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Temporal variability of damage potential in settlements – A contribution towards the long-term development of avalanche risk

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ABSTRACT: Recent studies on the avalanche risk in alpine settlements suggested a strong dependency of the development of risk on variations in damage potential. Based on these findings, analyses on probable maximum losses in avalanche-prone areas of the municipality of Davos (CH) were used as an indicator for the long-term development of values at risk. Even if the results were subject to significant uncertainties, they underlined the dependency of today's risk on the historical development of land-use: Small changes in the lateral extent of endangered areas had a considerable impact on the exposure of values. In a second step, temporal variations in damage potential between 1950 and 2000 were compared in two different study areas representing typical alpine socio-economic development patterns. The resulting trends were found to be similar, the damage potential increased significantly in number and value. Thus, the development of risk in settlements can for a major part be attributed to long-term shifts in damage potential.

1 INTRODUCTION

During the last decades, compensations for damage paid out by insurance companies due to harms resulting from natural hazards increased world-wide (e.g. MunichRe 2005). A similar trend could be observed in alpine countries on a regional level, recent examples affecting settlements and threatening traffic lines include the avalanche winter 1999 and the inundations in 1999, 2000 and 2002. This development illustrates the need for a sound, precautionary and sustainable dealing with natural hazard phenomena, taking into consideration the processes and the values at risk.

Risk resulting from natural hazards is defined as a function of the probability of a hazard process and the related extent of damage (Eq. 1). In accordance with the definition of United Nations (2004), specifications for the probability of the defined scenario (p_{Si}), the value of the object affected by this scenario (A_{Oj}), the probability of exposure of object j to scenario i ($p_{Oj,\,Si}$), and the vulnerability of object j in dependence on scenario i ($v_{Oj,\,Si}$) are required for the quantification of risk ($R_{i,\,j}$).

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

However, until now, there have only been few studies related to the development of risk resulting from natural hazard processes over time (Wilhelm 1997, Fuchs et al. 2004, Zischg et al. 2005). An increased use of hazard-prone areas for settlement and infrastructure has been assumed to be responsible for an increased risk and resulting losses during periods of high hazard activity (see e.g. Ammann 2001, Barbolini et al. 2002), particularly concerning avalanche hazards. Since (1) the natural avalanche activity seemed to be constant during the last 50 years (Laternser & Schneebeli 2002) and (2) the avalanche run-out areas were reduced due to the construction of permanent mitigation structures in the release areas, this assumption could be explained by (3) long-term shifts in the damage potential. Analysing this assumption within a field study in the municipality of Davos (CH), Fuchs et al. (2004) conclude that in general, the risk resulting from avalanche hazards decreased fundamentally since 1950. However, high ranges occurred during the sets of calculation. Small variations in the run-out lengths of the avalanche scenarios resulted in high scattering in the risk analyses, which provides evidence for the particular influence of the damage potential on the quantification of risk.

The objective of this study is to highlight these ranges and to contribute to a discussion focusing on the significance of damage potential when carrying out long-term risk analyses related to natural hazards. The spatial sensitivity of the results is discussed. The results from the case study in the municipality of Davos (CH) are compared to a similar study carried out in the municipality of Galtür (A). Both municipalities represent typical alpine villages dependent on winter tourism, thus, the results mirror recent developments in damage potential in alpine destinations.

The municipality of Davos is the largest municipality in the canton of Grisons in Switzerland (Fig. 1) and covers an area of 254 km^2. In 2000, approximately 13,000 inhabitants lived in Davos,

