within the starting scenario, the numbers for buildings, values and number of persons scatter at about plus/minus one third of the effective calculated numbers. In the area of the mitigation scenario, which represents the present state in the municipality of Davos, the variations are much higher. Here, the sensitivity of the red hazard zone becomes apparent: when expanding this zone by 20 m, the number of the endangered buildings increases by a factor of 1.8, and the insurance value increases by a factor of 2.1. The risk for persons is 4.6 times higher. In contrast, when reducing the area by 20 m in the direction of the release zone, the result for the number of endangered buildings is halved, the insurance value amounts to 60% of the starting risk, and the number of persons to 40%. Concerning the 300-year scenario, the relative values scatter much less. However, regarding absolute numbers, high fluctuations occur within the scenario "mitigation 2000", which can be attributed to the high concentration of assets in Davos in these days. This means that the results are highly sensitive to small changes within the accumulation areas, a fact which must be considered when interpreting the results.

In contrast to this, the consideration of reduction factors in the risk formula (see Eq. 1) seems to have a rather small influence on the range of the results. Since the 1980s it is standard practice to prescribe mandatory reinforcement structures for building projects within endangered areas. In Davos, these regulations are applicable to those 15% of all buildings which were erected after 1980 within the areas of a 300-year avalanche event (blue hazard zone).

Assuming that such reinforced buildings are able to resist to the design event, the risk would, at the most, decline by about 15%. On the scale used in this investigation, a change of this size is to be considered negligible, when taking into account the scattering of the results due to the flexible definition of the extent of the hazard zones by ±30 m.

3.4 Temporary population in accommodation facilities and spa tourism

The number of persons at risk in hotels, guest houses and spa clinics decreased remarkably between the years 1950 and 2000. This is mainly due to the reduction in the avalanche runout zones. Since 1950, the number of sanatoriums has decreased and the number of accommodation facilities has increased, since nearly all former sanatoriums have been transformed into hotels or guest houses.

The 1950 scenario includes 1041 guest beds in hotels and 1851 beds in sanatoriums. The average utilisation rate of the hotel and restaurant industry can no longer be determined for the winter season in 1950, so it was calculated using today's value of 60% (Davos Tourist Board, 2002, pers. comm.). The average utilisation of the clinic facilities was 83.7% in the year 1950 (Kurverein Davos, 1951). Thus, in the year 1950, 625 guests in hotels and 1550 guests in sanatoriums were within endangered areas. Including employees, 750 persons were endangered in accommodation areas and 2590 persons in spa resorts.

In the year 2000, only 81 guest beds in the hotel and guest houses category were situated in endangered areas. Assuming an utilisation of 60% during the winter season, and taking account of employees, this amounted to 59 persons. Sanatoriums were no longer endangered. Subdividing the utilisation within the winter season into months, it became evident that the peaks in utilisation were during the Christmas period and towards the end of February. According to the analysis of the avalanche bulletin of the SLF, these periods coincided exactly with periods when there was an above-average occurrence of days with high avalanche danger. As a result, risk peaks arose, but they did not appear as serious when considering the consequences in the year 2000 as they had been in the year 1950.

4 Conclusions

In the previous sections, the development of avalanche risk in the settled area of the municipality of Davos, Grisons, Switzerland, was presented. The investigation focused on the risk to buildings and persons between the years 1950 and 2000. It has been demonstrated that contrary to the assumption that the vulnerability of the community has increased, the risk in fact decreased fundamentally, even if Davos is a center of winter sports and home to a remarkable number of sanatoriums. The sole exception regarding the development of risk was in the category of residential buildings, where an increase in risk was already detectable at medium recurrence intervals (100 years).

