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Risk evolution in debris flow prone areas from 1950 - 2014 – two case studies conducted in Lai-Ji (来吉村), Taiwan, and Sörenberg, Switzerland

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Extended Abstract

INTRODUCTION

In the last decades the number of natural disasters has considerably increased worldwide. In recent literature it is widely accepted that human activity plays a key role for this development (e.g. Field et al. 2012, Fuchs & Keiler 2013). This induced that the concept of risk has become the common approach to assess the impact of natural hazards on settlement areas (Fuchs 2004). In the European Alps debris flows belong to the most dangerous and most damage-effective natural processes. Within the last decades the increasing temperatures caused by climate change led to permafrost thawing and changed the basic disposition in many alpine areas (Keiler et al. 2010, Zimmermann et al. 1997). The analysis of debris flows risk evolution is thus an important issue in mountain areas. However, few studies exist which focus on risk evolution over time based on a multi-temporal risk analysis (Fuchs et al. 2004, Keiler et al. 2006, Schwendtner et al. 2013) whereof only one study in Martell, Italy, analysed the evolution of debris flow risk (Schwendtner et al. 2013). Furthermore, low information is available on the development of the risk parameters and its impacts on risk evolution although different authors have emphasized that every risk parameter shows its own dynamics in time and space with increasing complexity between the different parameters (Bründl et al. 2010, Fuchs & Keiler 2013). In this study, the risk evolution and the development of the risk parameters have been analysed in two case studies in Lai-Ji, Taiwan, and Sörenberg, Switzerland from 1950 to 2014 (Fischer 2014).

In terms of natural hazards, risk can mathematically be defined as $R_{i,j} = f\,(p_{Si}, A_{Oj}, v_{Oj,Si}, p_{Oj,Si})$ whereas risk is a function of the probability of occurrence of the hazard scenario i (p_{Si}), the value of object j at risk (A_{oj}), the vulnerability of object j in dependence on scenario i ($v_{Oj,Si}$) and of the probability of exposure of object j in scenario i ($p_{Oj,Si}$) for the risk to object j in scenario I (e.g. Fuchs & Keiler 2013, Hübl et al. 2009). Although it has been emphasized that the importance of vulnerability analyses has grown due to global environmental change and socio-economic changes (Papathoma-Köhle et al. 2012a) there is still no standard methodology to assess the physical vulnerability (Papathoma-Köhle et al. 2011). In this study, vulnerability has been defined according to Fell et al. (2008: 86): „The degree of loss to a given element or set of elements within the area affected by the landslide. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property."

CASE STUDY SITES

Lai-Ji (來吉村) is a small village consisting of four settlements in central Taiwan (Figure 1). It is located in Alishan township, Chiayi county in the Taiwanese mountains. Natural hazards are ever-present as the island lies in a highly active earthquake zone. The ChiChi earthquake in 1999 with a moment magnitude of Mw 7.6 and the following typhoons induced many landslides and debris flows on the island (Chiou et al. 2007, Shou et al. 2011). On 8th August 2009 the typhoon Morakot triggered a debris flow in the torrent called DF055 (debris flow torrent number 055 in Chiayi county) which hit the settlements 3 and 4 of the village. 16 buildings were destroyed and 7 other buildings were severely damaged (Zheng 2010). Within only three days, the typhoon Morakot brought a precipitation sum of 2747 mm to the Lai-Ji area (Fischer 2014). After the event, only minor mitigation measures were implemented such as small concrete channels or slope stabilisation measures (Figure 1) because the government actively promotes the resettlement of the affected households (Fischer 2014).