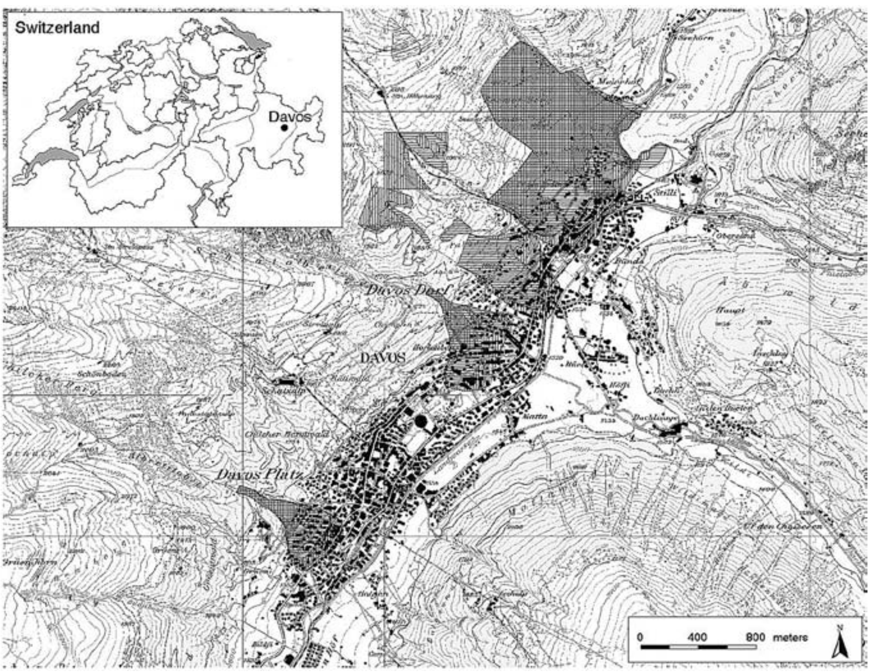

Figure 1. Study area within the municipality of Davos, Switzerland. The hatched grid shows the avalanche run-out areas (scenario$_{1950}$). Cross hatching represents the red hazard zone (30-year scenario), lined hatching the blue hazard zone (300-year scenario), and the continuous line the yellow hazard zone (area of powder snow avalanches), for explanations, see footnote 1. Reproduced with permission of Swiss Federal Office of Topography (BA057068).

and up to 45,000 tourists were present during winter time (BfS 2001). The altitude of the city centre is situated at 1560 m a.s.l., which illustrates its susceptibility to avalanche hazards. The centre of Davos is exposed to four main avalanche paths which are almost completely equipped with snow supporting structures in the release areas.

The municipality of Galtür is located 50 kilometres north-east of Davos in Tyrol, Austria, at an altitude of 1580 m a.s.l. The municipality covers an area of 121 km^2 and 770 inhabitants lived there in the year 2000 (Landesstatistik Tirol 2004). During winter time, up to 4000 additional persons were counted living in the hotels and guest houses of the village. Galtür is endangered by 26 avalanche paths, nine of which are equipped with defence structures in the starting zone. Major avalanche dams protecting the centre of Galtür were constructed after the avalanche event of 1999.

2 DEVELOPMENT OF PROBABLE MAXIMUM LOSS

This study aims to contribute to the discussion on development of risk over time. It focuses on the relative comparison of different system conditions resulting from socio-economic changes in alpine environments. The probable maximum loss (PML) resulting from avalanches in the year 1950 was compared to the remaining PML in 2000, considering technical mitigation measures implemented during the same period. Thus, according to Equation 1, data related to the process and to the values at risk were needed.

2.1 *Methods*

Changes in the extent of the avalanche accumulation areas were studied using the numerical avalanche model AVAL-1D (e.g. Christen et al. 2002a) in combination with the avalanche incident cadastre of former events. AVAL-1D is a one-dimensional avalanche dynamics program for the prediction of run-out distances, flow velocities and impact pressure of both dense flow and powder snow avalanches. The dense flow simulation is based on a Voellmy-fluid flow law, while the powder snow simulation follows Norem's description of powder flow avalanche formation and structure (Norem 1995). The avalanche calculation is based on a dry-Coulomb type friction (μ) and a velocity squared friction (ξ) and was carried out following the guidelines given in the manual (Christen et al. 2002b). The fracture depths were obtained using Gumbel's extreme value statistics on the possible maximum new snow heights within three days. The input parameters were calibrated on the basis of the legal hazard map.

The values at risk were obtained analysing the zoning plan, which was provided by the municipal administration of Davos. This plan contains detailed information about the location and perimeter of every building. Additional information, such as year of construction, type and replacement value were provided by the land registry office and analysed using GIS. The number of endangered permanent residents was derived from 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 exposed persons in hotels, guest houses and hospitals was quantified by the number of beds, multiplied by the degree of utilisation. To account for the employees working in hotels and hospitals the number of beds was increased by 20% (Davos Tourist Board 2002, pers. comm.) and 70% (BfS 2002), respectively.

