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Application of the marginal cost approach and cost-benefit analysis to measures for avalanche risk reduction – A case study from Davos, Switzerland

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ABSTRACT: Modern strategies for reduction of natural hazard risk combine technical, biological, organizational measures and land-use planning. The goal of planning strategies is to achieve maximum risk reduction at the lowest possible cost. In this study the application of the marginal cost approach and a cost-benefit analysis of different protection strategies against avalanche risk at the Schiahorn avalanche path in Davos, Switzerland, is presented. Both approaches suggest that the present risk reduction strategy meets the goals of economic efficiency and reduction of human fatalities. The study also shows that initial assumptions have a major influence on the results of cost-efficiency and cost-benefit analyses. Results of those studies should therefore be carefully interpreted in the context of those assumptions.

1 INTRODUCTION

Snow avalanches can pose a threat to people, buildings and infrastructures in densely populated mountainous areas like the Swiss Alps. Federal and cantonal forest laws in Switzerland require protection of human life and property by appropriate protection measures. Thus, reducing or managing avalanche risk in alpine valleys has been one of the key issues for local and regional authorities.

Since 1950, investments of over 1.5 billion CHF have been made to protect against avalanche danger using technical measures (Wilhelm et al., 2000). Starting with technical measures and protection forests in the 1950s, the introduction of land-use planning measures like hazard maps in the 1970s and organizational measures in the 1980s and 1990s continuously improved avalanche protection. The modern strategy for natural hazard protection requires a combination of technical, biological (e.g. protection forest), organizational measures, and land-use planning (Bründl et al., 2004). Due to decreasing public budgets, risk reduction strategies that maximize risk reduction and minimize investments are favoured. Therefore, the federal and cantonal authorities who subsidise risk reduction measures increasingly require cost-efficiency or cost-benefit analyses of proposed mitigation strategies (Haering et al., 2002). As a consequence, a guideline for costefficiency analysis of avalanche protection measures along traffic routes was developed in recent years in Switzerland (Wilhelm, 1999).

In this paper, a methodology for determining the net benefits of several avalanche risk reduction strategies for an alpine village is presented. The net benefits of risk reduction scenarios were calculated and compared for the Schiahorn avalanche path in Davos, Switzerland (Figure 1). It is shown that the results of the calculation of benefits are highly dependent on initial assumptions which often include considerable uncertainties. Potential applications for cost-benefit analysis in natural hazards management are identified. The potential of cost-benefit analyses as a tool to

Figure 1. Study site Schiahorn, Davos, Switzerland. Source: SLF.

improve management of natural hazards is discussed with regard to specific decision-making contexts and methodologies.

2 METHODOLOGY

2.1 *Risk reduction measures*

The risk of natural hazards depends on the probability of occurrence of a natural process combined with the probability of exposure to that natural process and the probability of damage resulting from that exposure (Varnes, 1984; Fuchs and Bründl, 2005). From a technical point of view, risk can be mathematically expressed using Equation 1.

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

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

Consequently, possible avalanche risk reduction measures include strategies that limit the likelihood of an avalanche release, as well as those that reduce exposure to and damage from avalanches.

For this study, scenarios with different extents of avalanche defence structures were considered, as well as scenarios with or without an evacuation of persons from the affected area, and scenarios considering or neglecting land use planning restrictions at the Schiahorn avalanche runout area in Davos, Switzerland. The observed release area at Schiahorn is located between 2060 and 2300 m a.s.l. and endangers a densely populated area of the community of Davos (Figure 1).

Avalanche defence structures reduce the probability of avalanches by retaining snow in potential avalanche release areas. The Schiahorn release area was divided into four sections and it was assumed that avalanche defence structures would be added in steps to progressively lower sections. The

