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ORIGINAL PAPER

Avalanche hazard mitigation strategies assessed by cost effectiveness analyses and cost benefit analyses—evidence from Davos, Switzerland

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Abstract This paper demonstrates the application of cost effectiveness analysis and cost benefit analysis to alternative avalanche risk reduction strategies in Davos, Switzerland. The advantages as well as limitations of such analysis for natural hazards planning are discussed with respect to 16 avalanche risk reduction strategies. Scenarios include risk reduction measures that represent the main approaches to natural hazards planning in Switzerland, such as technical, organisational, and land use planning measures. The methodologies used outline how concepts and techniques from risk analysis, hazard mapping, Geographic Information System, and economics can be interdisciplinary combined. The results suggest important considerations, such as possible sources of uncertainty due to different choices in the calculation of cost effectiveness ratio and net present value. Given the parameters and assumptions, it seems as if the current approach to avalanche risk reduction in the study area approximates to economic and cost efficiency and serves the aim of reducing risk to human fatalities.

Keywords Cost effectiveness analysis · Cost benefit analysis · Risk analysis · Natural hazards · Avalanches · Switzerland

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1 Introduction

Avalanches commonly occur in the alpine regions of Switzerland due to the combination of steep slopes with inclinations of 30°–50°, and high amounts of snowfall. Therefore, buildings, people, and infrastructure located in these regions are exposed to possible damage. The probability of occurrence of avalanches in the Swiss Alps appears to be constant over the historical record, although the frequency of avalanche events varies annually (Laternser and Schneebeli 2002). During the winter of 1999, high snowfall occurred in three consecutive storms, resulting in approximately 1,350 avalanches causing 17 human deaths inside buildings and on roads and an estimated direct and indirect loss of 750 million CHF (SLF 2000; Nöthiger et al. 2002). This loss resulted despite investments of 1.5 billion CHF in technical avalanche risk reduction measures between 1950 and 2000 (in 2000 values, SLF 2000).

The Swiss federal government requires local and cantonal authorities to protect human settlements from risks resulting from natural hazards (Fuchs and Bründl 2005). The Federal Forest Law of October 4th, 1991 and the Federal Hydraulic Engineering Law of June 21st, 1991 provide guidelines for protecting human life and property through forestry and engineering approaches. The federal guidelines for the consideration of avalanche risk in land-planning decisions were approved in 1984 (BFF and SLF 1984). These guidelines establish the basis for cantons and communes to consider avalanche incident documentation and avalanche hazard maps in land-planning decisions. Communities implement land-planning decisions following different guidelines established by cantonal authorities and based on analyses by private engineering companies.

The federal and cantonal government agencies that finance the implementation of natural hazards risk reduction strategies by local communities encourage cost effectiveness analyses and cost benefit analyses of proposed risk reduction projects (Haering et al. 2002). Several sources outline the conceptual basis for conducting cost benefit analyses within natural hazard management (e.g., Wilhelm 1997, 1999; Wegmann and Merz 2002; Wegmann and Wuilloud 2004; Gamper et al. 2006). However, the methodology of cost benefit analysis (CBA) has advantages as well as limitations for natural hazards planning (Kramer 1995; Mechler 2002; Fuchs and McAlpin 2005). The difficulty of determining the benefits of natural hazards risk reduction strategies presents a challenge for the use of cost benefit analyses as a decision-making tool (Alexander 2000; Gamper et al. 2006).

This paper demonstrates the application of cost effectiveness analysis (CEA) and CBA to alternative integrated risk reduction strategies at the Schiahorn avalanche path located in Davos, Switzerland (Fig. 1). These scenarios include risk reduction measures that represent the main approaches to natural hazards planning in Switzerland, such as technical, organisational, and land use planning measures (Bründl et al. 2004). The methodologies used outline how concepts and techniques from risk analysis, hazard mapping, Geographic Information System (GIS), and economics can be interdisciplinary combined. The appraisal identifies potential roles for the methods of CEA and CBA in natural hazards planning as decision support instruments and argues that the potential of such instruments as tools to improve natural hazards planning depends on the profundity of application within the underlying political decision-making process.