The vulnerability of buildings and persons as well as their probability of presence was considered in terms of PML, which traces back to actuarial procedures and is the largest potentially assumable loss. Following these ideas, the total avalanche run-out areas were considered when calculating the values at risk. The cumulative PML for the areas endangered by avalanches in the year 1950 was compared to the year 2000: First, the values at risk were quantified for the year 1950. Second, the values at risk for the year 2000 were calculated under consideration of a reduction of the run-out areas due to the construction of permanent mitigation structures, such as snow fences in the avalanche starting zones. The development of PML resulted from the comparison between the initial state in the year 1950 and the state in the year 2000, including the aggregation and expansion of values at risk during the same period.

The modelling of avalanche scenarios is affected by uncertainties resulting from model parameters on the one hand and from input parameters on the other hand. Following a suggestion outlined in Barbolini et al. (2002), the range resulting from those uncertainties was calculated on the basis of a confidence interval of 95%. Thus, as an example, the 30-year event was calculated with a range in the run-out length of ±20 m, and the 300-year event with a range of ±30 m.

2.2 *Results*

Based on the methods outlined above, the PML in areas affected by avalanches was determined for the municipality of Davos. The result section focuses on the relatively frequent event of a 30-year avalanche scenario and the relatively rare event of a 300-year avalanche scenario because these scenarios represent the outline of the red and blue hazard zone in Switzerland[1] and they represent the typical problems when dealing with design events in the area of risk analyses resulting from alpine hazards. Thus, emerging problems could be well demonstrated.

In the year 1950, 83 buildings with a total replacement value of approximately €107.6 million had been located inside the run-out areas affected by a 30-year avalanche scenario (Fig. 2). In the year 2000, 33 buildings with a replacement value of €19.3 million were situated inside the area affected by a 30-year avalanche, which is nearly 40% in number and 18% in value of the 1950s calculation. The endangered residential population amounted to 591 persons living in the area of a 30-year avalanche run-out zone in 1950. In 2000, in consequence of the construction of permanent mitigation measures, 87 residents remained exposed, which is an 85% reduction of PML. However, the range of these results was considerable: Inside the areas of a 30-year avalanche event, the number of buildings scattered almost 25% in number and value for the scenario 1950 and 50% for the scenario 2000. Concerning residential population, the values ranged from ±20% for the scenario 1950 to a remarkable factor of around 450% for the scenario 2000. Generally, the PML inside areas affected by a 30-year avalanche decreased regarding the exact values as well as the minimum and maximum values for the number and value of endangered buildings and for the number of affected persons. Compared to the results of the 300-year avalanche scenario, those values were relatively small.

Inside areas affected by the 300-year avalanche scenarios, a total of 161 buildings with a replacement value of almost €240 million were located in the year 1950 (Fig.2). In the year 2000, an

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[1] It is the responsibility of the Swiss cantons to protect people's life and property from natural hazards such as avalanches, landslides, erosion and rockfall in accordance with the Federal Law of 22nd June 1979 relating to land-use planning. Further implementation instructions result from the appropriate articles in the Federal Law of 4th October 1991 relating to forests and the Federal Law of 21st June 1991 relating to hydraulic engineering. According to these laws and associated decrees, the appropriate specialised offices of the federal authorities have to compile guidelines to encourage the consideration of natural hazards in land-use planning. The principles for general planning issues are published in Heinimann et al. (1998), whereas the *Guidelines for the Consideration of the Avalanche Danger in Land-Use Planning Activities* have been approved in 1984 (BFF & SLF 1984). These guidelines describe the two main instruments for the inclusion of avalanche dnager in land-use planning, namely avalanche incident documentation and the avalanche hazard map. This hazard map divides an examined area into different subsections with different danger levels according to the severity and the likelihood of potential avalanche hazards (BFF & SLF 1984).

Red indicates area 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 reoccurence 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.