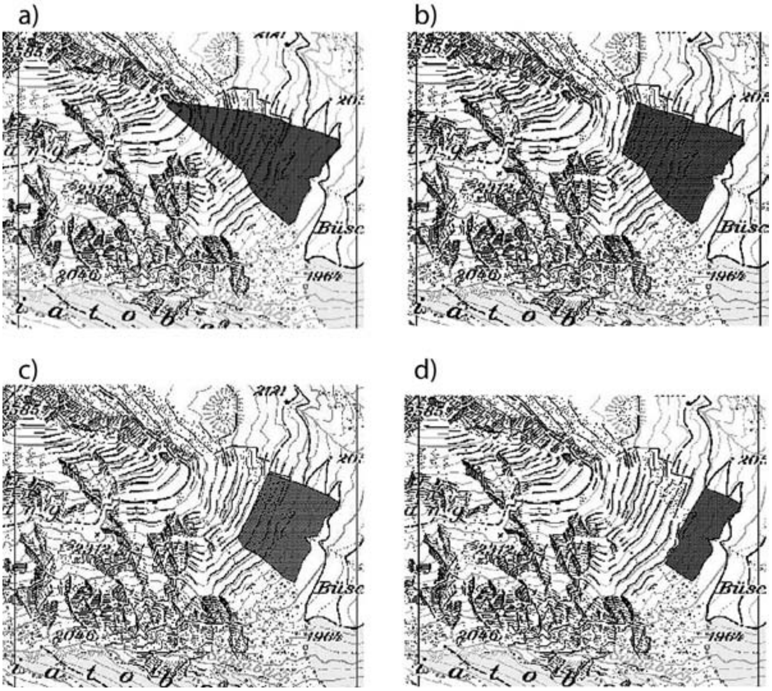

Figure 2. The avalanche release areas in the Schiahorn study area. In Figure 2a release area 1 with 0 hectares of avalanche defence structures is shown. In Figure 2b release area 2 with 1.6 hectares of avalanche defence structures is shown. In Figure 2c release area 3 with 2.9 hectares of avalanche defence structures is shown. In Figure 2d release area 4 with 5.0 hectares of avalanche defence structures is shown. The increases in the area of avalanche defence structures corresponded to equal decreases in the release area.

increases in avalanche defence structures corresponded to equal decreases in the extent of the release area (Figure 2).

The run-out areas and pressures of avalanches associated with each risk reduction scenario were modelled using a numerical 2-D avalanche run-out model (Gruber et al., 1998). The model assigned friction parameters to terrain in the release areas based on an automatic classification of the terrain as open, confined, gully, or flat (Gruber et al., 1998). The 30- and 300-year avalanche events were modelled based on estimates of the fracture depth which were based on statistical analysis of maximum snow accumulation for three-day periods using a historical record (Salm et al., 1990). As this record only exists for about 60 years, the estimate of snow accumulations for the 300-year event was extrapolated from the statistical record. Using a simulation resolution of 12.5 meters, the avalanche run-out model provides an absolute accuracy of about 50 meters for the run-out distances and associated pressures of the red[1] and blue zones[2] (Gruber et al., 1998). Run-out distances for a 300-year scenario are shown in Figure 3.

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[1] The red zone is defined as the area potentially endangered by avalanches with a pressure of more than 30 kPa and a recurrence period of up to 300 years or with a pressure of less than 30 kPa and a recurrence period of up to 30 years.

[2] The blue zone is defined as the area potentially endangered by avalanches with a pressure less than 30 kPa and a recurrence period of between 30 to 300 years.

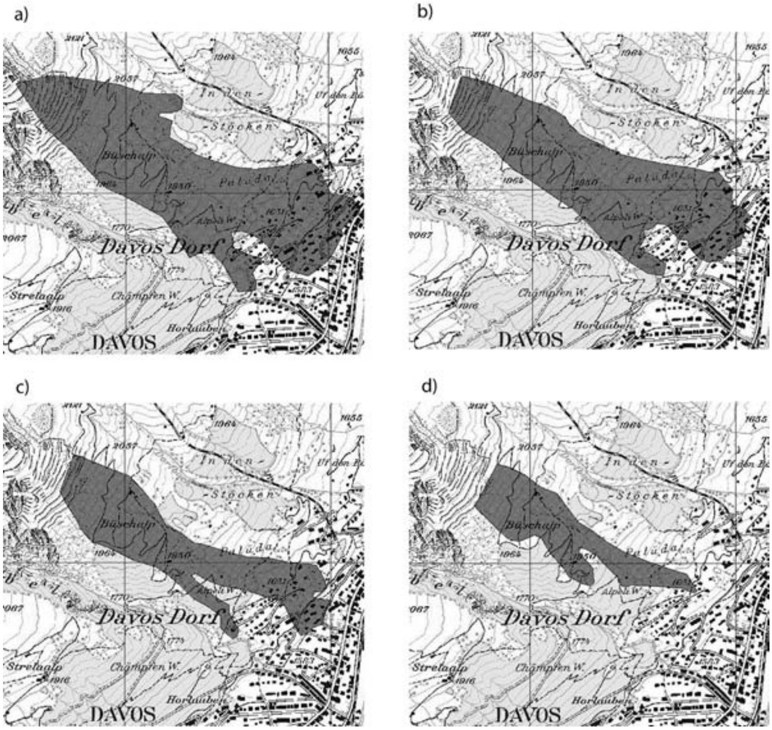

Figure 3. Avalanche run-out areas for the 300-year event resulting from the scenarios that included forest and either 0, 1.6, 2.9, or 5.0 hectares of avalanche defence structures. Figure 3a shows avalanche run-out for scenario with no avalanche defence structures, Figure 3b shows avalanche run-out with 1.6 hectares of avalanche defence structures, Figure 3c shows avalanche run-out with 2.9 hectares of avalanche defence structures, and Figure 3d shows avalanche run-out with 5.0 hectares of avalanche defence structures.

