Nationwide assessment of the climate sensitivity of natural hazard processes in Switzerland A fuzzy logic approach

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ABSTRACT

Information about the changes that may be expected with respect to natural hazard processes is crucial to the development of climate change adaptation strategies. To assess the impacts of climate change on the magnitude and frequency of natural hazard processes, a methodology was developed, which is based on existing spatial data, literature analyses and expert knowledge and uses fuzzy logic to assess the sensitivity of natural hazard processes to changes in the climate. Evaluation rules were defined for an intermediate and an extreme climate scenario in the case of gravitational processes, avalanches, debris flows and torrent processes. The results of the study present a differentiated view of the changes to be expected as a function of the regions and processes involved. The greatest changes may be expected in the Alps. Permafrost degradation and changes in water availability result in an increase in the frequency and magnitude of rock fall. The frequency of small and medium-sized torrent processes will increase significantly for the same reason.

KEYWORDS

natural hazards; climate change; GIS; fuzzy logic

INTRODUCTION

Changes in precipitation and temperature arising from climate change can influence not only the magnitude and frequency of natural hazard processes but also their spatial distribution (Schweiz. Eidgenossenschaft 2012). However, the impacts vary according to the features of the natural landscape. Hence, the knowledge of where such changes may be expected is a central factor in the development of climate change adaptation strategies. There are many studies which analyze the impact of climate change on natural hazards whereof many refer to the Alpine region (c.f. Stoffel et al. 2013, Stoffel et al. 2014, Gobiet et al. 2014, Pavlova et al. 2014). But there are few that relate to lower areas in Switzerland. A nationwide, spatially differentiated overview about the climate change impact on natural hazards is still missing. In the context of a project on the climate sensitivity of natural hazard processes, which was commissioned by the Federal Office for the Environment (FOEN), a methodology was developed that enables the nationwide assessment of the sensitivity of natural hazard process-

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es to changes in the climate in Switzerland. The focus of this paper will be on the methodological approach. In the second part a brief overview of the results is presented.

METHODOLOGICAL APPROACH

The links between the climate and process systems on the Earth's surface are complex. The reasons for this include nonlinearities, retardation and hysteresis effects (Knight & Harrison 2013). As a result, analyzing the changes in natural hazard processes due to climate change using numerical models is very complicated and, due to the data situation, only possible for small investigation areas and individual processes. Hence an alternative methodological approach, which is described below, was selected for the project described here.

The availability of spatially resolved, comprehensive and homogeneous base data on hazard processes and their influencing parameters is a precondition for such a nationwide analysis. Such data are available in the form of the intermediate and final results of process simulations, which were carried out for all of Switzerland in the context of the development of the protective forest index maps (SilvaprotectCH) (BAFU 2008). These data cover block and rock falls, snow avalanches, shallow landslides and torrent processes (debris flows, bed load transport). However, in some instances they are encumbered by significant inaccuracies, which must be taken into account in their further use. This is possible using fuzzy logic that is based on Zadhe's fuzzy set theory (1965). Unlike the boolean logic, where a value can only belong to one class, in the fuzzy logic the classes, the so-called linguistic variables, can overlap to incorporate the fuzziness of the data. The variables are combined logically, using fuzzy rules. These rules can be derived from literature, data analysis or expert knowledge. Fuzzy logic is applied in many fields, amongst others in expert systems. Fuzzy logic based expert systems are also used for the analysis of natural hazard processes. Several examples are related to landslides (Brauner & Ganahl 1999, Regmi et al. 2010, Thiery et al. 2014) and Zischg et al. (2005) used it for assessing the risk posed to transport routes by wet snow avalanches.