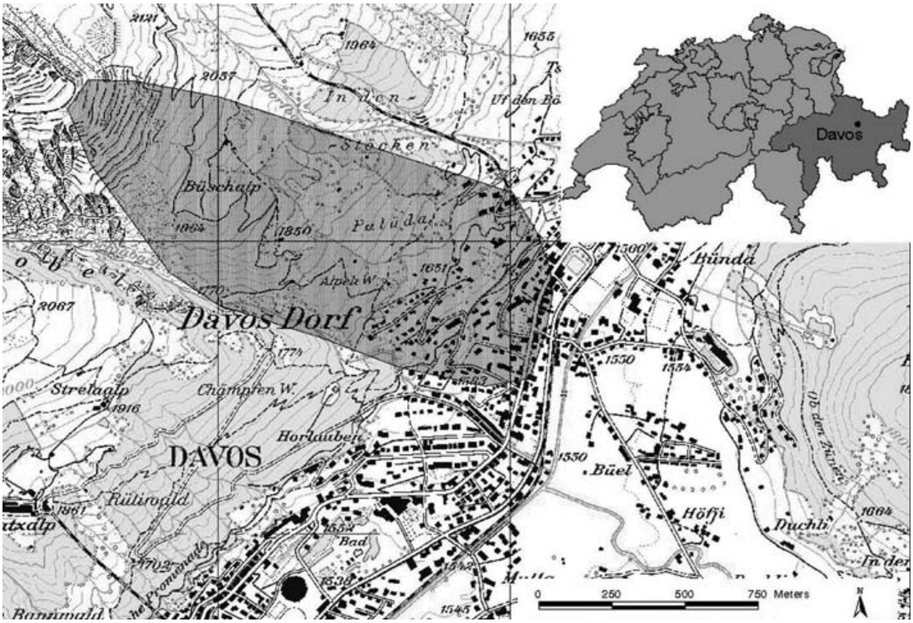

Fig. 1 The Schiahorn study area in Davos, Switzerland. Reproduced with permission of SWISSTOPO (BA035092)

2 Methodology

2.1 Cost effectiveness analysis and cost benefit analysis

Societal and political decisions about mitigation measures concerning natural hazards are generally based on a multiplicity of interests due to the variety of parties involved. In recent years, cost effectiveness and cost benefit analyses emerged as appropriate tools to meet this multiplicity of interests, since the results of those methods reflect the affected parties and lead to an efficient decision basis. Hence, there is a particular need for methodologies ensuring the consideration of all these interests and providing simultaneously a reliable basis for the final decision-maker. Furthermore, since protective measures are provided by federal and cantonal authorities in Switzerland, the implementation of mitigation measures should be based on criterions like cost and economic efficiency to ensure an optimal allocation of resources and the optimal provision of risk reduction from a societal point of view. The following discussion will outline that CEA and CBA fulfil the abovementioned standards and can therefore be defined as decision-support systems, i.e., as instruments able to define an appropriate basis for decision-making.

CEA and CBA are able to evaluate public as well as private spending because of the arising costs and benefits, hence on the basis of positive and negative impacts. The comparison of costs and benefits differs in each method. While CEA assesses the costs in monetary terms, it leaves the benefits on a natural, physical level and produces a result that shows the effectiveness of different alternatives proportionally to the arising costs. Consequently, CEA works with different dimensions aiming at selecting the best alternative out of a range of potential alternatives and illustrating the relative position of each alternative. As opposed to CEA, CBA goes one step further and evaluates both factors—costs and benefits—on a monetary level. As a result, all alternatives can be ranked by applying the criterion of economic efficiency, using the net present value (net benefit – net cost), the benefit-cost ratio or the internal rate of return.

Consequently, CEA only provides information whether a certain project alternative is more cost efficient than another one, but not if a certain project alternative contributes to an increase in welfare (Groot et al. 2004). In contrast CBA is able to evaluate this shift in welfare by using the criterion of economic efficiency that reflects the societal optimal level of a certain good provision. Briefly, the analysis of cost effectiveness can be described as a "truncated form of cost benefit analysis" (Mishan 1998, p. 110).

Both methods use a similar way of conducting the analysis and can be structured using three main steps: First, the project alternatives including the arising (economic) impacts of each option are defined.

Second, based on the physical quantification of the relevant impacts, CEA and CBA deviate evaluating costs and benefits. CEA leaves the benefits as they were physically quantified (e.g., saved human lives or avoided accidents) whereas the costs are monetarily evaluated (taking the opportunity costs or the market price). CBA works in a common metric and therefore transfers positive and negative effects into monetary terms by using economic methods like hedonic pricing or contingent valuation.

Third, the methods meet each other again when discounting the cost and benefit flows before applying the results and conducting a sensitivity analysis. Concerning the results, CEA works with different ratio approaches (e.g., cost effectiveness ratio or fixed cost ratio) and can therefore be described as multidimensional. CBA establishes the net present value (or, as an alternative, the benefit-cost ratio or the internal rate of return), which is the sum of discounted gains minus the sum of discounted losses; this criterion is met if the benefits of an alternative exceed the associated costs.

According to the three stages described above, the alternatives regarding mitigation measures in the commune of Davos will be described in the following section to provide an overview of the possible alternatives or scenarios for the forthcoming CBA and CEA.

2.2 Mitigation measures under consideration

The risk of natural hazards is represented by the probability of occurrence of a natural process that might cause damage, combined with the probability of exposure to that process and the amount of damage resulting from that exposure (Varnes 1984; Heinimann et al. 1998; Borter 1999; Fuchs et al. 2004, see Eq. 1).

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

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; $v_{Oj,Si}$ = 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. The following analyses refer to mitigation measures that are currently in use for avalanche risk reduction and therefore demonstrate possible alternatives in the commune of Davos, Switzerland.