Forests can decrease avalanche risk when they are located in potential avalanche release areas (Bebi et al., 2001; Brang et al., 2001). At Schiahorn the release area is located above the tree line. Therefore forest can not prevent the release of large avalanches. The forest at Schiahorn only prevents the release of smaller avalanches and is not maintained as a protection forest. For the cost-benefit calculations in this study, the forest at Schiahorn is therefore not regarded as protection forest. However, forest located in the avalanche path will decrease avalanche speed which influences the run-out distance of an avalanche. For this reason, the forest in the transit area was modelled by setting the turbulent friction parameter ξ of the model to $400\,\mathrm{m/s^2}$.

Evacuation was assumed to decrease the expected human fatalities for each risk reduction scenario in a 30- or 300-year avalanche event. The efficiency of evacuations to reduce the risk of human fatalities depends on the specific circumstances during a period of increased avalanche danger. During an evacuation risk might temporarily increase because people being evacuated and those conducting the evacuation are in the endangered terrain and outside of buildings. Given the uncertainty associated with evacuation as a risk reduction strategy, evacuation efficiency was accounted to be either 30% or 90%.

Another way to reduce exposure to avalanches is to prohibit habitation in endangered areas. Current regulations in Switzerland allow year-round habitation in already existing buildings in the red zone, but prohibit new construction. In the blue zone buildings must be reinforced and it was assumed that these buildings would not be damaged. The Schiahorn area includes both red and blue zones. For the scenarios in which land use planning restrictions were not considered we assumed the level of building development and habitation in the year 2000. For the scenarios with land use planning restrictions, we assumed no building development or habitation in the red zone. When an avalanche occurs, buildings in the avalanche path reduce the run-out distance.[3]

2.2 *Calculation of annual damage*

The determination of the damage potential was conducted in three steps. First, the results of the 2-D avalanche run-out model and a Geographic Information System (GIS) were used to determine the expected areas, buildings, and dwellings inside the red and blue zones for each risk reduction scenario for 30- and 300-year avalanche events. This approach was used in similar studies (Fuchs et al., 2004). Data on the location of buildings and the number of dwellings in each building for the year 2000 were provided by the community of Davos and imported into the GIS. Blue and red zones associated with each of the scenarios were classified and joined with the demographic data to find the number and value of buildings as well as the number of dwellings in either the red or the blue zone for each of the scenarios. To account for the number of people, 2.4 persons per dwelling were assumed (BfS, 2001). For some of the scenarios, the red or blue zones included hotels. The number of persons in the hotels was calculated as the number of beds multiplied by an average occupancy rate of 70% for hotels in Davos during the winter season (Davos Tourist Board, 2002, pers. comm.).

Second, the damage potential of each scenario, defined as the value of all buildings and persons in the affected area, was monetarized. The values of the affected buildings were determined using the reconstruction values in the year 2000. The reconstruction values are an acceptable approximation for the social value of buildings because of missing or possibly distorted market values caused by state interventions in the real estate market. This approach assumed that the reconstruction values were independent of avalanche risk and of market demand (Fuchs and McAlpin, 2005).

Third, the monetary value of human fatalities associated with each scenario for a given avalanche event was determined using two different approaches. First, the human capital approach was used (Linnerooth, 1979). The average discounted present value of a person in Switzerland was calculated using the average remaining working years, derived from the average age and average retirement age, and the average annual salary (BfS, 2002). The present value of the remaining income of a person in average was summed up to 1,425,864 CHF.

The second approach to valuate human life can be derived from the costs which have been spent for saving one human life by protection measures. This concept implies that only limited financial resources are available for safety measures. Using empirical data of safety projects allows to calculate the amount of money which has been spent so far to protect one human life (implied costs of averting a fatality). This amount of money depends whether people are able to influence the risk or not. The ability to reduce the risk by own decisions can be defined in four categories: category 1 for 100% voluntary risk (e.g. rock climbing), category 2 for risks, which can be considerably influenced by a person (e.g. car driving), category 3 for risks which can be influenced only by less degree (e.g. travelling by train) and category 4, in which risk must be taken 100% non-voluntary (e.g. living in the vicinity of a nuclear power plant). The amount of money for reducing risk is increasing from category 1 to 4 by a factor of one thousand. This concept has been successfully used for risk valuation and the optimization of financial resources for risk mitigation of technical risks (Bohnenblust and Schneider, 1984; Bohnenblust, 1998). For this study it was assumed that living in a red or blue avalanche hazard zone corresponds to category 3 which means expenditures in the magnitude of 5 to 10 million CHF to protect one human life (Merz et al., 1995; Planat, 2004).

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[3] The avalanche run-out model accounted for the effect of buildings in the avalanche path on run-out distance and area by increasing the friction coefficient ξ for areas with building development.

Table 1. Reduction factors for calculating expected damage from avalanches to buildings in the run-out area. The values represent probabilities that a building is hit by an avalanche.