For the evaluation of the climate sensitivity of natural hazard processes, the data were linked with the help of fuzzy rules. The rules were defined on the basis of literature research and expert hearings. Based on the concept of disposition (BUWAL 1998), evaluation rules are defined for each process for the basic disposition, the variable disposition and the triggering process. These rules were applied on the basis of grid data with a resolution of 10 meters for the detailed analyses over the whole of Switzerland and on the level of the 22,400 catchment areas from the division of Switzerland into catchment areas (BAFU, year not specified) for the spatial aggregation of the final results (Figure 1). This required the efficient implementation of the fuzzy analyses in the GIS environment. This was achieved by integrating Matlab's fuzzy logic tools into ArcGIS as geoprocessing tools. The calculations were then implemented as Python Script. This means that new calculations can be carried out efficiently if better base data or new insights relating to the evaluation become available.

CLIMATE SCENARIOS

Two climate scenarios, one medium and one extreme, were deduced for the sensitivity analysis from the Swiss Climate Change Scenarios CH2011 (2011). The ensembles from 10 model chains for 188 temperature stations and 565 precipitation stations were used. The A1B emissions scenario (Nakicenovic & Swart 2000) provided the basis for these scenarios. The median values for the time horizon 2060 were used for the medium scenario, and the 97.5 % percentiles for the time horizon 2085 were used for the extreme scenario. The scenarios distinguish three regions. The scenarios for seasonal temperatures and seasonal precipitation are presented in Table 1 and Table 2 respectively. In addition, scenarios for heavy precipitation were defined on the basis of the extended CH2011 scenarios (CH2011, under review), and scenarios for the snow/rain distribution for different elevation ranges were derived from transient simulations.

Table 1: Decisive seasonal temperature scenarios for medium and extreme scenario

Season	Central Plateau, Jura		Pre-Alps, Alps		South Switzerland	
	medium [Δ°C]	extreme [Δ°C]	medium [Δ°C]	extreme [Δ°C]	medium [Δ°C]	extreme [Δ°C]
DJF	+2	+3	+2	+3	+2	+4
MAM	+2	+3	+2	+3	+2	+4
JJA	+2	+5	+3	+5	+3	+5
SON	+2	+4	+2	+4	+2	+4

Table 2: Decisive seasonal precipitation scenarios for the medium and extreme scenario

Saison	Central Plateau, Jura		Pre-Alps, Alps		South Switzerland	
	medium [Δ%]	extreme [Δ%]	medium [Δ%]	extreme [Δ%]	medium [Δ%]	extreme [Δ%]
DJF	+5	+25	0	+20	+10	+10
MAM	+5	+20	+5	+10	0	0
JJA	-10	-5	-10	-5	-15	-15
SON	-5	+25	0	+20	0	0

IMPLEMENTATION OF THE METHODOLOGY: EXAMPLE ROCK FALL

The implementation of the methodological approach is described in greater detail below using the example of the rock fall process. According to the National Platform of Natural Hazards (PLANAT) we define rock fall as a large volume of rock (> 100 m^3) detached en masse.

The hypothesis that changes in the permafrost and in the availability of water are the main factors was adopted as a basis for the rock fall sensitivity analysis. Thawing permafrost results in a reduction in the stability of rock faces and increases the disposition for rock fall (c.f. Gruber & Haeberli 2007). Changes in water availability influence the water pressure in fissures, which is an important triggering factor (c.f. Gruner 2008, Schneuwly & Stoffel 2008). Both factors can alter the magnitude and frequency of rock falls. In addition, new rock fall areas can evolve from glacier retreat, such as the Eiger rock slide (Oppikofer et al., 2008) (this point is not further developed). The structural characteristics of the rock body are also significant. However, nationwide data are lacking on this parameter, thus it could not be included in the evaluation.

The assessment of the permafrost degradation incorporated, first, the permafrost index from the Permafrost Index Map of Switzerland (BAFU 2005), and, second, the exposition. The permafrost index provides qualitative data on the areal distribution, thickness and temperature of permafrost bodies. The higher the index, the greater the likelihood that permafrost is present and the thicker and colder the permafrost bodies will be. The exposition is used as an indicator of the influence of short-wave radiation or sensitivity to temperature increase. South-facing rock faces react less sensitively than north-facing ones as the radiation towards the south already gives rise to higher energy input today and this will not change significantly in the future. However, the change in temperature will have a stronger impact in north-facing rock faces (Salzmann et al. 2007).