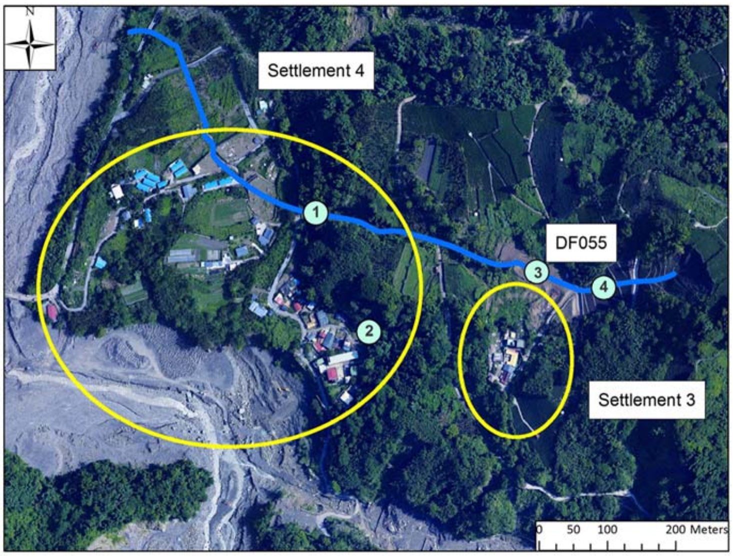


Figure 1: Investigation area and minor mitigation measures (1-4) in Lai-Ji (aerial photo from 2011; Fischer 2014).

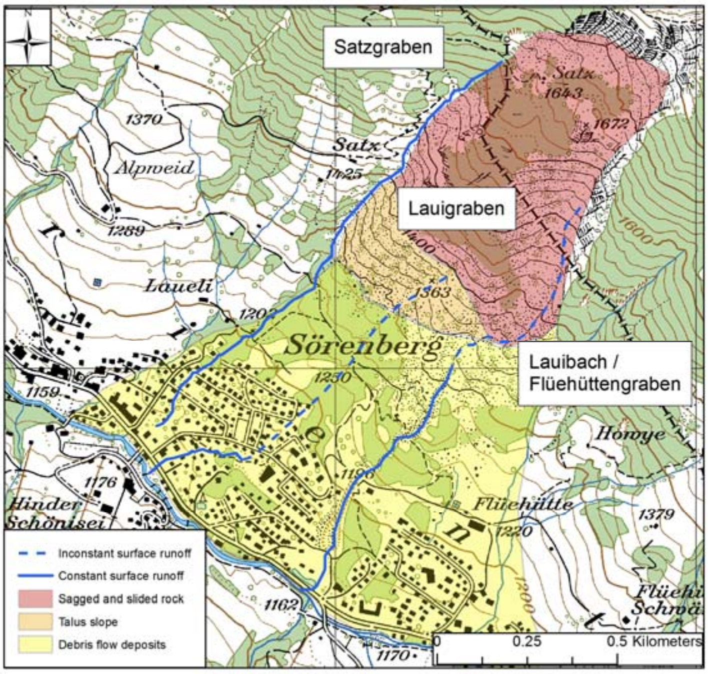


Figure 2: Investigation area in the Laui, Sörenberg (Fischer 2014).

Sörenberg is a small tourist resort in the Swiss Prealps in the canton of Lucerne (Zimmermann 2006). A building boom started in the 1960s in the settlements Laui and Flüehütte which lie on an ancient debris fan. The slopes above the settlements belong to a deep-seated sagging (red in Figure 2; investigation area subdivided after Manser (1991)) which affects the three torrents Satzgraben, Lauigraben and Lauibach / Flüehüttengraben. Six landslide events with subsequent debris flows occurred in the 20th century whereas the last one was on 14th May 1999 (Holliger 2002, Zimmermann

2006). After long rain periods a slide of approximately 250'000 m^3 loosened rock was released from the sagging mass and flowed several hundred meters downhill (Zimmermann 2004). 20 debris flows developed out of the deposited slide mass within several months but did only cause minor damages in the settlement area (Zimmermann 2006). Nevertheless, extensive protection measures were taken including a contingency plan and structural measures with two debris collectors in the Satzgraben, a debris collector in the Lauigraben and protection dams in all three torrents which were completed in autumn 2014 (Fischer 2014).

METHODS

Similar to recently conducted risk evolution analyses (e.g. Schwendtner et al. 2013) a quantitative multi-temporal risk approach has been applied which consists of four work steps: the hazard analysis, the analysis of elements at risk, the vulnerability analysis and the risk calculation. Each analysis has been conducted for multiple time steps whereas study site specific methodologies have been applied.