Return period	Red zone	Blue zone
Probability of location in the avalanche run-out area		
30 year	0.5	–
300 year	0.5	0.8
Probability of damage to buildings		
30 year	0.3	–
300 year	1.0	0.3
Cumulative probability of damage to buildings		
30 year	0.15	–
300 year	0.5	0.24

For the calculation of expected fatalities in damaged buildings, the number of persons in buildings in the red and the blue zone was multiplied first by the reduction factor (Table 1) and second by the probability factor of fatality 0.46. This factor was derived by an analysis of former avalanche events in Switzerland, where 46% of the people buried by an avalanche inside a building died (Wilhelm, 1997).

The expected damage for a scenario *i* was calculated using Equation 2:

$$\begin{aligned} ED_i = {} & [(NP_{red\,i} \cdot PD_{red\,i}) + (NP_{blue\,i} \cdot PD_{blue\,i})] \cdot VP \cdot P_f \cdot (1 - EE_i) + \\ & + (VB_{red\,i} \cdot PD_{red\,i}) + (VB_{blue\,i} \cdot PD_{blue\,i}) \end{aligned} \tag{2}$$

where ED_i = expected damage for scenario *i* [CHF], $NP_{red\,i}$ = total number of persons in the red zone, $PD_{red\,i}$ = probability of damage to buildings in the red zone [0.15 for a 30-year event; 0.5 for a 300-year event], $NP_{blue\,i}$ = total number of persons in the blue zone, $PD_{blue\,i}$ = probability of damage to buildings in the blue zone [0 for a 30-year event; 0.24 for a 300-year event], VP = value of person [in CHF, either 1.4, 5 or 10 Mio./person], P_f = probability of fatality for persons in damaged buildings [0.46], EE_i = Evacuation effectiveness [0.30 or 0.90], $VB_{red\,i}$ = total value of buildings in the red zone [CHF], $VB_{blue\,i}$ = total value of buildings in the blue zone [CHF].

The annual expected damage of a scenario was calculated by dividing the expected damage by 30 for a 30-year event and by 300 for a 300-year event, respectively. This value represents the annual collective risk, including the monetarized risk to persons and to assets.

2.3 *Calculation of individual risk*

The individual risk of persons living in endangered areas was calculated in two steps. First, the annual collective risk was derived by dividing the expected number of fatalities of a 30-year event by 30 and those of a 300-year event by 300. Second, this value was divided by the number of endangered persons and afterwards multiplied by a factor of 0.35. This factor takes into account that there is potential avalanche danger (factor 0.5) for only six months of the year, and that the probability that persons occupying houses during that period is 70% (factor 0.7). The result is a mean value of individual risk of persons living in endangered areas at Schiahorn and neglects the fact that individual human behaviour differs.

2.4 *Calculation of annual benefits*

The benefits of each scenario for the 30- and 300-year avalanche event were calculated as the difference in the annual expected damage between the scenario without risk reduction measures (base scenario), and the annual expected damage of scenario *i* with risk reduction measures.

$$ATB_i = AED_0 - AED_i \tag{3}$$

where, ATB_i = total annual benefits of a given scenario [CHF], AED_0 = annual expected damage for the base scenario [CHF], and AED_i = annual expected damage for a given scenario [CHF].

2.5 *Calculation of annual costs*

The costs included the initial and maintenance costs of avalanche defence structures, evacuation and land-use planning. Using Equation 4 (Wilhelm, 1999) for annual cost calculations of the avalanche defence structures, initial costs I_0 of 1 million CHF per hectare were assumed (Margreth, 2000):

$$C_a = C_m + \frac{(I_0 - Ln)}{n} + \frac{(I_0 + L_n)}{2} \cdot \frac{i}{100} \tag{4}$$

where C_a = annual costs [CHF], C_m = maintenance costs [= 1% of I_0 *in* CHF], I_0 = initial costs [CHF], L_n = remaining costs after the life of the measure [0 CHF], n = life of measure [100 years], i = interest rate.

Costs of evacuations were calculated applying Equation 5:

$$C_e = \frac{(C_h \cdot t_e \cdot N_{Ae} \cdot N_b) + (N_p \cdot C_{acc} \cdot N_t)}{n} \tag{5}$$

where C_e = annual cost of evacuation [CHF/a], C_h = hourly wage of persons conducting the evacuation [CHF], t_e = average time needed for evacuation of one building [h], N_{Ae} = number of persons of the avalanche safety service conducting the evacuation [1], N_b = number of buildings to be evacuated [1], N_p = number of persons to be evacuated [1], C_{acc} = costs for board and lodging of evacuated people per day [CHF], N_t = number of days persons are evacuated, n = recurrence interval for evacuation [1].