The elevation range and size of the catchment area above the area under consideration were taken into account for the evaluation of the water availability. For the calculation of the catchment area a multiple flow direction approach has been applied to account for both, surface runoff and subsurface flow (Quinn et al. 1991). If water can only flow from a small area above a rock face, sensitivity is lower than it would be if it can flow from a larger area. Elevation range was used as an indicator for the change in the distribution of the precipitation in snow and rain and the seasonal change in the total water availability (Table 3). Due to the greater winter precipitation and shift in snow melt in locations above 1,200 m asl, according to the extreme scenario, increased water inflow may be expected in the Central Plateau and Jura. The decline in the snow melt is overcompensated by the increased precipitation at this altitude in spring. The water inflow is unchanged or declines in summer. It increases strongly at all altitudes in autumn. The situation is largely comparable in the Alps and Pre-Alps. In spring alone, the water availability does not increase below 2,500 m asl. In south Switzerland, a – possibly strong – increase in water inflow may be expected at lower and medium altitudes. The water inflow declines in spring (exception altitudes > 2,500 m asl) and summer and remains unchanged in autumn.

Table 3: Combination of the seasonal changes in precipitation and snow melt for the extreme scenario (R: rain, SM: snow melt, -: decrease, +/-: unchanged, +: increase, ++: strong increase)

Altitude	DJF			MAM			JJA			SON		
	R	SM	Total	R	SM	Total	R	SM	Total	R	SM	Total
Central Plateau, Jura												
< 1200	++	+/-	++	++	-	+	+/-	+/-	+/-	++	+/-	++
> 1200	+	+	++	++	-	+	+/-	+/-	+/-	++	+/-	++
Pre-Alps, Alps												
< 1200	++	+/-	++	+	-	+/-	+/-	+/-	+/-	++	+/-	++
1200 - 2500	+	+	++	+	-	+/-	+/-	+/-	+/-	++	+/-	++
> 2500	+/-	+/-	+/-	+/-	++	++	+/-	-	-	++	+/-	++
South Switzerland												
< 1200	+	+/-	+	+/-	-	-	-	+/-	-	+/-	+/-	+/-
1200 - 2500	+	+	++	+/-	-	-	-	+/-	-	+/-	+/-	+/-
> 2500	+/-	+/-	+/-	+/-	+	+	-	-	-	+/-	+/-	+/-

The permafrost degradation and water inflow were evaluated using fuzzy rules. The sensitivity of the rock fall process in relation to climate change was then deduced from these parameters. To this end, statements were made on changes in magnitude and frequency. Fuzzy rules were also applied here. Up to this point, the evaluation of sensitivity was still carried out on the level of the individual grid cells without taking into account whether rock fall process areas are present or not. In the concluding step, the grid data were aggregated to the catchment areas from the subdivision of Switzerland into catchment areas (BAFU, year not specified). This involved, first, sampling based on the process areas (Fig. 1 a). The proportion of process areas per square kilometer was calculated from this. The sensitivity level was then determined from the grid for each sample point. The 25 %, 50 % and 75 % percentiles of the sensitivity evaluation were calculated on the basis of these data (Fig. 1 b). The sensitivity was deduced from the percentiles and proportion of process area using fuzzy rules (Fig. 1 c and d).