2.2.1 Permanent mitigation measures

In the Schiahorn avalanche path, snow fences where constructed in the avalanche release areas as a permanent mitigation strategy. Since the early 20th century, the release areas have been equipped with 3,315 m’ of stonework, 2,240 m’ of mixed terraces, 4,262 m’ of permanent snow rakes and 1,125 m’ of wooden snow rakes, for a total of 10,942 m’ of defence structures (Fuchs and McAlpin 2005). However, not all avalanche releases could be eliminated by such constructions, as shown in the avalanche winter of 1999 in Switzerland (SLF 2000). First, avalanches could be triggered in the clearances between snow fences, and second, if snow depths exceed the height of the snow fences, avalanches could be triggered above them.

2.2.2 Land use planning

In Switzerland, land use regulations were introduced in the 1960s and 1970s to control the development of settlement in areas endangered by natural hazard processes. The federal guidelines for the consideration of avalanche risk in land-planning decisions were approved in 1984 (BFF and SLF 1984). These guidelines establish the basis for cantons and communes to consider avalanche incident documentation and avalanche hazard maps in land-planning decisions. The avalanche hazard maps are based on the avalanche pressure of defined design events and distinguish between three areas with different hazard levels (for further information on the Swiss system of avalanche hazard zoning, see the Appendix 1). Communities implement land-planning decisions following those guidelines. Current land use planning regulations prohibit new constructions in the red hazard zone and set standards for the construction of new buildings inside the blue hazard zone (GVA 1994).

2.2.3 Organisational measures

In avalanche risk management organisational measures include artificial release of avalanches, closure of traffic routes and endangered areas and evacuation of people. They are taken shortly before an expected event.

Evacuations are officially ordered by local authorities in situations with high avalanche danger and are an effective method to prohibit harm to people being located in avalanche-prone areas. The decision to evacuate depends on a variety of local factors, including the number and type of endangered buildings, weather forecasts, and the judgement of local officials responsible for evacuation (Bründl et al. 2004). The ability of evacuations to reduce the risk of human fatalities remains relatively uncertain due to the peak in risk, which occurs during evacuations: residents and professionals who conduct the evacuation are exposed to a high probability of injury or fatality if an avalanche occurs while they are outside of the buildings. Thus, evacuations require a risk-minimising strategy, which depends on the specific circumstances during a period of increased avalanche danger. Additionally, the ability of officials to reduce the risk of human fatalities by evacuations depends on the cooperation of residents. Experience in Switzerland suggests that evacuations may reduce the risk of human fatalities by as little as 30% (Margreth 2005, pers. comm.).

2.3 Determination of risk reduction scenarios

Following Eq. 1, data on the probability of occurrence of avalanches as well as data on damage potential affected by those avalanches are needed for the determination of avalanche risk. In a subsequent step, different alternatives in risk reduction strategies are evaluated with respect to the all-over reduction of avalanche risk in the Schiahorn avalanche path.

2.3.1 Determination of avalanche scenarios

For the calculation of the benefits of mitigation measures, 30-year avalanche scenarios were defined which represent the red zone of a hazard map in Switzerland.

In order to obtain the run-out distance of avalanches assuming different scenarios, the Schiahorn release area was divided into four sections according to the surface of the terrain and the avalanche incident map. 30-year avalanche events were modelled based on estimates of the snow fracture depth in each of the four release areas. The estimates for fracture depth were based on statistical analyses of maximum snow accumulation for three-day periods over the historical record (Salm et al. 1990). A numerical 2-D avalanche run-out model calculated the avalanche run-out areas and forces associated with each scenario (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). Using a simulation resolution of 12.5 m, the avalanche run-out model has been shown to have an absolute accuracy of about 50 m for the run-out distances and associated forces in the red hazard zones, and a relative accuracy between the scenarios of about 25 m (Gruber et al. 1998). Considering these uncertainties during the further processing, the model results provide mean estimates and thus represent the most probable alternatives in the risk reduction strategies.

2.3.2 Risk reduction strategies

The Schiahorn release area was divided into four sections and it was assumed that snow fences would be added in steps to progressively lower sections. According to Fig. 2, an area of 0, 1.6, 2.9 and 5.0 ha was considered to be equipped with snow fences. The increases in the area of snow fences corresponded to equal decreases in the release area. The avalanche run-out model assumed that snow fences would eliminate all avalanche releases from the area where the fences were located.

Evacuation was assumed to decrease the human fatality rate expected for the different risk reduction scenarios. Given the uncertainty associated with evacuation as a risk reduction strategy, the benefits of each scenario were calculated assuming that evacuations reduced human fatalities, which were referred to in the discussion as the effectiveness of evacuation, by either 90% or 30% (Hefti 2004, pers. comm.).