Hazard analysis

The goal of the hazard analysis was the definition of plausible debris flow scenarios and the generating of intensity maps which can be created through modelling (e.g. Fuchs et al. 2004, Keiler et al. 2006) or the reconstruction of an occurred event based on photographic documentation (Papathoma-Köhle et al. 2012b, Schwendtner et al. 2013). In Lai-Ji, one hazard scenario has been generated based on a reconstruction of the event in 2009 on the basis of photos and aerial photos. In Sörenberg, eight hazard scenarios have been modelled with RAMMS debris flow (Christen et al. 2012). The definition of bed load scenarios with a recurrence interval of 100 years for the three torrents Satzgraben, Lauigraben and the Lauibach / Flüehüttenbach by the canton of Lucerne have been used as input data (Fischer 2014). The bed load volumes were modelled for each torrent with and without the recently implemented structural mitigation measures as well as for a combined scenario of all three torrents. The probability of the applied scenarios was neglected in the risk analysis as the application of magnitude-frequency relationships for debris flows have been criticized recently (Keiler & Fuchs 2014).

Analysis of elements at risk

The analysis of elements at risk focused on physical economic damage to building structures expressed in New Taiwanese Dollars (TWD) in Lai-Ji and in Swiss Francs (CHF) in Switzerland. In Lai-Ji, the building structure values were calculated by using the average structure unit costs in TWD / m^2 for different building structure materials and building types of the Taiwanese Chiayi county (Taiwan Architects Association 2007, Fischer 2014). Due to poor data availability the elements at risk were only determined for the three time steps 1970, 2009 and 2012, based on aerial photos and a field survey. In contrast, cantonal building insurance data were used for the determination of the building structure values in Sörenberg in the time steps 1950, 1960, 1970, 1980, 1990, 2000 and 2014.

Vulnerability analysis

The vulnerability analysis has been conducted quantitatively. The standardized methodology to develop a site specific vulnerability curve based on the documentation of a past event by Papathoma-Köhle et al. (2012a) was however not applicable in any of the two case studies. While no information are available on economic damages of the debris flow event in 2009 in Lai-Ji, the last debris flows in Sörenberg did only cause minor damages. In the Swiss case study an empirical vulnerability function (equation 1) which has been developed by Papathoma-Köhle et al. (2012b) based on different case studies in the South Tyrol, Italy, has been applied instead. This vulnerability curve describes the vulnerability (V) as the ratio of the intensity (I) expressed as deposition height to the degree of loss.

$$V = 1 - e^{-1.528(\frac{I+2.432}{2.432}-1)^{2.285}} \quad (1)$$

However, this function is not transferable to Taiwan because the construction styles differ considerably. As there are no empirical data on intensity-damage ratios available in Taiwan, physically calculated fragility curves have been applied for different Taiwanese building structure materials (Fischer 2014). These fragility curves differ reinforced brick and reinforced concrete (equation 2), brick (equation 3) and wood and sheet metal buildings (equation 4).

$$f_{bldg}(h) = \begin{cases} 0, if\ h = 0 \\ 0.0169 * h^3 + 0.0236 * h^2 + 0.0032 * h + 0.0249, if\ 0\ m < h < 3.5 \\ 1, if\ h \geq 3.5\ m \end{cases} \quad (2)$$

$$f_{bldg}(h) = \begin{cases} 0, if\ h = 0 \\ 0.0158 * h^3 - 0.0051 * h^2 + 0.1167 * h + 0.0133, if\ 0m < h < 3.5\ m \\ 1, if\ h \geq 3.5\ m \end{cases} \quad (3)$$

$$f_{bldg}(h) = \begin{cases} 0, if\ h = 0 \\ -0.8889 * h^3 + 2 * h^2 - 0.1111 * h, if\ 0m < h < 1.0\ m \\ 1, if\ h \geq 1.0\ m \end{cases} \quad (4)$$

whereas: f_{bldg} = fragility / vulnerability of the investigated building
h = inundation height

Risk calculation

As the probability of the hazard scenarios are neglected in this study and the probability of presence of building structures can be set to 1, the risk of a building in a specific scenario is calculated as the product of the building structure value and the building structure vulnerability depending on the intensity in the corresponding scenario. The risk of a scenario is thus the sum of the risk to all affected buildings.