For the Schiahorn area it was assumed that two members of the avalanche safety service need two hours for evacuation of one building at a hourly wage of 80 CHF which gives the cost of 320 CHF per building per evacuation (Hefti, 2004, pers. comm.).With a maximum of 53 buildings in the run-out zone of the avalanche, the costs per evacuation were calculated to be 16,960 CHF. Costs for board and lodging were assumed to be 200 CHF per person and day, and an evacuation was defined to last two days which produced costs of 95,600 CHF per evacuation. In total one evacuation costs 112,560 CHF. One evacuation in twenty years yields an annual cost of 5,628 CHF. Initial costs of establishing the avalanche safety service were neglected because total cost could not be attributed to specific avalanche-prone areas in Davos.

The cost of land use planning restrictions on habitation in the red zone was the total insured value in the year 2000 of the buildings in the red zone.

2.6 *Calculation of annual net benefits*

The annual net benefits of each scenario were calculated as the difference of total annual benefits and total annual costs of each scenario (Equation 6).

$$ANB_i = ATB_i - ATC_i \tag{6}$$

where ANB_i = total annual net benefits of a scenario [CHF], ATB_i = total annual benefits of a given scenario [CHF], and ATC_i are total annual costs of a scenario [CHF].

3 RESULTS

3.1 *Application of the marginal cost approach*

In the field of technical risks, the marginal cost approach based on cost-efficiency analysis was introduced over 20 years ago to derive the optimal risk reduction strategy given limited financial resources (e.g. Rowe, 1977; Schneider, 1978; Bohnenblust and Schneider, 1984; Bohnenblust, 1998). This approach argues that from a financial point of view the marginal costs for risk reduction strategies of all risk systems should be equal. In consequence, costs for risk reduction to a certain element (e.g. one human life or one unit of money) should not exceed a specified amount of money.

In order to derive the optimal risk reduction strategy, all measures and their combinations are illustrated in a risk-cost graph, using an ex-post approach, as shown in Figure 4 for the 300-year scenario at Schiahorn.

In Figure 4 all considered measures and combinations of measures are represented as one point in the diagram. The curve is constructed by starting with the initial risk without any measures (scenario 1). Second, the measure or the combination of measures with the highest ratio of risk reduction and cost is marked in the diagram (scenario 1E). From that point on, every additional measure (or combination of measures) with its additional amount of risk reduction and the associated additional costs is indicated in the diagram by a point. Cost-efficiency of these additional measures will decrease with every step and all these additional points are connected to a curve. The optimal risk reduction strategy is given by the point where a tangent with a given slope touches the curve. The slope of this tangent is defined by the desired ratio of risk reduction expressed either as a monetary value (e.g. CHF/year) or as one human life and the associated costs to reduce this risk, expressed in CHF/year. In this example risk to persons and to assets are both expressed in monetary values (CHF/year). Human life was valuated at 5 million CHF which corresponds to marginal costs of risk category 3 (section 2.2). Therefore the slope of the tangent is -1.

Figure 4 illustrates that evacuation (scenario 1E) is the measure with the highest ratio of risk reduction and associated costs ($\Delta R/\Delta C$). The remaining annual individual risk under the assumptions that

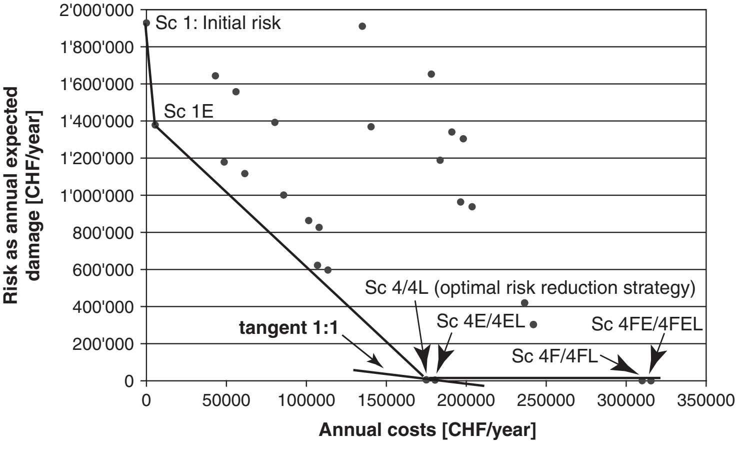


Figure 4. Risk-cost curve for identification of the optimal risk reduction strategy for the 300-year scenario. The optimal risk reduction curve connects all those points with high annual net benefits. In this example risks to persons and assets are both expressed in monetary values. For this example human life is valuated with 5 million CHF. Where a tangent with a slope of -1 meets the risk–cost curve (units at both axes are equal), the optimal risk reduction strategy is derived.

people are endangered only during six months and that they remain indoors for 16 hours every day during the winter months is $3.8 \cdot 10^{-4}$ which is above the protection targets of individual risk (Merz et al., 1995; Planat, 2004).