The risk reduction scenarios allowed for the possibility to reduce exposure to avalanches by the prohibition of habitation in endangered areas. Thus, regarding building development, two sets of calculation, with and without land use planning

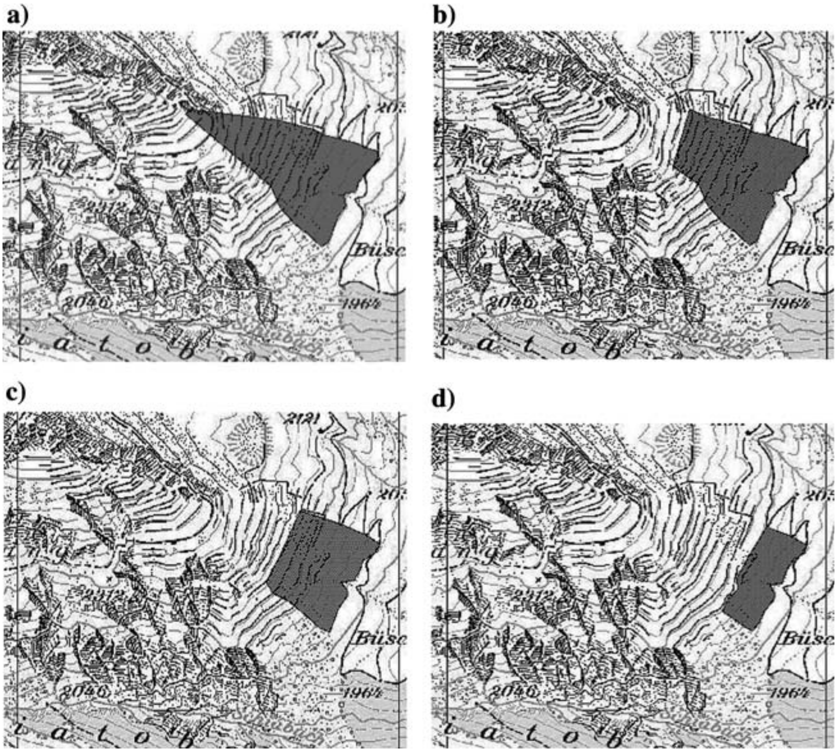

Fig. 2 The avalanche release areas in the Schiahorn study area. (**a**) Release area 1, with 0 ha of snow fences and an area of 7.6 ha. (**b**) Release area 2, with 1.6 ha of snow fences and an area of 6.0 ha. (**c**) Release area 3, with 2.9 ha of snow fences and an area of 4.7 ha. (**d**) Release area 4, with 5.0 ha of snow fences and a release area of 2.6 ha. Reproduced with permission of SWISSTOPO (BA035092)

restrictions, were conducted. For the scenarios with land use planning restrictions, no building development or habitation in the red zone was assumed. In contrast, the level of building development and habitation in the year 2000 was assumed for those scenarios without land use planning restrictions. During an avalanche event, buildings located in the avalanche path show similar effects than avalanche retarding mounts and thus reduce the run-out distance. The avalanche run-out model accounted for the effect of buildings in the avalanche path on run-out distance and area by an increase in the friction coefficient ξ for areas with building development.

The risk reduction scenarios included different combinations in the amount of snow fences, evacuations, and land use planning restrictions in terms of alternatives (alternative 1: snow fences, alternative 2: snow fences and evacuation, alternative 3: snow fences and land use regulations, alternative 4: snow fences, evacuation and land use regulations, see Table 1). The results of the 2-D avalanche run-out model were combined with data on the affected damage potential resulting from the four alternatives in mitigation strategies using a GIS. Some model results showed discontinuous avalanche run-out, which contradicts observed avalanche behaviour. Therefore, these model results were corrected following previous experience of avalanche run-out using the avalanche incident cadastre of the Schiahorn area.

Table 1 Net benefits [CHF] for the alternative 1: snow fences, alternative 2: snow fences and evacuation, alternative 3: snow fences and land use planning and alternative 4: snow fences, evacuation and land use planning

Alternatives	Total cost [CHF]	Total benefit [CHF]	Net present value [CHF]
(1) Snow fences			
Scenario 1	3,815,000	0	– 3,815,000
Scenario 2	3,945,372	6,576,366	2,630,994
Scenario 3	3,542,479	13,165,481	9,623,002
Scenario 4	6,235,536	13,165,481	6,929,945
(2) Snow fences and evacuation			
Scenario 1	3,841,193	3,777,969	– 63,224
Scenario 2	3,971,565	8,465,350	4,493,785
Scenario 3	3,568,672	13,165,481	9,596,809
Scenario 4	6,261,729	13,165,481	6,903,752
(3) Snow fences and land use			
Scenario 1	74,360,000	13,165,481	– 61,194,519
Scenario 2	37,398,372	13,165,481	– 24,232,891
Scenario 3	3,542,479	13,165,481	9,623,002
Scenario 4	6,235,536	13,165,481	6,929,945
(4) Snow fences, evacuation and land use			
Scenario 1	74,386,193	13,165,481	– 61,220,712
Scenario 2	37,424,565	13,165,481	– 24,259,084
Scenario 3	3,568,672	13,165,481	9,596,809
Scenario 4	6,261,729	13,165,481	6,903,752

The scenarios are based on the amount of snow fences, outlined in Sect. 2.3.2

2.4 Determination of costs and benefits

In order to meet the stated prerequisites for the study, positive and negative effects in terms of costs and benefits resulting from the protection measures described above were analysed.