RESULTS

Intensity maps

The reconstruction of the debris flow event of 2009 in Lai-Ji based on a photographic event documentation resulted in the intensity map in Figure 3. The map shows three different flow paths of the process. Reddish areas which indicate deposition heights between 2 and 3 meters can be detected at the edge of settlement 3 as well as at the flattening of the slope in the northern and southern parts of settlement 4. It can also be stated that major parts of the settlement 4 were hit even though the deposition height was mostly lower than 1 meter. The modelling with RAMMS debris flow in Figure 4 shows the modelled combined scenario in case of parallel events in the Satzgraben, the Lauigraben and the Lauibach / Flüehüttengraben without mitigation measures (scenario 4). In this scenario, bed load volumes of 35’000 m^3 were modelled in the Satzgraben, 25’000 m^3 in the Lauigraben and 100’000 m^3 in the Lauibach / Flüehüttengraben. This results in high maximum flow heights of up to 2 meters or higher in the upper settlement area of the Laui due to the Satzgraben and the Lauigraben, while the debris flow process in the Lauibach is slower with the consequence that almost the entire debris cone is affected but with a low intensity. The implementation of mitigation measures however effectuated that two of four scenarios do not reach the settlement area anymore (Fischer 2014). The 9 intensity maps (1 from Lai-Ji and 8 from Sörenberg) have been further used as a basis for the risk analyses.

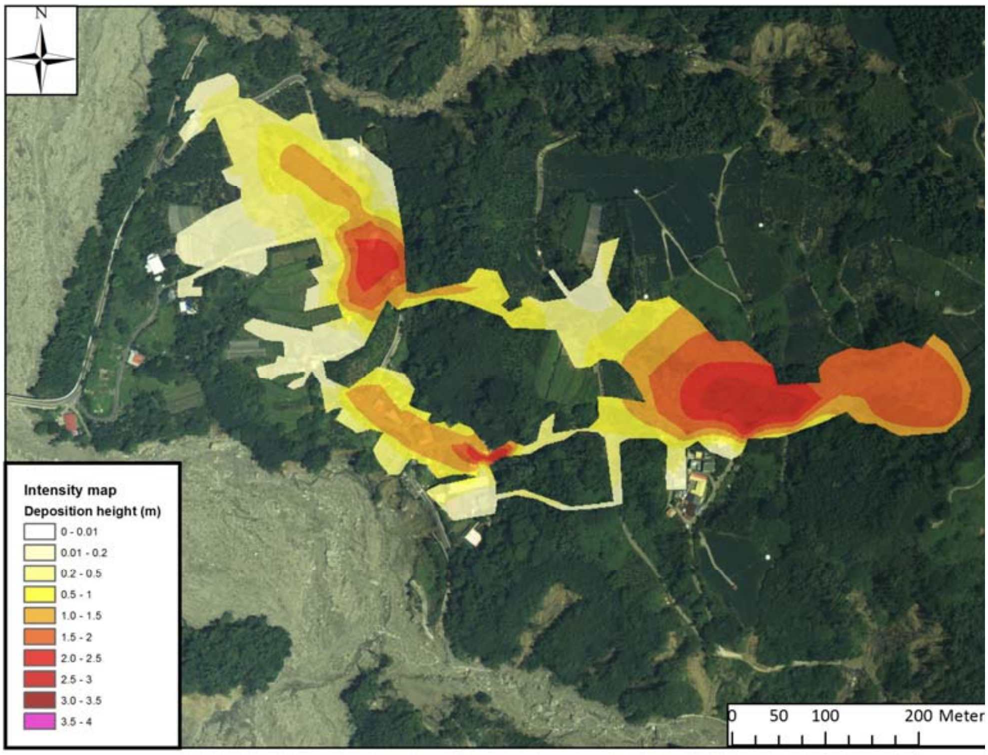


Figure 3: Intensity map of the DF055 in Lai-Ji based on photographic event documentation (Fischer 2014).