The measures with the next best ratio of $\Delta R/\Delta C$ is given by scenario 4 (5.0 ha of avalanche defence structures) and scenario 4EL (scenario 4 combined with evacuation (30% efficiency) and land-use planning restrictions). The remaining annual individual risk with the outlined assumptions above is $1.3 \cdot 10^{-6}$ which is within the protection targets for risk category 3 (Merz et al., 1995, Planat, 2004).

The same risk reduction is produced by scenario 4FE and 4FEL (4EL + forest). These scenarios taking the forest into account produce no additional risk reduction. The annual costs of these scenarios are higher due to maintenance costs of forest. The other points in Figure 4 above the risk-cost curve show adverse ratios of risk reduction and costs.

These results demonstrate that the combination of measures, 5.0 ha of avalanche defence structures in combination with evacuation and land use planning restriction, fulfil the marginal cost criterion. Therefore, the protection goal of a minimisation of collective risk, as suggested by the Swiss strategy of "protection against natural hazards" (PLANAT, 2005), is met.

In the next step, it is shown which risk reduction strategy results in the highest annual net benefits.

3.2 *Annual net benefits based on 30-year scenarios*

The results of calculations of annual net benefit for the 30-year scenario are presented in Figure 5a–c. Annual net benefits of different scenarios were calculated assuming that human life was either valuated using the human capital approach (1.4 million CHF/person) or with 5 or 10 million CHF/person representing the sum which should be spent to save one human life endangered by technical risks of risk category 3 (see section 2.2).

The results of the 30-year scenario assuming defence structures as the only measure (Figure 5a) showed an increasing annual net benefit from scenario 1 to 3 (0 to 2.9 ha of the release area protected by avalanche defence structures). In scenario 4 annual net benefit is decreasing because of increasing costs for the additional avalanche defence structures. When the human capital approach was used for valuation of human life, net benefits remain negative.

The considerable effect of evacuation as additional protection measure is shown in Figure 5b. The columns illustrate for each scenario the results of net benefit calculation for 30% and 90% evacuation efficiency and for different valuation of human life. The calculations with the human capital approach show that annual net benefits are small or even negative, respectively. Assuming an evacuation efficiency of 30% and a valuation of human life with 5 million CHF show that scenario 3E produces the highest annual net benefits with 133,000 CHF. The same outcome is obtained with a valuation of human life with 10 million CHF. However, evacuation had no influence in scenario 3E and 4E, because no human fatalities were expected.

When an evacuation efficiency of 90% was assumed, highest annual net benefits are produced by scenario 1E with 193,000 CHF (5 million per human life) and 392,000 CHF (10 million per human life), respectively.

The results of the calculation taking into account land-use planning restrictions (Figure 5c) show that scenario 1L produces the highest annual net benefits with 69,000 CHF for the human capital approach, 227,000 CHF for the 5 million CHF approach and 448,000 for the 10 million CHF approach.

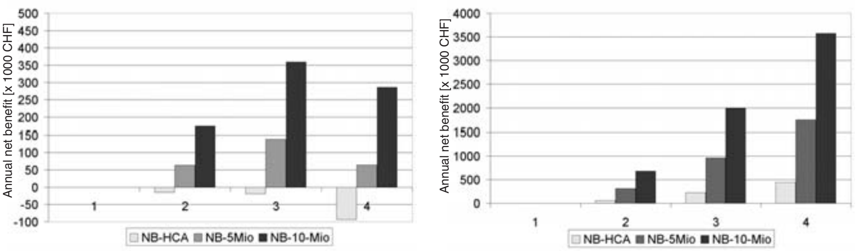
In most scenarios the results for the 30-year scenarios clearly show that the absolute values of the annual net benefits are dominated by the valuation of human life. In scenarios taking evacuation as a protection measure into account the efficiency of evacuation has a major influence. In scenario 1E (Figure 5b), the annual net benefit with 90% evacuation efficiency (5 million CHF approach) exceeds the annual net benefits calculated with 30% evacuation efficiency with the 10 million CHF approach for the valuation of human life.

3.3 *Annual net benefits based on 300-year scenarios*

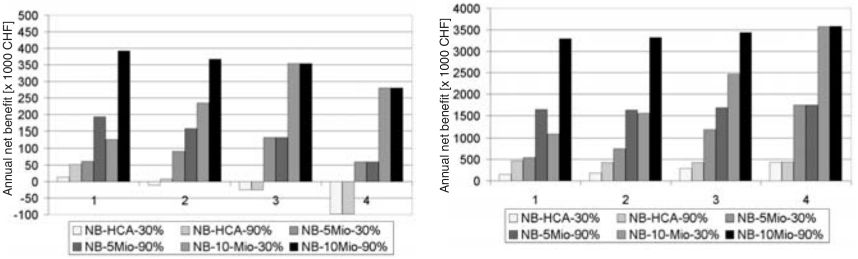
The calculation of the annual net benefit for the 300-year scenario are presented in Figure 5d–f. As for the 30-year scenario two approaches for valuation of human life were considered.