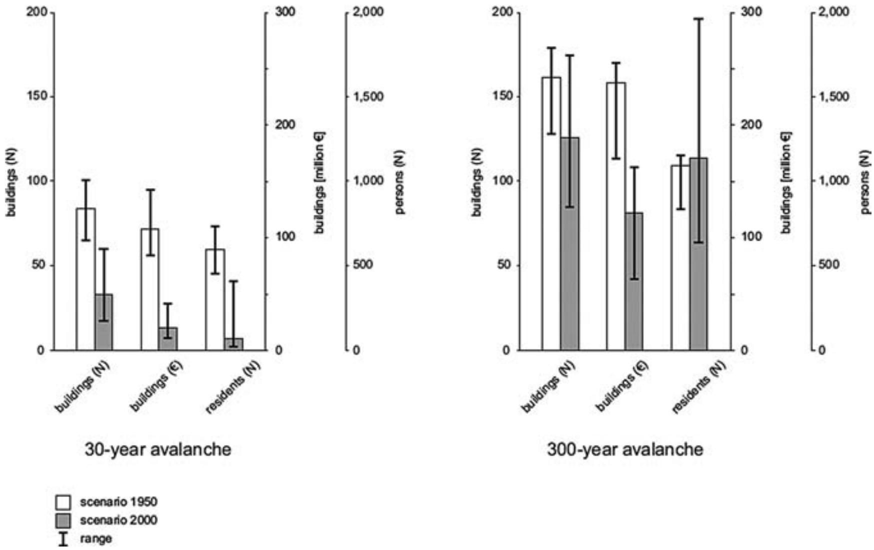

Figure 2. Scenario$_{1950}$ and scenario$_{2000}$ resulting from 30-year and 300-year avalanche events in the municipality of Davos (CH), and associated uncertainties following the suggestions outlined in Barbolini et al. (2002). For the 30-year scenario, the ranges regarding the buildings are relatively similar, while the range resulting from the residents in the year 2000 is remarkably high. For the 300-year scenario in the year 2000, the highest range occurred within the category of endangered residential population, while the lowest variations were found for the number of buildings.

amount of 125 buildings with a total value of almost €122 million remained endangered, including 28 buildings that had been constructed in the period before 1950 and 97 buildings that were constructed between 1951 and 2000. Thus, the 2000s results correspond to almost 78% in number and around 50% in value of the 1950s calculation. Inside the areas of the 300-year avalanche scenarios, 1098 residents lived in the year 1950. In the year 2000, this value increased slightly to 1137 persons. In comparison to the areas affected by the 30-year avalanche scenarios, the range – in absolute numbers – is significantly higher. Regarding the 300-year avalanche events, the values of the scenario 2000 scattered remarkably higher than those of the scenario 1950. The highest range was found in the category of residents for the scenario 2000, were the number ranged from 636 to 1971 persons. Particularly in the category of residential population it became evident that the range of the scenarios was higher than the difference between the scenario 1950 and the scenario 2000.

Regarding temporal population in hotels, guest houses and hospitals, the 1950s scenario of the 300-year avalanche events included 1041 guest beds in accommodation facilities and 1851 beds in hospitals. Applying an average rate of utilisation of 60% (Davos Tourist Board 2002, pers. comm.) to hotels and 83.7% to hospitals (Kurverein Davos 1951), 625 guests in accommodation facilities and 1550 patients in hospitals remained vulnerable. Including labour force, these numbers account to 750 persons and 2590 persons, respectively. In the year 2000, 81 guests remained in the category of hotels and guest houses. Assuming an utilisation of 60% during the winter season and including employees, 59 persons were endangered. Hospitals were no longer endangered.

2.3 *Conclusions*

In the previous sections, the development of PML between 1950 and 2000 was presented for the municipality of Davos (CH). Based on the assumptions outlined in the methods section, the PML decreased remarkably for both, areas affected by 30-year avalanches and areas affected by 300-year avalanches. The sole exception was in the category of residents within the 300-year scenario, where an increase in PML was verifiable. The associated range was considerable, resulting from a dense utilisation of development land in the studied area. Small variations in the extent of the accumulation areas (± 20 m for the 30-year avalanche events and ± 30 m for the 300-year avalanche events) demonstrated a significant importance of the temporal and spatial analysis of values at risk.