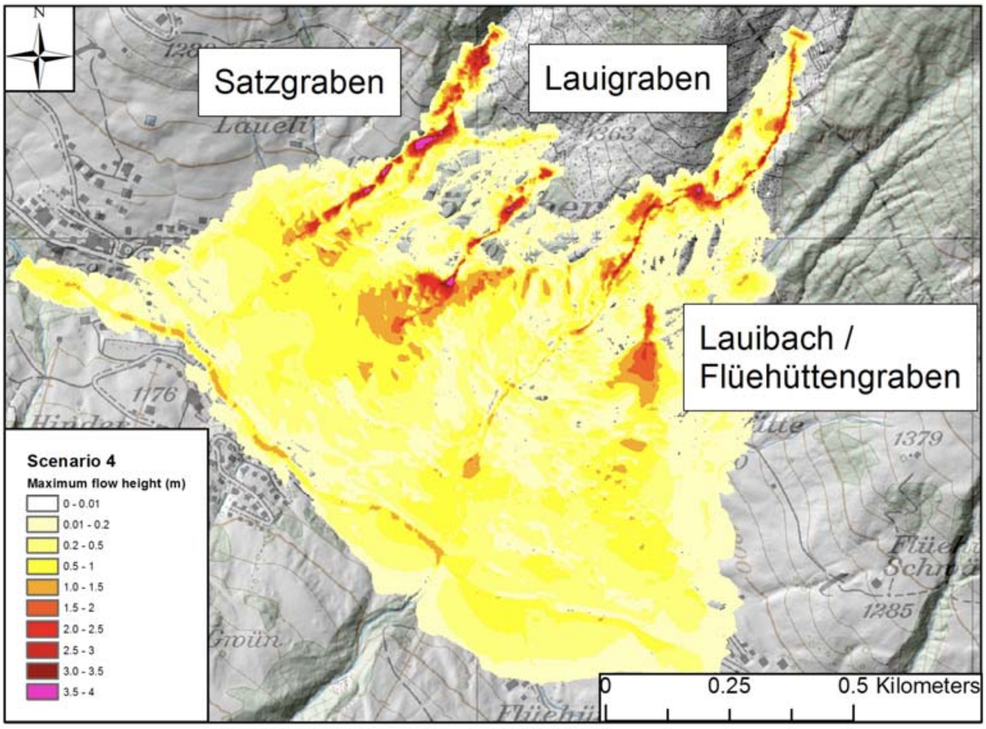
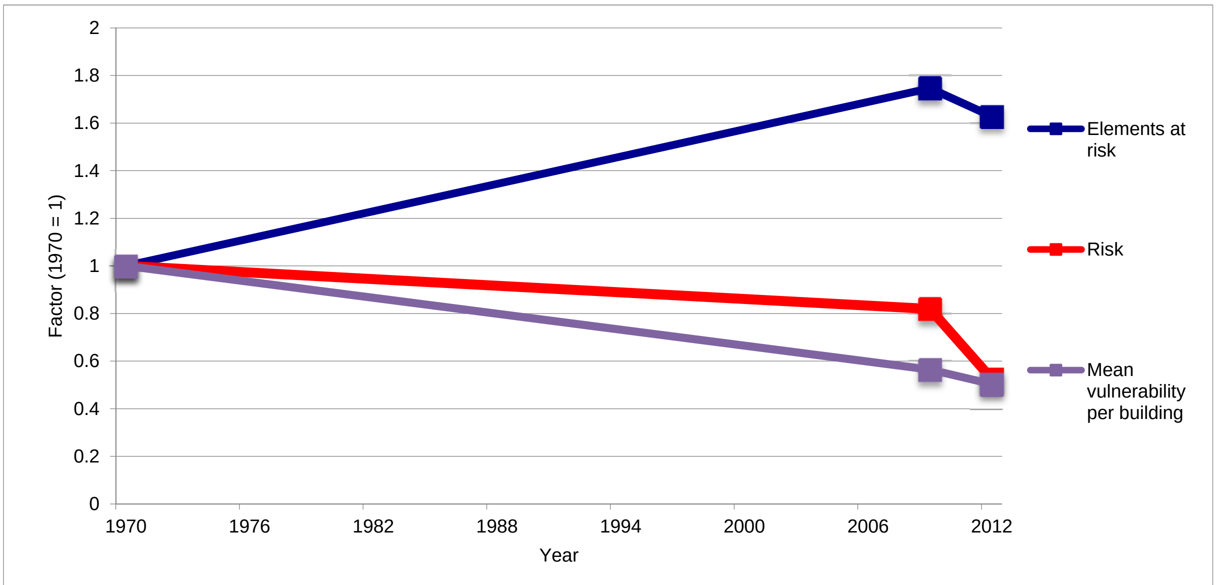


Figure 4: Intensity map of the combined scenario (scenario 4) of all three torrents in the Laui, Sörenberg, modelled with RAMMS (Fischer 2014).