The maps in Figure 2 show that, according to the extreme scenario, an increase or strong increase in frequency may be expected for most of Switzerland at grid level. In the case of magnitude, a reduction or no change may be expected in the Central Plateau and Jura, and in the Pre-Alps and lower altitudes of the Alps. However, a strong increase may be expected at higher altitudes in the Alps. The increase in frequency may be explained by the greater water inflow in autumn, winter and spring in the Central Plateau and Jura. Due to the increase in

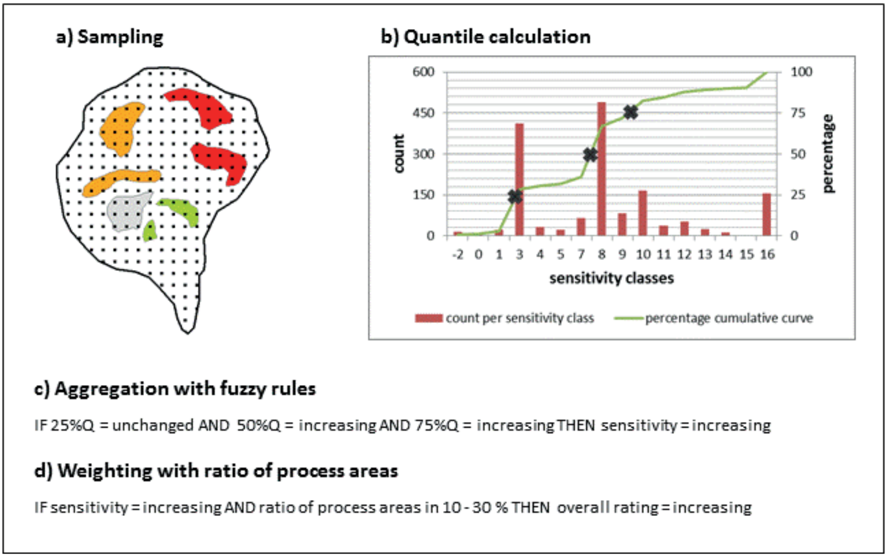

Figure 1: Spatial aggregation concept at catchment area level

frequency and limited rock material in areas without permafrost magnitude declines according to the magnitude-frequency relationship (c.f. Hungr et al. 1999). However, this relationship applies only with respect to a larger area. In south Switzerland, a reduction in frequency may be expected at lower altitudes while no change may be expected in the situation at higher altitudes. In the case of magnitude, with the exception of areas at the highest altitudes, an unchanged situation may be expected. The decline in precipitation is the main factor here.

According to the aggregation to the level of the catchment areas, the changes are limited to the higher locations in the Alps and scattered areas in the Pre-Alps. The density of rockfall areas is low in other areas, which explains why no major changes may be expected here. A strong increase in rock fall frequency may be expected at the higher attitudes across the Bernese, Valais and Grison Alps, and also in the Uri and Glarus Alps. The same applies to magnitude. The reason for this is the increasing instability of rock faces due to permafrost degradation and the increased water availability. A decrease may be expected in some areas of the Pre-Alps as there no permafrost occurs.