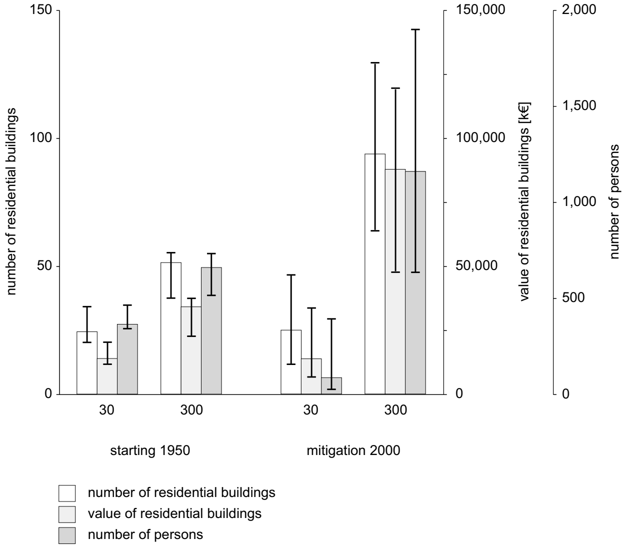

Fig. 6. Illustration of the range of the 30- and 300-year scenarios concerning residential buildings according to the error bars on the basis of a 95% confidence interval for the avalanche runout length taking into account a variation of ±20 m (30 years) and ±30 m (300 years). A decrease in potential damage is detectable regarding small recurrence intervals, while a remarkable increase is detectable regarding rare events. The error increased fundamentally in the scenario mitigation 2000, which can be ascribed to the development of buildings within the avalanche prone areas until the year 2000.

Presenting the risk spatially, it was evident that the major problem areas occur outside the so-called red hazard zone, which represents the outer line of an 30-year avalanche event. In this area, the erection of new buildings is forbidden by law. All buildings within the area of the 30-year scenario were erected before the building ban was implemented. The increased risk in the range of the 100-year scenario and the 300-year scenario can be ascribed to the fact that certain requirements, such as reinforced walls, are prescribed when building in those areas. However, there is no general prohibition of building development. Furthermore, almost 70% of the buildings in those areas were erected before the introduction of hazard maps and the appropriate implementation rules (65 residential buildings, with a total insured value of EUR 53 498 000).

When considering the development of risk to persons, the problem arises that, for seasonal reasons, the number of persons in the area reaches its peak just in wintertime nowadays. In contrast, in the year 1950, the main part of the risk was generated as a result of the numerous endangered sanatoriums. Though the absolute number of endangered persons declined by 95% in the period under consideration, certain risk peaks have to be assumed within this risk category. As a result, mitigation strategies such as the short-term evacuation of persons or the temporary closure of roads play a major role in reducing risk.

The principal development of risk within the scenarios showed that relatively frequent events tend to result in smaller risk than rare events with grave effects. This shows that the construction of avalanche defence structures to reduce the accumulation areas has contributed greatly to the reduction of risk from frequent events. Compared with the situation in the year 1950, the remaining risk in the year 2000 was comparatively small. Since the introduction of the hazard maps, and the building ban resulting from it, the damage potential within the range of a 30-year avalanche event need not increase in the future. Thus, the remaining risk in those areas can be interpreted as socially accepted residual risk. With regard to the resident population, the remaining risk amounts to 1.3 demises per year, expressed as PML, which is according to the predefined assumptions in this study a high value compared with other risks. The corresponding PML for damage to buildings was 1.1 in figures and EUR 650 000 in actuarial value.

The investigation provides specific information regarding the development of avalanche risk in the municipality of Davos, Grisons, Switzerland. General statements referring to a larger area (canton, country) might be difficult to make, since small-scale disparities have a very important influence on the diversification of risk. The spatial distribution of damage potential is heavily influenced by the historical growth of settlements on the one hand and modern methods of spatial planning on the other hand. The historical development of the settlement is determined by the availability of suitable areas for development and land ownership patterns. Nowadays it is mainly instruments of spatial planning that are used to structure this historically determined development, resulting in the fact that certain decisions made in recent decades, relating to the choice of settlement locations, cannot be corrected any more. In the whole Alpine area, there are only very few examples of hazard-induced resettlements, for example the hamlet Untervalzur in the Paznaun valley in Austria.