The investigation provides specific information regarding the development of avalanche risk in the municipality of Davos (CH), based on analyses of PML. General statements referring to a larger area (canton, country) might be difficult to deduce, since small-scale land-use disparities have a significant influence on the diversification of risk. The spatial distribution of damage potential is substantially influenced by the historical growth of settlements on the one hand and spatial planning issues on the other hand. When analysing the development plan, this could be proven by relatively larger buildings downwards the slope and smaller buildings upwards the slope, representing the respective buildings codes and the underlying admissible floor space indices.

In addition to the described range of the results from the analyses on PML, several inherent uncertainties regarding the application of the risk equation (Eq. 1) should be considered when analysing risk over time:

(1) Regarding the probability of presence ($p_{Oj,\,Si}$) of endangered persons, the question is how to determine their number at the specific time of occurrence of an avalanche event. The permanent residential population could be empirically determined using the average number of persons per domicile. The temporally variable number of persons in hotels and hospitals could be approximated using the number of beds and the corresponding average utilisation. Concerning infrastructure facilities, such as buildings of the public sector or cable car stations, such statistics are for the most part not available. Thus, high uncertainties should be taken into consideration when assessing the probability of presence of endangered persons, or the calculation should be a priori carried out using a value in terms of an upper limit. Furthermore, the spatial probability of presence is subject to considerable temporal changes, as presented by Keiler et al. (2005).
(2) Further uncertainties are connected to the vulnerability factor ($v_{Oj,\,Si}$). Concerning the vulnerability of buildings towards the impacts of avalanches, consolidated findings allowing for a spatial application are still missing (IUGS 1997, Jónasson et al. 1999, Keylock & Barbolini 2001). Assumptions, as for example presented in Wilhelm (1997), can only partly contribute to this problem. Future research is needed to obtain significant empirical data on the relevant parameters for the determination of the vulnerability of buildings.
(3) Moreover, future research concerning the behaviour of avalanches in the accumulation areas is needed, especially related to the structure of buildings. Buildings can have similar effects on avalanches as avalanche retarding mounds. Due to a shift in the building pattern within the accumulation area, buildings oriented towards the valley bottom tend to result in smaller risk than buildings that are located closer towards the transit area. Independently from the related political implications and the associated impacts on land-use planning, further investigations on this effect should be carried out, because of the probable reduction of the accumulation areas and, as a consequence, the resulting risk.

Independent from these methodical restrictions resulting from application of the risk equation (Eq. 1), trends arising from the shifts in damage potential should be taken into consideration, leading to an enhanced understanding of the long-term development of risk in settlements.

3 DEVELOPMENT OF DAMAGE POTENTIAL

Apart from today's land-use regulations and the associated legal fundamentals, land utilisation and building development is based on historical settlement growth and resulting land-use patterns. For this reason, detailed studies on the spatial distribution of values at risk are major issues in dealing with risk, particularly for tourism-dependent municipalities, as stated in Keiler (2004) for the municipality of Galtür (A) and Fuchs & Bründl (2005) for the municipality of Davos (CH). However, only few approaches and conceptual proposals describe the determination of damage potential, focusing more on fatalities and direct damage cost of specific events than on methodological issues. Related to settlements, early studies by Björnsson (1980) and more recent studies by Glade & Crozier (1996), Jóhannesson & Arnalds (2001), Stethem et al. (2003), Kleist et al. (2004) and Merz et al. (2004), have to be mentioned.

Due to the lack of comparative studies, additional analyses concerning the temporal development of damage potential have been carried out in the municipality of Galtür (Keiler 2004). Results from both of the municipalities based on areas affected by avalanches are presented in the following sections. Focusing on emerging trends in the development of damage potential, the comparative study deliberately neglects different legal land-use and planning regulations in the two alpine countries.

3.1 *Values at risk in Davos*

The number and value of buildings in the studied area rose considerably between 1950 and 2000 (Fig. 3). The total number of buildings has almost tripled, from 161 in 1950 to 462 in 2000. This increase was due to the shift from 51 to 256 in the category of residential buildings, while in the other categories of buildings the number of buildings was approximately unchanging. A significant increase in number dated back in the 1960s and 1970s before the legally hazard map came into force (Fuchs & Bründl 2005).