The results of scenarios 1 to 4 (Figure 5d) show that the annual net benefit is increasing when the area of avalanche defence structures is extended. The highest annual net benefit is produced by scenario 4 with 441,000 CHF (human capital approach), 1,748,000 CHF (5 million CHF), and 3,576,000 CHF (10 million CHF).

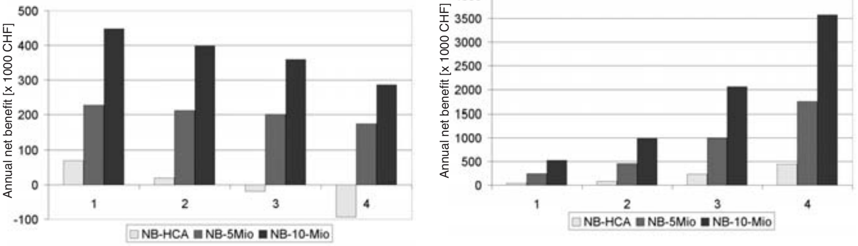
The results for scenarios 1E – 4E (Figure 5e) indicate that higher annual net benefits can be achieved when the area of avalanche defence structures and the efficiency of evacuation is increased. As shown in Figure 5e, evacuation efficiency has an greater effect on the annual net benefit than the assumed value of human life. In scenario 1E, annual net benefits with 90% evacuation efficiency and a valuation of human life with 5 million CHF are higher than those with 30%


a) 30-y scenario with avalanche defense structures (a.d.s)

d) 300-y scenario with avalanche defense structures (a.d.s)


b) 30-y scenario a.d.s + evacuation

e) 300-y scenario a.d.s + evacuation


c) 30-y scenario a.d.s + land-use planning

f) 300-y scenario a.d.s + land-use planning

Figure 5. Results of calculation of annual net benefit for a 30-year (a–c) and a 300-year scenario (d–f) at Schiahorn. Scenario 1–4 represents the situation with either 0, 1.6, 2.9, or 5.0 hectares of avalanche defence structures (a.d.s), respectively. NB-HCA describes annual net benefits using the human capital approach for valuation of human life, NB-5Mio annual net benefits valuating a human life with 5 million CHF, and NB-10Mio annual net benefits valuating a human life with 10 million CHF.

evacuation efficiency and a valuation of human life with 10 million CHF. However, results using the human capital approach demonstrate that the annual net benefits decreases slightly with larger areas of avalanche defence structures. The results with a valuation of human life with 5 or 10 million CHF show a slightly increasing annual net benefit with a larger area of avalanche defence structures. In scenario 4E evacuation efficiency has no influence on the annual net benefit because no human fatalities are expected in this scenario.

The calculations with land-use planning and avalanche defence structures as mitigation measures (Figure 5f) show that annual net benefits are increasing when the area of avalanche defence structures is extended. Compared to scenario 1–4 (Figure 5d) scenario 1 yields positive annual net benefits. Like for the other scenarios annual net benefits increase when human life is valuated higher.

4 DISCUSSION

The cost-efficiency analysis and the application of the marginal cost approach allow to identify that combination of protection measures among several alternatives which provides the highest possible risk reduction relative to risk reduction to cost. Consequently applied, the marginal cost approach offer the possibility for a proportional allocation of financial resources during the planning of safety measures. Although developed as ex-ante decision tools for the planning of measures, they can contribute to an ex-post discussion whether existing risk reduction strategies correspond to a given relation of risk reduction to costs or not. In the presented example of Schiahorn it was shown that the current approach consisting of avalanche defence structures, evacuation and landuse planning restrictions fulfills the marginal cost criteria and therefore the protection targets of collective risk (Planat, 2004).

Concerning the individual risk it was shown that the current strategy also fulfills the protection targets of individual risk. Assuming a person remains indoor every day during the winter months, the individual risk for this person is $1.3 \cdot 10^{-6}$. This is within the protection targets of risk category 3 for individual risks (Merz et al., 1995; Planat, 2004).

This result is confirmed by the cost-benefit-analysis which suggests that the current approach to avalanche risk reduction at Schiahorn maximizes net benefits and reduces the risk of human fatalities. The results of the 300-year scenario indicated that a decrease in the amount of avalanche defence structures from the current level (5 ha, scenario 4) would produce a decrease in annual net benefits. Inclusion of evacuation increased the annual net benefit and incorporates additional risk reduction for persons if avalanche defence structures were not able to prevent avalanches.

The results based on the 30-year scenario demonstrated that evacuation and land-use planning restrictions represent the most appropriate risk reduction strategy for this situation. The actual extent of avalanche defence structures produced positive annual net benefit only for a 300-year scenario. For the 30-year scenario, depending on the valuation of human life, negative values of annual net benefit were calculated.

