Large-scale risk assessment on snow avalanche hazard in alpine regions

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Abstract. Snow avalanches are recurring natural hazards that affect the population and ~~transport~~ infrastructure in mountainous regions~~during the winter months~~ , such as in the ~~most~~ recent avalanche winters ~~of~~ 2018 and 2019, ~~where large damages were~~ when considerable damage was caused by avalanches throughout the Alps. ~~Decision~~ Hazard decision makers need detailed information on the spatial distribution of ~~the hazard and risk~~ avalanche hazards and risks to prioritize and apply appropriate adaptation strategies and mitigation measures ~~to~~ and thus minimize impacts. Here, we present a novel risk assessment approach for assessing the spatial distribution of avalanche risk by combining large-scale hazard mapping with a state-of-the-art risk assessment tool, where risk is understood as the product of hazard, exposure, and vulnerability. Hazard disposition is modeled using the large-scale hazard indication mapping method RAMMS::LSHIM, and risks are assessed using the probabilistic Python-based risk assessment platform CLIMADA, developed at ETH Zürich. ~~The avalanche~~ Avalanche hazard mapping for scenarios with a 30-, 100-, and 300-year return period is based on a high-resolution terrain model, 3-day snow depth increase, automatically determined potential release areas, and protection forest ~~information~~data. Avalanche hazard for 40,000 ~~single~~ individual snow avalanches is expressed as avalanche intensity, measured as pressure. Exposure is represented with a detailed building layer indicating the spatial distribution of monetary assets. ~~Vulnerability of the~~ The vulnerability of buildings is defined by damage functions based on the software EconoMe, which is in operational use in Switzerland. The outputs of the hazard, exposure, and vulnerability analyses are combined to quantify the risk in spatially explicit risk maps. The risk considers the probability and intensity of snow avalanche occurrence, as well as the concentration of vulnerable, exposed buildings. Uncertainty and sensitivity analyses were performed to capture inherent variability in the input parameters. This new risk assessment approach allows ~~for the quantification of avalanche risk on large scales~~ to quantify avalanche risk over large areas and results in maps ~~that show~~ displaying the spatial distribution of risk at specific locations. Large-scale risk maps can assist decision makers in identifying areas where avalanche hazard mitigation and/or adaption is needed~~to address current and future avalanche risk~~.

1 Introduction

In ~~a time of~~ densely populated mountainous landscapes ~~and~~ with continuous socio-economic growth and changing climate conditions, society is increasingly exposed to natural hazards (Zgheib et al., 2020). In mountainous regions such as the Alps, avalanches are a significant natural hazard in winter, causing damage to buildings and infrastructure. In the past 20 years, ~~countries situated in the European Alps~~ Alpine countries such as Switzerland have experienced multiple catastrophic avalanche situations. The winter 2017/18 was the first since the catastrophic avalanche winter ~~of 1999 (Wiesinger and Adams, 2007)~~ in 1999, (Wiesinger and Adams, 2007) during which the highest avalanche danger, level 5, was forecasted for wide areas across the Swiss Alps. In January 2018, 2.5 to 5m of snow fell at higher altitudes within 25 days. Numerous avalanches in the categories "large" and "very large" were counted (Zweifel et al., 2019). In total, over 380 avalanches ~~caused a damage to~~ damaged buildings, traffic routes, or important infrastructure in Switzerland (Bründl et al., 2019), making it ~~to~~ the most severe avalanche winter in recent years~~, not only in Switzerland, but also in Austria,~~. This was also the case in Austria and Germany (MeteoSchweiz, 2019; Pancevski, 2019; ZAMG, 2020; Trachsel et al., 2020). ~~Also in~~ In the following winter 2018/19, ~~for example, exceptional snowfall events occurredwhich caused high~~ exceptional snowfalls again occurred, causing substantial damages throughout Switzerland (Trachsel et al., 2020). Such events show that even in highly developed, well adapted countries, society is still vulnerable to ~~extreme snowfall events causing avalanche hazards~~avalanches. Strategies, methods, and risk assessments to counteract this threat are well developed in most areas in the Alps, but they need to be continuously developed to strengthen and improve the resilience of the population and ~~their~~ its assets (Zgheib et al., 2020).