The results presented are restricted to the predefined assumptions. Due to existent uncertainties, the risk formula was reduced to the product of a defined recurrence interval and the corresponding extent of damage, whereas the latter was evaluated under consideration of PML. Consequently, the obtained risk represents an upper limit, which might be fallen below when taking into account the other factors presented in Eq. (1). Nevertheless, the determination of temporal changes of PML leads to a better understanding of the development of risk in settlements. Additionally, the calculation of error bars has shown how sensitive the determination of damage potential reacts on small changes in the length of the avalanche runout zones. This clarifies that the results of risk analyses should contain, apart from an accurate value, the size of the range.

Since the vulnerability of buildings towards avalanches could only roughly be estimated until now, there is a particular need for future research in this area. Furthermore, a level of the socially accepted risk has to be defined. Only then it can be ascertained whether or not there is a need for action due to the probable exceedance of the risk level.

Acknowledgements. The authors want to thank two anonymous reviewers for their suggestions improving the paper and P. Barnett from the University of Applied Sciences, Winterthur, for improvements to earlier versions of the English manuscript. M. Fischer of the GVA building insurance company of Grisons provided the necessary database. The research for this paper was partly carried out with the support of a grant from Munich Re reinsurance company, Germany.

Edited by: T. Glade
Reviewed by: H. Staftler and another referee

References

Adams, J.: Risk, Routledge, London, 1995.

Ammann, W.: Integrales Risikomanagement - der gemeinsame Weg in die Zukunft, Bündnerwald, 5, 14–17, 2001.

Barbolini, M., Natale, L., and Savi, F.: Effects of release conditions uncertainty on avalanche hazard mapping, Natural Hazards, 25, 225–244, 2002.

Bartelt, P., Salm, B., and Gruber, U.: Calculating Dense-Snow Avalanche Runout Using a Voellmy-Fluid Model with Active/Passive Longitudinal Straining, J. Glaciol., 45, 150, 242–254, 1999.

BfS (Swiss Federal Statistical Office) (ed.): Statistisches Jahrbuch der Schweiz 2001, Verlag Neue Züricher Zeitung, Zürich, 2001.

BfS (Swiss Federal Statistical Office): Krankenhausstatistik, http://www.statistik.admin.ch/stat_ch/ber14/gewe/dtfr14i.htm, 20.07.2003.

Borter, P.: Risikoanalyse bei gravitativen Naturgefahren, Umwelt-Materialien, 107/I, II, BUWAL, Bern, 1999.

Burkard, A. and Salm, B.: Die Bestimmung der mittleren Anrissmächtigkeit d_0 zur Berechnung von Fliesslawinen, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, Interner Bericht, 668, 1992.

Burton, I., Kates, R., and White, G.: The Environment as Hazard, The Guilford Press, New York, 1993.

Christen, M., Bartelt, P., and Gruber, U.: AVAL-1D: An Avalanche Dynamics Program for the Practice, Proc. INTERPRAEVENT 2002 in the Pacific Rim – Matsumoto, Oct. 14–18, 2002, 2, 715–725, 2002a.

Christen, M., Bartelt, P., and Gruber, U.: AVAL-1D, Numerische Berechnung von Fliess- und Staublawinen, Manual zur Software, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, 2002b.

Cutter, S.: Vulnerability to Environmental Hazards, Progr. Human Geogr., 20, 4, 529–539, 1996.

Fell, R.: Landslide Risk Assessment and Acceptable Risk, Can. Geotech. J., 31, 261–272, 1994.

Förster, M.: Ausführliche Dokumentation ausgewählter Staublawinenereignisse und Bestimmung ihrer Eingangsparameter für die Verifikation von Staublawinenmodellen, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, Interner Bericht, 730, 2000.

Hollenstein, K.: Analyse, Bewertung und Management von Naturrisiken, vdf-Hochschulverlag, Zürich, 1997.

Issler, D.: Modelling of Snow Entrainment and Deposition in Powder-Snow Avalanches, Ann. Glaciol., 26, 253–258, 1998.

Jónasson, K., Sigurdsson, S., and Arnalds, T.: Estimation of Avalanche Risk, Icelandic Meteorological Office, Reykjavik, 1999.