However, the analysis has shown how assumptions in the calculation affect the results of cost-benefit analysis. Several uncertainties have to be considered when interpreting the results. The first uncertainty is related to the run-out distance and the intensity of every modelled avalanche event. A change of 30 m in run-out distance can have a considerable effect on risk especially for 300-year events as it was shown for other avalanche paths in Davos (Fuchs et al., 2004). Larger run-out distances than the modelled distances decrease net benefits of avalanche defence structures.

The second uncertainty affects the effectiveness of protection measures. Avalanche defence structures where assumed to provide full protection also for a 300-year event which is an optimistic view. Avalanche defence structures are constructed regarding the maximum snow height with a return period of 100 years. Thus uncertainty remains on damages as consequence of smaller avalanches releasing above fully snow-covered defence structures.

An additional uncertainty is given during special snow conditions. Avalanches can release in areas equipped with avalanche defence structures by loose snow moving through the structures.

Therefore, probably slight overestimation of net benefits has to be assumed for the 300-year scenario. Accounting for smaller avalanches, releasing above fully snow covered avalanche defence structures in a 300-year scenario, would probably affect net benefits to a less degree because expected damage would remain very small.

Evacuation as additional protection measure increases net benefits. However, there is an uncertainty on its effectiveness. The ability of evacuations to reduce risk of human fatalities remains uncertain due to the peak in risk during evacuations, when residents and members of the local avalanche safety service who conduct the evacuations are exposed to avalanches while they are outside of buildings. Success of evacuation also depends on the cooperation of residents. If evacuations should be successful it is essential that they are conducted at the right time. If an evacuation is conducted too early and no event happens afterwards, the acceptance of evacuation would probably decline. When an evacuation is conducted too late, risk can considerably increase. Therefore an assumption of evacuation efficiency of 30% seems to be more realistic than an efficiency of 90%.

In this study, risk was calculated as annual damage by summing up potential damages of buildings and the attributed monetary value of potential human fatalities. We valuated human life with two different approaches. Using the human capital approach we approximated the value of human life by quantifying the potential income of a person which is lost for the economy when this person dies (present value of gross income). This is only one aspect of the economic value of human life and neglects other factors like the net income and the value of remaining life time. Additionally, there are further uncertainties like e.g. the number of the economically active people of a population as well as the number of persons who do not have a fixed income (Wilhelm, 1997). Due to this uncertainties, this method is often be considered as insufficient (Wilhelm, 1997). Thus, we assume that the calculated value of 1,425,864 CHF per one human life is too low.

The second approach represents a value of the public willingness to pay for protection measures which has been determined in the field of technical risks several years ago (Merz et al., 1995). It represents the sum of money which has been spent by a society for prevention of a statistical death (implied cost of averting a fatality, ICAF). The uncertainty associated with this method is that expenditures for safety measures includes in many cases not only those for the rescue of life but also for the reduction of other types of damage. This value is only valid for a comparable risk field and this country where it was developed. Proske showed in a summary that willingness to pay (or ICAF) could differ by a magnitude of several factors (Proske, 2004).

The results of this study show that the monetary value of human life has a major influence on the results. A sensitivity analysis with several values for human life suggested that it exceeded in most of the considered scenarios the effect of risk reduction measures on the annual net benefit of protection measures and underlined the fact that assumptions have a major influence on the results of a cost-benefit analysis.

However, incorporating a high valuation of human life in cost-benefit analysis contributes to compatibility between the goals of maximizing net benefits and protecting persons which is the primary goal of the Swiss national strategy for protection against natural hazards (Planat, 2005).

5 CONCLUSIONS

The results show that the risk reduction strategy at Schiahorn consisting of avalanche defence structures, land-use planning restrictions, and organizational measures such as evacuation of persons in case of high avalanche danger meets the goals of economical efficiency and of the reduction of human fatality risk. Combining several protection measures delivers additional safety in case that one of the measures fails.

The optimal risk reduction strategy can be easily visualized with a risk-cost curve and a tangent whose slope is given by the relation of risk reduction and associated costs (marginal cost criteria).

A maximum reduction of risk at a given amount of money which fulfills the marginal cost criteria as a protection target for collective risks is only one of the goals during a planning phase of protection measures. Risk reduction strategies must also fit other goals of a community such as ecological or social factors. One goal could be that protection measures can help to preserve a decentralized settlement of alpine regions. However, these goals should clearly be stated in measure planning.

The assumptions which must be made for a cost-efficiency and a cost-benefit analysis have a strong influence on the results. Therefore both approaches can be easily misused in order to obtain desired results. It is essential that assumptions are clearly stated and that calculation procedures are easily reproducible.

In spite of the discussed limitations both approaches should play an increasing role in the planning of safety measures and should be one of the basic elements for sustainable development.

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