The total value of buildings increased by a factor of almost four. In 1950, the total sum of insured buildings was € 240 million and in 2000, the total sum was € 930 million. In 1950, the proportion of residential buildings was less than 15%, compared to the total amount of endangered buildings. Until 2000, this ratio changed to almost 50%. Regarding the category of hotels and guest houses as well as the category of special risks, nearly no increase in value could be observed. However, those categories showed a higher average value per building than residential buildings.

The number of endangered persons increased slightly. In 1950, a permanent residential population of 1098 persons was exposed to avalanche hazards, until 2000 this value increased to 1137 persons. This is a relatively moderate increase of 3.6%, compared to the increase in tangible assets. If the classification into different building functions is carried out, this increase turned out to be larger. In residential buildings, 673 persons were concerned in 1950 and 1116 in 2000, which is an increase of two thirds. 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 Swiss Federal Institute of Snow and Avalanche Research SLF, these periods coincided exactly with periods when there was an above-average occurrence of days with high avalanche danger. As a result, temporal risk peaks may possibly arise, as described in Fuchs et al. (2004).

3.2 *Values at risk in Galtür*

The values at risk were determined based on methods outlined in Keiler (2004). The total number of buildings inside avalanche-prone areas in the municipality of Galtür rose by a factor of 2.5 (Fig. 3), from 41 in 1950 to 108 in 2000. This increase is due to the relative development in the category of hotels and guest houses, and – obviously less important – in the category of agricultural buildings. The number of buildings in all other categories stayed nearly constant. The decrease in the number of residential buildings since 1980 resulted from a modification of buildings formerly used for habitation to accommodation facilities subsequently used for tourism.

The total value of buildings rose by a factor of almost six. In 1950, the total value of buildings amounted to € 12 million and in 2000 to € 64 million. Since the 1960s, the category of hotels and guest houses held the highest proportion of the total amount of endangered values per decade and per category. In 1950, the proportion of hotels and guest houses was about 30%, compared to the total value of buildings. In 2000, this ratio changed to approximately 75%. In contrast, the number and value of residential buildings showed nearly no change between 1950 and 2000. Generally, the