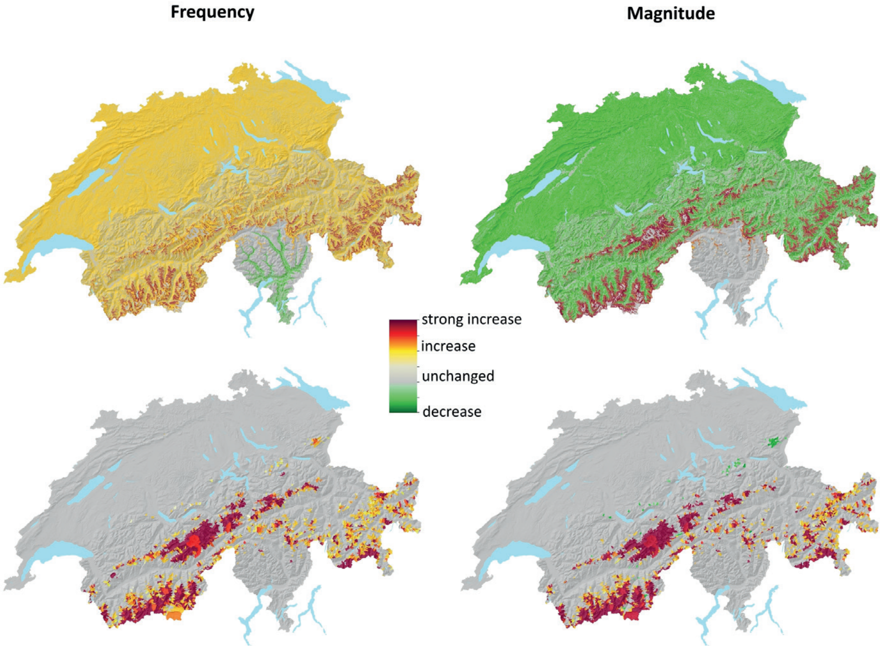

Figure 2: Results for rock fall at grid level (above) and catchment area level (below)

RESULTS

The results for all of the evaluated processes are presented in a highly generalized form in Figure 3. The overview presents a differentiated picture of the changes to be expected according to the region and processes involved.

In the case of slope processes in the Jura and the Central Plateau no major changes may be expected with the exception of an increase at shallow landslides on steep slopes. With regard to avalanches in the Pre-Alps the reduction in snowfall in this region will lead to a decline in frequency and magnitude but also to unchanged conditions in some cases. The frequency and magnitude of block fall in the Pre-Alps will decrease or remain unchanged as a decline in freeze-thaw days causes less weathering and, therefore, less material is available for such events. An increase in shallow landslides on steep slopes may be expected as precipitation falls increasingly as rain, particularly in the winter, when evapotranspiration is low.

The biggest changes may be expected in the Alps. According to both scenarios, permafrost degradation and the increase in water availability will prompt an increase in the frequency and magnitude of rock falls. Moreover, according to the extreme scenario in particular, an increase in avalanche activity may be expected at high elevation where precipitation continues to fall as snow while precipitation in winter will increase. In the case of hillslope