Kates, R.: Natural Hazard in Human Ecological Perspective: Hypotheses and Models, Econ. Geogr., 47, 438–451, 1971.

Kates, R. and Kasperson, J.: Comparative Risk Analysis of Technological Hazards (A Review), Proc. Natl. Acad. Sci. U.S.A., 80, 7027–7038, 1983.

Keylock, C. and Barbolini, M.: Snow Avalanche Impact Pressure – Vulnerability Relations for Use in Risk Assessment, Can. Geotech. J., 38, 2, 227–238, 2001.

Keylock, C., McClung, D., and Magnússon, M.: Avalanche Risk Mapping by Simulation, J. Glaciol., 45, 150, 303–314, 1999.

Körner, H.: Modelle zur Berechnung der Bergsturz- und Lawinenbewegung. Proc. INTERPRAEVENT – Bad Ischl, 8–12 September 1980, 2, 15–55, 1980.

Kurverein Davos: Geschäftsbericht 1950/51, Kurverein, Davos, 1951.

Laternser, M. and Schneebeli, M.: Temporal Trend and Spatial Distribution of Avalanche Activity During the Last 50 Years in Switzerland, Natural Hazards, 27, 201–230, 2002.

Morgan, G., Rawlings, G., and Sobkowicz, J.: Evaluating Total Risk to Communities from Large Debris Flows, Proc. 1st Canadian Symposium on Geotechnique and Natural Hazards, Geotechnique and Natural Hazards – Vancouver, BC, Canada, 6–9 May 1992, 225–236, 1992.

Munich Re : Topics – Annual Review: Natural Catastrophes 2001, Munich Re, Munich, 2002.

Ninck, A.: Wissensbasierter und objektorientierter Ansatz zur Simulation von Mensch-Umwelt-Systemen, Geographica Bernensia, G43, 1–154, 1994.

Noethiger, C., Elsasser, H., Bründl, M., and Ammann, W.: Indirekte Auswirkungen von Naturgefahren auf den Tourismus – Das Beispiel des Lawinenwinters 1999 in der Schweiz, Geogr. Helv., 2, 91–108, 2002.

Norem, H.: Shear Stresses and Boundary Layers in Snow Avalanches, Norwegian Geotechnical Institute, Oslo, Technical Report 581240–3, 1995.

Renn, O.: Individual and Social Perception of Risk, in: Ökologisches Handeln als sozialer Prozess, edited by Fuhrer, U., Birkhäuser, Basel, 27–50, 1995.

Ritzmann-Blickenstorfer, H.: Historische Statistik der Schweiz, Chronos, Zürich, 1996.

Schneebeli, M., Laternser, M., Föhn, P., and Ammann, W.: Wechselwirkungen zwischen Klima, Lawinen und technischen Massnahmen, vdf-Hochschulverlag, Zürich, 1998.

SLF: Neue Berechungsmethoden in der Lawinengefahrenkartierung, Kursunterlagen, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, 1999.

SLF: Der Lawinenwinter 1999, Eidgenössisches Institut für Schnee- und Lawinenforschung, Davos, 2000.

Slovic, P.: Trust, Emotion, Sex, Politics, and Science: Surveying the Risk-Assessment Battlefield, Risk Analysis, 19, 4, 689–701, 1999.

United Nations: Living with Risk, A Global Review of Disaster Reduction Initiatives, Preliminary Version (July 2002), United Nations, Geneva, 2002.

Varnes, D.: Landslide Hazard Zonation: a Review of Principles and Practice, UNESCO, Paris, 1984.

Wilhelm, C.: Wirtschaftlichkeit im Lawinenschutz, Mitt. Eidgenössisches Institut für Schnee- und Lawinenforschung, 54, Davos, 1997a.

Wilhelm, C.: Zur Entwicklung des Lawinenrisikos in der Schweiz, Proc. Risikobewertung und Naturraumprävention von Wildbächen und Lawineneinzugsgebieten – Universität für Bodenkultur Wien, 24–25 September 1997, 112–127, 1997b.