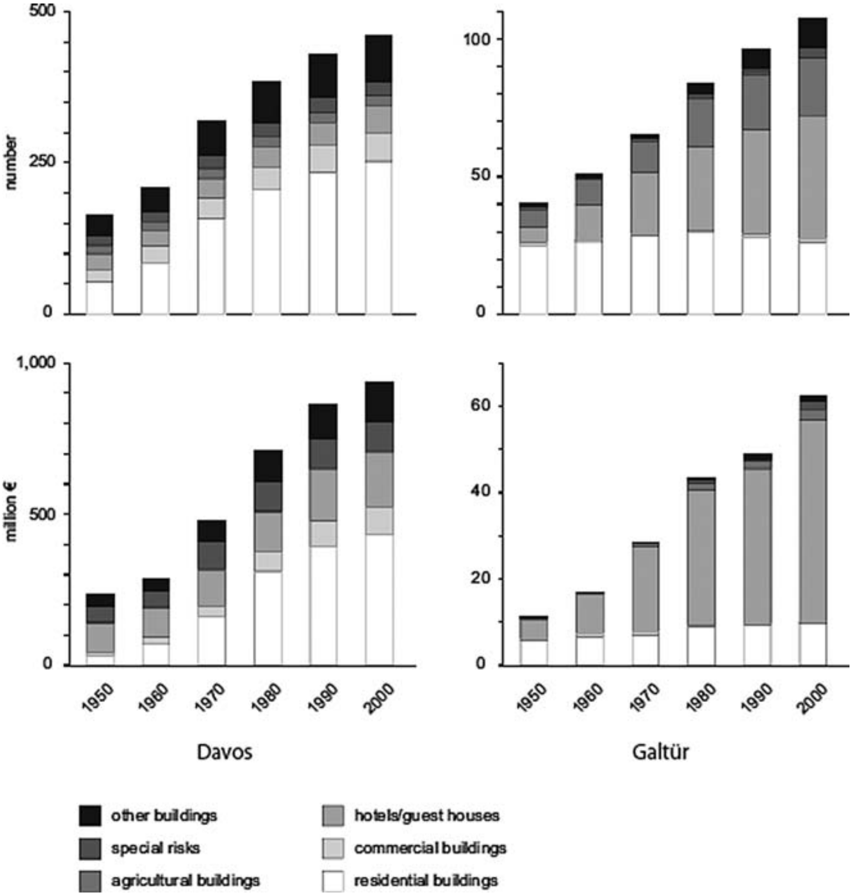

Figure 3. Development of damage potential in Davos (CH) and Galtür (A) related to the respective avalanche-prone areas, subdivided in decades and building functions.

number of buildings in the community of Galtür has risen above average in comparison to the district of Landeck and the federal state of Tyrol. In 2000, a quarter of the total value of all buildings in the municipality was found to be located in the avalanche-prone areas. The proportional increase in the value of buildings was significantly higher than the proportional increase in the number of buildings. Buildings inside avalanche-prone areas showed a lower average value as buildings outside those areas. These findings were in accordance to similar results for the community of Davos.

The number of endangered persons increased substantially. In Galtür, in 1950, approximately 850 persons were located inside exposed areas, consisting of 460 residents and 390 tourists. Until the year 2000, this value increased to 4700 persons, 770 of which were residents and 3930 were tourists. The increase in residential population was about 60%, while the increase in temporal population was a factor of ten. Thus, considerable diurnal risk peaks might occur, as presented in Keiler et al. (2005).

3.3 *Conclusions*

The results of an analysis of damage potential in Davos (CH) and Galtür (A) suggested a similar trend, even if the community of Galtür and the community of Davos have different historical roots. Both municipalities have undergone significant socio-economic changes during the 20th century. While Davos was transformed into a winter sports destination from a traditional health resort, Galtür developed from a farming village to a centre of sustainable winter tourism. Since 1950, a significant change in the number and value of buildings has taken place in both studied municipalities, and, as a consequence, a remarkable increase was detectable in residential and temporal population. Endangered areas were increasingly protected by technical mitigation measures since the 1950s (Davos) and 1960s (Galtür). Parallel to those technical tools, spatial planning instruments were introduced.

In Davos, the increase in damage potential was caused by a significant increase in the category of residential buildings, while in Galtür this increase could mainly be attributed to an increase in accommodation facilities. These results can be attributed to (1) the different socio-economic development of the municipalities and (2) the different legal situations in Switzerland and Austria. While in Austria, the construction of secondary residences was restricted by law until the late 1990s, no such restrictions could be found in the canton of Grisons, Switzerland. In both municipalities, the highest increase in number and value was spatially located at the outer boundary of the endangered areas. These findings are also represented by the high range shown in Figure 2 for the municipality of Davos. Thus, relatively small variations in the lateral extent of the areas affected by avalanches have a high impact on the values at risk. For this reason, a possible improvement in the delimitation of areas affected by natural hazard processes regarding a decrease of objects at risk could possibly be implemented using a fringe instead of a line.

4 DISCUSSION

Temporal changes in risk can primarily be attributed to the outlined spatiotemporal variations in damage potential. The analysis of tangible assets as well as intangibles is a quantitative procedure for comparative studies in different regions and for different hazard processes. Thus, risk analyses should consider those alternations by expanding the today's procedures by appropriate methodical approaches as well as practical implementations.

The long-term trend in the development of damage potential described above is superposed by a short-term fluctuation resulting from diurnal peaks in values at risk, particularly consisting of persons commuting to and from tourist destinations. The combination of those two phenomena should be carefully observed and integrated in the methodology of risk analyses, as shown by Keiler et al. (2005) for the community of Galtür. Similar problems related to road networks are discussed in Margreth et al. (2003) and Zischg et al. (2005). In dealing with natural hazards in a proactive manner, this aspect should be strengthened and incorporated into the respective legal fundamentals.

Since the presented development of values at risk is based on the utilisation of formerly endangered areas for settlement, a continuing maintenance of technical mitigation measures is indispensable. Otherwise, their protective effect will be lost, which would result in a remarkable increase in endangered values and persons, and consequently in risk.

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