2.4.1 Determination of costs

Costs can be defined as negative impacts or effects of protective measures since they cause qualitative and quantitative decreases of goods or an increase in prices, and therefore a decrease in welfare. In this context, it is essential to introduce the concept of opportunity costs. Opportunity costs describe the most valuable forgone alternative and therefore the negative effect that includes the using up of resources (or inputs to production), for instance if an hour of labour or a bag of cement is used up in constructing a dam, it cannot be used simultaneously in constructing a bridge (Hanley and Spash 1998). Consequently, opportunity costs aim to assess the true cost of every alternative by considering various courses of action. Determining opportunity costs for all possible alternatives is in general very time-consuming; therefore, market prices are often used as an alternative.

Thus, the costs associated with snow fences were evaluated in terms of construction costs. The initial capital expenditures for snow fences were assumed to be approximately 1 million CHF per hectare in 2000 (Margreth 2000). This value was calculated using Eq. 2, based on the real interest rate, which takes the inflation into account and therefore allows the comparison of expenditures in different years.

The real interest rate i_{real} was calculated on the basis of the nominal interest rate i_{nom} and the inflation J, using Eq. 3. The nominal interest rate was derived from the average rate of interest of the confederate bonds, provided by the Swiss National Bank. The rate of inflation was provided by the Swiss Federal Statistical Office.

$$K_n = \left(1 + \frac{p \cdot s}{100}\right)^n \cdot K_0 \tag{2}$$

where, K_n = present value of the total capital at the expiration of the validity [CHF]; p = real interest rate [%]; s = interest period [1]; n = term [1]; K_0 = opening captial [CHF].

$$i_{\mathrm{real}} = \left(\frac{1 + i_{\mathrm{nom}}}{1 + J}\right) - 1 \tag{3}$$

where, i_{real} = real interest rate [%]; i_{nom} = nominal interest rate [%], J = rate of inflation [%].

An annual maintenance cost of 1% of the investments for snow fences was assumed based on the estimation that the snow fences are repaired or replaced every 50–100 years (Margreth 2005, pers. comm.).

Exposure to avalanches can be reduced by a prohibition of habitation in endangered areas. In Switzerland, current regulations allow continued habitation in existing buildings in the area affected by a 30-year avalanche event (red zone), but prohibit new constructions. Thus, the costs of land use planning restrictions in the red zone were assumed to be the total insured value in 2000 of the buildings (see Sect. 2.4.2) in the red zone of each scenario, presuming that land use would not be possible.

Costs of evacuation were calculated applying Eq. 4:

$$C_{\mathrm{e}} = \frac{(C_{\mathrm{h}} \cdot t_{\mathrm{e}} \cdot N_{\mathrm{Ae}} \cdot N_{\mathrm{b}}) + (N_{\mathrm{p}} \cdot C_{\mathrm{acc}} \cdot N_{\mathrm{t}})}{n} \tag{4}$$

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]; C_{acc} = costs for board and lodging of evacuated people per day [CHF]; N_{t} = number of days persons are evacuated [1]; n = recurrence interval for evacuation [1].

For the Schiahorn area it was assumed that two members of the avalanche safety service need 2 h for evacuation of one building at an hourly wage of 80 CHF, which yields 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 lasting two days, which produced costs of 95,600 CHF per evacuation. In total, one evacuation for the Schiahorn area amounted to 112,560 CHF.

2.4.2 Determination of benefits

Depending on the individual viewpoint, protection measures imply a wide range of positive effects for a community. In this study positive effects (benefits) were assumed as prevented damage on buildings and human life.

Data on the location of buildings and the number of dwellings in each building for the year 2000 in Davos was provided by the commune of Davos. Using GIS, the location of the buildings and the number of dwellings in the red zone was identified.

For scenarios including hotels and guest houses, the number of people was calculated by multiplying the number of beds by an average occupancy rate of 70% during the winter season (Davos Tourist Board 2004, pers. comm.).

In a subsequent step, the damage potential (people and buildings) was quantified by using the common metric money. This way of monetarising can be used as long as market prices exist like for buildings, cars or infrastructure. However, if non-market goods, like human lives or the value of recovery have to be assessed, economic concepts such as the willingness to pay (WTP) or the willingness to accept (WTA) approach have to be used to determine the monetary value.

Different approaches can be used to convert the benefits of buildings into monetary values. The first choice for revealing the societal preferences towards buildings would be the market price. However, since it is the philosophy of the mandatory building insurer to underwrite the risk due to the replacement value to be able to compensate for an eventual total loss and to enable a replacement of the damaged building at any time, it does make sense to use the replacement value within this study, neglecting any risk-dependent change in the demand within the real estate market. Furthermore, this value serves as a basis for the expressed preferences of the societal accepted value of protection against natural hazards in Switzerland. Following this method, data concerning the insured replacement value of all buildings affected was collected, as provided by the mandatory building insurer (GVA building insurance company of Grisons, for explanations on the Swiss system of mandatory building insurance, see the Appendix 2).