Risk evolution and evolution of the risk parameters

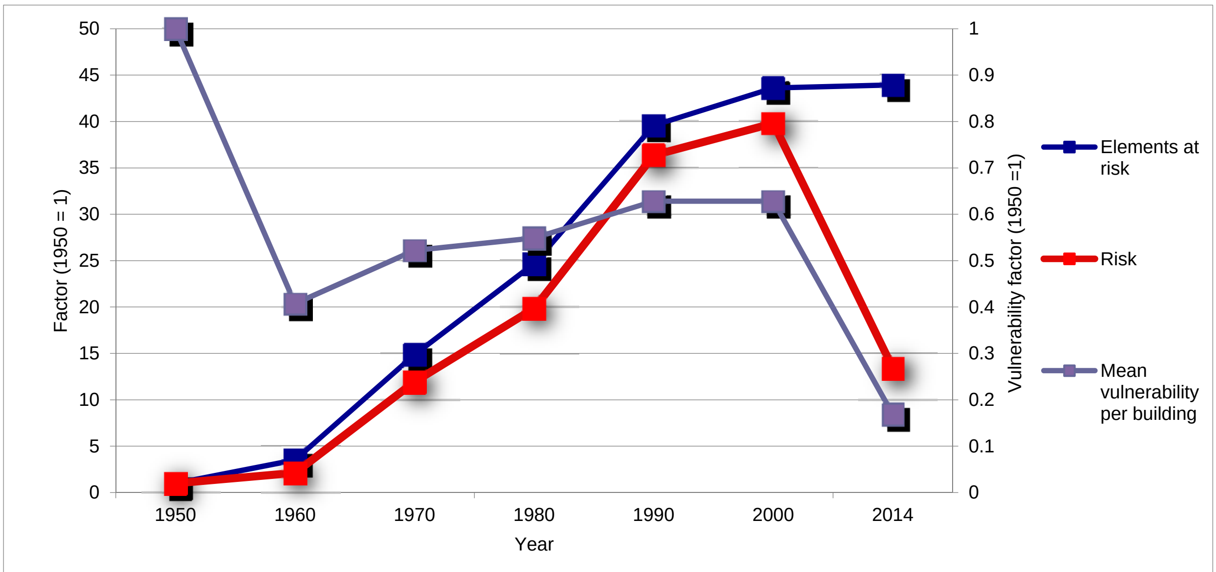
Figure 5 shows the proportional development of risk and the risk parameters in Lai-Ji from 1970 to 2012 (the values from 1970 have been used as factor 1). The blue graph indicates an increase of values at risk by the factor 1.7 until 2009 which can be reasoned with a settlement expansion in this time period. After the debris flow event in 2009, the values at risk slightly decreased because some destroyed houses were not rebuilt. In contradiction to the blue graph, the mean vulnerability per building (violet graph) decreased throughout the entire investigated time period to the factor 0.56 in 2009 and to 0.5 in 2012. This is the consequence of the settlement development which mainly took place in low intensity areas and the change of building structure materials from wood to brick, reinforced brick and reinforced concrete (Fischer 2014). Although the first mentioned reason does not risk influence the risk which indicates that the mean vulnerability per building may be misleading, the risk graph (red) also decreased in the investigated time period to the factor 0.8 in 2009. This can be explained with the change of building structures. In 2012, the risk even shortened to 0.5 but this went along with a decrease of values at risk and is thus less remarkable (Fischer 2014).



Parameter	1970	2009	2012
Elements at risk	1	**1.7**	1.6
Vulnerability	1	**0.56**	0.5
Risk factor	1	**0.8**	0.5

Figure 5: Proportional development of risk and risk parameters in Lai-Ji from 1970 to 2012 (the values of 1970 have been used as factor 1; Fischer 2014).

The proportional development of risk and the risk parameters of the combined scenario including the Satzgraben, the Lauigraben and the Lauibach / Flüehüttengraben from 1950 to 2014 in Sörenberg is illustrated in Figure 6. The blue graph indicates a building boom which reached its peak from the 1960s to the 1980s with over 100 newly built buildings in each of the three decades. The values at risk thus jumped to the factor 43.6 in 2000 and 43.9 in 2014 (Fischer 2014). The mean vulnerability per building (violet graph) decreased between 1950 and 1960 to the factor 0.41, showed then a constant increase until 2000 to 0.63 before the value considerably decreased due to the implemented mitigation measures to the factor 0.17. It has to be considered that an empirical vulnerability curve has been used in this case