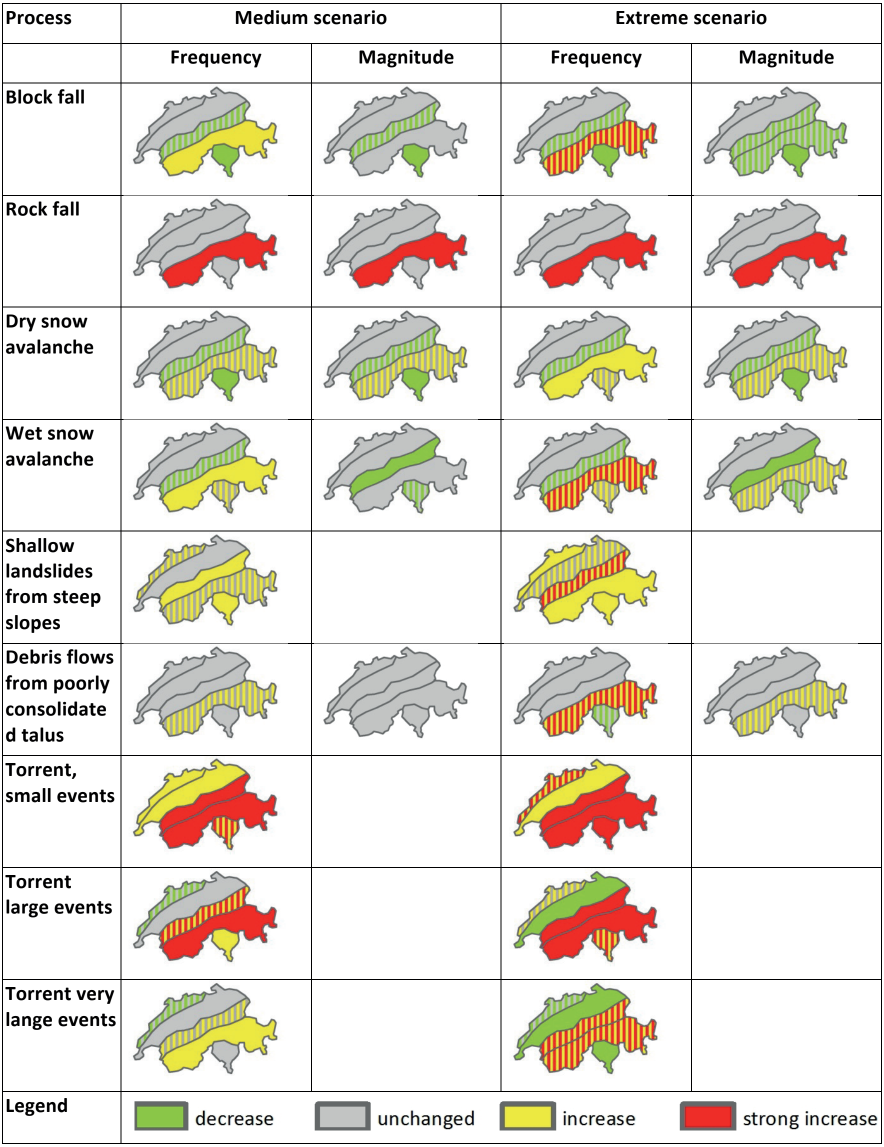

Figure 3: Results of the sensitivity analysis for both scenarios and the different processes

debris flows from poorly consolidated talus, an increase in frequency may be expected due to the thawing of the permafrost. The results in south Switzerland are inconsistent.

A decrease or no change may be expected for the majority of processes. Shallow landslides from steep slopes and wet snow avalanches (extreme scenario only) are the exceptions here. In both cases an increase of frequency may be expected.

For the sensitivity assessment of torrent processes sediment yield and triggering events are taken into account. Changes in the sediment yield were derived from the assessment of the slope processes, in which only areas relevant for the sediment yield were considered. The assessment of the sensitivity of triggering events was derived from the climate scenarios. The sensitivity of torrent processes was assessed for three magnitudes.

For the medium scenario in all regions an increase or strong increase of small events may be expected. The reason for this is the increase in the triggering events. In the Jura and the Central Plateau, this results in a decrease or unchanged conditions in large or very large events, as available bed load is limited. In the Pre-Alps, where many ancient deposits exist and in the Alps, where degradation of permafrost and glacier retreat cause an increase of sediment yield, an increase or a strong increase for large or very large events may be expected. In the extreme scenario in almost all regions a strong increase in triggering events must be expected. This results in an increase or a strong increase in small events. The limited availability of loos material in the Central Plateau leads to a decrease of large and very large torrent events. In the Jura increased sediment yield from shallow landslides leads partly to an increase of large events. With regard to very large events, this increase of shallow landslides cannot compensate the increase in frequency. In the Pre-Alps and Alps with its large additional sediment yield an increase or strong increase of large und very large events may be expected, despite the increase in frequency. In south Switzerland the situation is heterogeneous. With regard to large events an increase may be expected, due to several ancient deposits in higher regions. But very large events will decrease.

DISCUSSION AND CONCLUSIONS

In the context of the above-described project it was possible to develop a methodology which enables the efficient assessment of the sensitivity of natural hazard process related to climate change. Recent events in Switzerland (e.g. August 2005, October 2011) indicate an acceleration of processes, especially in the periglacial area, but also in the Pre-Alps. This is in correspondence with the results from this study. The new periglacial hazard index map, which was elaborated based on detailed input data for the Bernese Oberland (Tobler et al. in rev.) also coincide in most part. Effects of climate change as described in Stoffel & Huggel (2012) or in a detailed study on rock fall (Perret et al. 2006) are reproduced in the here presented results. But there are also some limits which must be considered when using the result from this study. Thus, the study is limited to the analysis of the disposition and the triggering events. The reach of hazard processes is not included. Furthermore, new process chains that could become relevant in the context of climate change (e.g. flood waves, triggered by a rock avalanche falling into a new glacier lake) are not considered. However, the results are valuable to determine areas for more detailed studies, they can be used for the planning of monitoring concepts and they show where climate change effects must be taken into account when hazard maps are revised. For this the data produced in this study will be made available to the cantonal authorities.

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