To conduct a CBA on the decision about which measures should be realised, it is necessary to evaluate human lives monetarily just to ascribe humans the same estimation as other prevented damage potential components. As outlined above, monetarisation becomes complex when markets are missing. Since human lives do not have a market they can only be evaluated using different socio economic approaches: On the one hand the WTP or WTA concept can be applied, resulting in a revelation of the individual preferences towards a certain good such as human life. The valuation methods needed are usually divided into two categories: direct and indirect methods (Mishan 1998). While indirect methods seek to recover estimates of individuals' WTP by observing their behaviour in related markets (hedonic pricing or travel cost method), direct methods infer individual preferences for environmental quality by asking them to state their preferences (Hanley and Spash 1998). These approaches are consequently able to provide the value of statistical life (VSL), which is the WTP for an altered mortality risk divided by an appropriate risk reduction.

Since studies dealing with the VSL for the alpine region are still subject to ongoing research (Leiter and Pruckner 2005) the human capital approach was applied within this study. This method aims at calculating the total loss of the human production potential because of illness or death. The discounted present value of an average 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). Applying Eq. 5 for the annuity value with the interest paid at the end of the period, a present value of the remaining income of an average person was calculated with 1,425,864 CHF. The real interest rate of 1.3% was derived using Eq. 3 from the long-term interest rate and inflation from 1980 to 2000 (IMF 2004).

$$R_0 = r \cdot q^{-n} \cdot \frac{q^n - 1}{q - 1} \tag{5}$$

where, R_0 = annuity value [CHF]; r = payment [CHF]; $q = 1 + i$, i = real rate of interest (1.3%); n = term [1].

The monetary values of the possible damage potential (buildings and human lives) in the red zone were multiplied by reduction factors in order to calculate the expected damage. The reduction factors vary depending on the intensity of the avalanche event, particularly by the pressure of the avalanche. Since the red zones are defined by the frequency of avalanche events with certain intensities, the reduction factors followed empirical assumptions (Wilhelm 1997):

- A reduction factor of 0.5 was applied accounting for the probability that an avalanche would damage only some of the exposed buildings, which was based on the observation that avalanches cover only part of the whole avalanche accumulation area (Fig. 3).
- The probability of damage to buildings was set to 0.3 for an avalanche pressure between 0 and 30 kPa/m^2. Thus, the cumulative probability of damage to buildings was calculated by a factor of 0.15.

Analysing the avalanche database of the Swiss Federal Institute for Snow and Avalanche Research, it was shown that the fatality rate for persons inside buildings is 46% (Wilhelm 1997). Thus, this average fatality rate was assumed and the

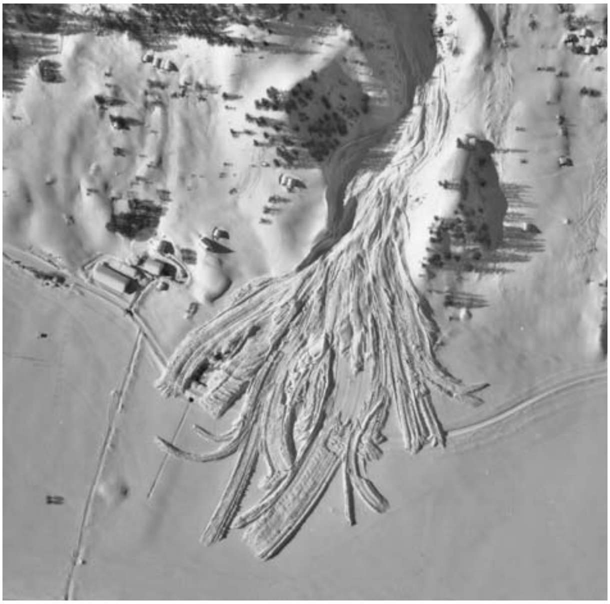

Fig. 3 Finger-shaped avalanche accumulation during the winter 1998/99 westwards the municipality of St. Ulrichen, Switzerland, showing how avalanches spread so that they only cover part of the entire avalanche path. Reproduced with permission of the Swiss Federal Office of Topography

expected value of fatalities was calculated by multiplying the number of persons in the red zone first by the probability of damage to buildings in this zone and second by 0.46 (Eq. 6).

$$ED_i = (NP_{\text{red}i} \cdot PD_{\text{red}i}) \cdot VP \cdot P_{\text{f}} \cdot (1 - EE_i) + (VB_{\text{red}i} \cdot PD_{\text{red}i}) \tag{6}$$

where, ED_i = Expected damage for scenario i [CHF]; $NP_{\text{red}i}$ = Total number of persons in the red zone [1]; $PD_{\text{red}i}$ = Probability of damage to buildings in the red zone [0.15 for a 30-year event]; VP = Value of persons; P_{f} = Probability of fatality for persons in damaged buildings [0.46]; EE_i = Evacuation effectiveness, [0.90 or 0.30]; $VB_{\text{red}i}$ = Total value of buildings in the red zone [CHF].