Parameter	1950	1960	1970	1980	1990	2000	2014
Elements at risk	1	3.5	14.9	24.7	39.6	**43.6**	**43.9**
Vulnerability	1	0.41	0.52	0.55	0.63	**0.63**	**0.17**
Risk factor	1	2.1	11.9	20.3	37.7	**41.1**	**13.4**

Figure 6: Proportional development of risk and risk parameters in the combined scenario of all three torrents in Sörenberg from 1950 to 2014 (the values of 1950 have been used as factor 1; Fischer 2014; © Geoinformation Kanton Luzern).

study in contrast to the case study in Lai-Ji which means that tbuilding types and building structure types were not differed. The change of the vulnerability parameter is thus a direct consequence of the location of the settlement expansion. The risk graph (red) follows the blue graph from 1950 to 2000 which that the elements at risk were the risk dominant parameter in this time period, while the vulnerability parameter was risk determining between 2000 and 2014 due to the implementation of mitigation measures. Although the risk reached factor 41.1 in 2000 before it was reduced by two-thirds due to the mitigation measures, the risk of the combined scenario is in the year 2014 still 13.4 times higher than it was in 1950 (Fischer 2014).

Obviously, the risk situation has changed in both case study sites during the investigated time period from 1950 to 2014. But no general risk determining parameter could be observed and no general trend for debris flows risk evolution exists as shown in Table 1. This table includes the risk evolution of all 9 analysed scenarios. The scenarios A-D in Sörenberg included the implementation of mitigation measures between 2000 and 2014 while they were neglected in the scenarios 1-4. In Lai-Ji, only negligible measures were conducted. Table 1 thus shows four different risk evolution paths. A risk increase is likewise possible in study sites with mitigation measures (dark green) as in study sites without measures (dark red), but also risk decreases are possible with (light green) or without (light red) mitigation measures. The three observed risk evolution paths in Sörenberg are consistent with the recent literature (Fuchs et al. 2004, Keiler et al. 2006, Schwendtner et al. 2013). Study sites like Lai-Ji which show a risk decrease despite a settlement expansion in the endangered area are however rare. Empirical data are required to figure out to which extent that the change of building structure types actually influences the vulnerability and to which extent the result of this study is driven by the applied methods.

Table 1: Proportional development of the risk scenarios A-D (including mitigation measures) and 1-4 (excluding mitigation measures) in Sörenberg and Lai-Ji considering all objects at risk and the building structures only (the oldest values have been used as a basis (factor 1.0) which have been in 1950 in Sörenberg and in the 1970s in Lai-Ji; Fischer 2014; © Geoinformation Kanton Luzern).

Decade	Sörenberg scenario A	Sörenberg scenario B	Sörenberg scenario C	Sörenberg scenario D	Sörenberg scenario 1	Sörenberg scenario 2	Sörenberg scenario 3	Sörenberg scenario 4	Lai-Ji
1950s	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
1960s	2.7	3.4	2.1	2.1	2.7	3.4	2.1	2.1	
1970s	17.1	22.5	11.8	11.9	17.1	22.5	11.8	11.9	1.0
1980s	26.7	32.6	20.8	20.3	26.7	32.6	20.8	20.3	
1990s	59.8	47.7	37.3	37.7	59.8	47.7	37.3	37.7	
2000s	65.6	49.9	41.1	41.1	65.6	49.9	41.1	41.1	0.9
2010s	**0.0**	**0.0**	**14.3**	**13.4**	**65.8**	**52.7**	**50.0**	**47.5**	**0.6**

CONCLUSIONS

In this study, the current debris flow risk situation as well as former states of risk since the mid-20th century have been investigated in two debris flow prone areas in Lai-Ji, Taiwan, and Sörenberg, Switzerland, based on a multi-temporal risk analysis. In both case studies all parameters have been highly dynamic over time. The case study of Sörenberg underlines that a massive settlement expansion may lead to a considerable risk increase (of factor 13 or 14 in two scenarios) despite the implementation of mitigation measures. On the other hand shows the case study of Lai-Ji that a decent settlement expansion can be compensated by an improvement of the building vulnerability and even lead to a reduction of risk. However, it can be concluded that no general trend of risk evolution could be observed and no implicit risk determining parameter exists.

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