In a last set of calculations, the benefits of each scenario for the 30-year avalanche events were calculated as the difference in the expected damage between the base scenario, without any risk reduction measures, and the scenario i (Eq. 7).

$$TB_i = ED_0 - ED_i \tag{7}$$

where, TB_i = Total benefits of a given scenario [CHF]; ED_0 = Expected damage for the base scenario [CHF]; ED_i = Expected damage for a given scenario [CHF].

3 Results

The following results from the study at hand will outline the differences between the application of CEA and CBA. The estimations of cost effectiveness ratio and net present value are based on the alternatives of different levels of risk reduction introduced above, i.e., alternative 1: snow fences, alternative 2: snow fences and evacuation, alternative 3: snow fences and land use planning and alternative 4: snow fences, evacuation and land use planning.

3.1 Cost effectiveness analysis

Starting with the results of the CEA it has to be recapitulated that CEA monetarises the arising costs but not the deriving benefits and includes therefore two different metrics. While costs are measured in monetary values, benefits are only qualified, such as lives saved. Hence, the cost effectiveness ratio is a ratio that can be taken as the average cost per unit of effectiveness. Consequently the result is information on cost effectiveness and thus a relative ranking of the arising alternatives. This can be shown using the results of the conducted CEA. Taking the alternative 2 as an example and calculating the cost effectiveness ratio of the different levels of risk reduction applying snow fences and evacuation, the effectiveness level is based on the number of protected buildings or saved lives, but not both of them together, since it is impossible to scale the two different levels down to one single metric when using CEA. While protected buildings would lead to a ranking of 2, 1, 3, and 4 (ordered from the most cost effective to the least cost effective), the cost effectiveness of alternative 2 using saved people (prevented fatalities) can be ranked down by 1, 2, 3 and 4 (ordered from the most cost effective to the least cost effective). These rankings outline that it is indeed possible to calculate an order of precedence for each effectiveness option, but it is not realisable to combine these results for achieving an absolute ranking including all positive impacts (effects), such as saved lives and buildings.

This shortcoming outlines the necessity of the CBA to scale all possible impacts of a protective measure down to one single metric unit, namely money. Even though this process can be complex and time-consuming, the monetarisation of the benefits leads to an economic and cost efficient outcome by creating an absolute ranking of all possible alternatives.

3.2 Cost benefit analysis

In Table 1, results of the CBA are presented for the 30-year avalanche scenario. At all considered alternatives a ranking of alternatives 3, 4, 2, and 1 resulted within the different scenarios, ordered from the most economic and cost efficient to the least economic and cost efficient. These results indicate that due to the relatively high costs of snow fences, sheeting the avalanche starting zone with around 2.9 ha of snow fences would be the optimal risk reduction strategy, which is about 60% of the total possible starting zone.

However, when comparing the different alternatives relatively, alternative (1) and (3) show slightly higher net present values of CHF 9,623,002 than alternatives (2) and (4) with CHF 9,596,809. Thus, unlike the results of CEA presented above, a precise ranking of different alternatives becomes possible since all costs and benefits could be compared in the same metric unit.

The results also proved that a scenario including a higher amount of technical mitigation measures does not necessarily lead to higher net present value. In general, if inside the area affected by a 30-year avalanche event habitation would be prohibited, the highest cost would result due to the assumption that the buildings located inside this area could not be used any more. On the other hand, due to the relatively low cost of evacuation and due to the fact that relatively few people live inside the area affected by the avalanche scenario, evacuation, from an economic point of view, is not necessarily the most efficient risk reduction strategy. Nevertheless, since the study carried out only describes the situation for a 30-year design event, the results can just be interpreted for this single event. The over all risk reduction, including all possible avalanche scenarios, would result in a higher benefit, and thus, in higher net present values.

4 Conclusion

The results from CBA and CEA suggested a good approximation to economic and cost efficiency of the risk reduction strategy currently applied in the Schiahorn area, including the reduction of fatality risk. Nevertheless, the conducted cost effectiveness and cost benefit analyses provide uncertainties which need to be discussed.

First, the calculated net present values would have been higher if avalanche events with different return periods were included in the calculation of the benefits.

Second, an increase in the number of buildings and persons (due to a possible extent of areas for land development) in the Schiahorn area would have increased the net benefits calculated for the risk reduction scenarios.

However, construction of buildings in endangered areas would also increase the risk that remains due to uncertainties about the probability of natural hazards occurrence and the effectiveness of risk reduction measures, as presented by Fuchs et al. (2005) and Keiler et al. (2005) for the development of damage potential in the communities of Davos (CH) and Galtür (A). These uncertainties could for the most part be attributed to impreciseness and randomness of process models, since the models used to build avalanche scenarios only mirror the average spatial and temporal occurrence of events. Studies on modelling uncertainties based on input parameters carried out by Barbolini et al. (2002) had shown a relatively high spatial variability in the run-out zones. If this variability would be applied to the risk model, high scattering of the results will occur, as exemplarily presented by Fuchs et al. (2004) for the commune of Davos. Furthermore, the estimation of the intensity of the avalanche events also implies uncertainty, since the reduction factors are approximations of the average susceptibility of buildings to damage and fatalities of persons exposed to avalanches, however, the actual damage would depend on the specific resistance of buildings and persons to harm.

In addition, indirect impacts such as negative effects of snow fences on the landscape (indirect costs) or increased tourism revenues due to reduced risk (indirect benefits) were excluded. Assumptions concerning the valuation method of the benefits of natural hazards risk reduction can also affect the results of CBA. The value of endangered human lives, included as a benefit factor of risk reduction, can be given as an example to increase the result of CBA (net present value) since human life is thereby monetarised. The human capital approach used provides an opportunity to incorporate the economic value of human life into CBA, but does not include the explicit consideration of the non-economic values of humans, commonly known as intangible values. These values can only be incorporated when economic methods like hedonic pricing or contingent valuation are used to reveal the individual preferences towards a certain risk reduction. Using these findings the VSL can be calculated.

The results of the conducted analyses also contain uncertainty about the effectiveness of risk reduction measures. A combination of risk reduction measures may offer more reliable risk reduction for persons and buildings than scenarios that use only one single measure. The findings recommended that evacuation and land use planning restrictions together with a lower amount of snow fences could offer a higher net present value including a more cost efficient way than a higher amount of snow fences without other measures.

The results supported the argument that the optimal approach to natural hazards risk reduction depends on the particular hazard, the aims of the affected community and relevant decision processes. Minimising human fatalities may be the main priority, with an economic efficiency—thought of as a shift in welfare—as a secondary goal. Although there may be gains in economic efficiency from changing the supply of natural hazard protection, the decision to supply more or less protection is a political one. This decision is related to the society's level of risk acceptance, and should only be discussed on a participative basis.

An appraisal of CBA for natural hazards planning depends on the framework of using the methodology. In Switzerland, decisions in natural hazard management define goals, means, and resources of natural hazards planning policies and occur at the federal, cantonal, communal, and individual levels. CBA may serve a number of intended purposes at different stages of the decision process.

Thereby, local authorities propose natural hazards risk reduction projects for funding by cantonal and federal agencies. CBA is commonly used to justify funding for a proposed risk reduction strategy. In this role, CBA serves to promote the allocation of resources for alternative risk reduction strategies and offers information on the net present value of these strategies and therefore on the most efficient outcome. Incentives to present the most favourable evaluation of a proposed risk reduction project may arise in the promotional phase of the decision process. These incentives limit the potential of CBA to provide objective and reliable information for natural hazards planning. CBA will indicate the optimal risk reduction strategy for a given community only if the analysis evaluates all possible approaches in reference to the aim of the community.

The potential of CBA depends on its proper integration in the decision-making process as an equitable, transparent, and flexible instrument. Transparency as to assumptions used to calculate costs and benefits and the uncertainty contained in the results will increase the ability of decision-makers to use findings of cost benefit analyses. Decision-makers have a responsibility to understand that cost benefit analyses provide only part of the necessary information for natural hazards planning. Aims other than economic efficiency, such as alternative contextual factors or constraints provide additional, necessary information for decision-making.

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Appendix 1

The avalanche hazard map divides a studied area into different subsections with different hazard levels according to the severity and the likelihood of designed avalanche events (BFF and SLF 1984).

Red indicates areas where pressure from avalanches with recurrence intervals T between 30 and 300 years exceeds a lower limit that ranges from 3 kPa for $T = 30$ years to 30 kPa at $T = 300$ years. The entire area affected by (dense flow) avalanches with $T < 30$ years is also marked in red.

Blue indicates areas where pressure from avalanches with recurrence intervals T between 30 and 300 years falls below 30 kPa. Areas affected by powder avalanches with reoccurrence intervals $T < 30$ years and a pressure < 3 kPa are also marked in blue.

The run-out areas of powder avalanches with reoccurrence intervals $T > 30$ years and a pressure < 3 kPa are marked in yellow, as well as theoretically not excludable but extremely rare avalanches with a reoccurrence interval $T > 300$ years.

Appendix 2

In Switzerland, 19 of 26 cantons conduct a mandatory insurance system for buildings, underwriting natural hazards damage unlimited until the legally certified reinstatement values. Those insurers are organised as independent public corporations based on cantonal law, and cover approximately 80% of all Swiss buildings with an insured value of around 1.5 billion Swiss Francs. Within the individual canton, each insurer operates as a monopolist regulated by public law. Apart from the insurance policies, the business segments include loss prevention and risk management. In this context, cantonal insurers perform a sovereign function, consulting municipalities in all concerns on building permits and spatial planning activities.

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