To cope with natural hazards threatening exposed assets, various ~~institutions~~ organisations have introduced the concept of risk to the field of natural hazards. The IPCC for instance defines risk as the likelihood ~~for~~ of the disturbance of the normal functionality of a society due to a hazardous physical event under vulnerable social conditions (= vulnerability) with economic, material or environmental consequences (IPCC, 2014), see also Fig. 1. According to this definition, the risk concept can also be applied to events with harmful consequences to the environment and environmental systems. ~~A consideration of~~ Considering the impacts of natural hazards ~~to~~ on the environment is ~~generally also of importance to the authors of this study. But since the~~ also important to us. However, since damage to human life ~~'s~~ and man-made objects is of greater direct importance to society and decision makers, this concept is ~~mostly~~ generally applied to infrastructure and buildings, as it is ~~also~~ in this study.

The concept of risk ~~has been~~ was introduced in Switzerland in the late 1990s to support decision makers for dealing with natural hazards (Heinimann et al., 1998; Borter, 1999; Bründl et al., 2009). The risk concept ~~became also~~ also became the central element of the Strategy for Natural Hazards of the National Platform Natural Hazards (PLANAT) in Switzerland (PLANAT, 2009, 2018). Overviews ~~on natural hazards~~ of natural hazard risks and vulnerabilities ~~in~~ at different spatial scales were generated by various ~~institutions~~ organisations in the last decade (MATRIX Consortium, 2013; van Westen and Greiving, 2017; Fuchs et al., 2019; FOEN, 2020). These studies vary from vulnerability surveys (Fuchs et al., 2015) to multi-risk and resilience approaches (Kappes et al., 2012; Komendantova et al., 2016). Projects such as RoadRisk carried out by the Swiss Federal Roads Office (ASTRA, 2012) or the National Risk Overview initiated by the Swiss Federal Office for the Environment (FOEN, 2020) were created ~~with a lot of effort and long project duration's~~laboriously. Such projects ~~indicate the demand~~ underline the need

for large-scale risk surveys.

~~What is missing so far is a~~ A method to assess avalanche risk at a regional or national scale is currently lacking, with a state-of-the-art hazard mapping tool ~~, which would~~ to allow decision-makers to identify hot spots of avalanche risk. The ~~so-produced risk maps show in short term studies where detailed assessment would be necessary to develop appropriate risk management~~ risk maps produced by this approach would show detailed short-term assessments to facilitate risk management decisions.

The goal of this study is to ~~suggest~~ present a framework for assessing avalanche risk ~~at a large scale, as it is presented~~ over widespread areas, as shown in Fig. 1. The method was applied in a ~~case study to a region~~ regional case study in central Switzerland, but ~~could~~ can be deployed anywhere ~~in the world. Since the components of risk are not constant, such~~ worldwide. Such a framework can also ~~help to depict~~ be useful to identify and visualise changes of the components of risk, such as hazard, exposure and vulnerability over time and space. In this paper, we focus on the presentation of the framework for the current risk situation, which will serve as a ~~platform~~ baseline for modelling expected climate and socio-economic induced changes of risk in future.

~~Especially in the context of climate change and population growth, new~~ New strategies and tools ~~that assist~~ to systematically identify risk and respond to threats in exposed areas are of increasing importance, especially in the context of climate change and population growth, (IPCC, 2012). Changes in the climate system and their influence on local weather phenomena do not only affect us ~~already~~ now (CH2018, 2018), but will likely lead to an increase of the frequency and magnitude of natural hazards in the years to come (IPCC, 2014). In particular, various studies indicate that changes in the climate system, such as ~~temperature rise~~ rising temperatures and an increase of extreme precipitation events, will likely influence gravity-driven hazards (Mani and Caduff, 2012; Ballesteros-Cánovas et al., 2018), ~~such as~~ including snow avalanches.

~~The paper is organised as follows. First, we present the methods in detail followed by a section in which we show how these new methods operate and how they can be applied to specific examples, such as the case study in central Switzerland. In the results section, we depict the spatial distribution of the calculated risks, analyse the uncertainties and perform a sensitivity study. Finally, we discuss progress and limitations of the new method and conclude, how this framework might contribute to a dialogue on the changes of risk at a large scale.~~

2 Methods

2.1 Risk

In the context of natural hazards in Switzerland, risk is defined as the product of hazard potential, objects at risk (exposure) and their vulnerability (Borter and Bart, 1999). In more detail, Bründl et al. (2016), defines risk as the damage that is statistically expected due to the hazard intensity (= caused by avalanche impact pressure) in a given scenario, calculated as the product of the expected damage and the frequency (= 1/return period) of this scenario.

In this study, the risk tool CLIMADA is used for risk assessment and therefore we use the definition of the framework developers. It is a similar but extended definition of the IPCC risk concept by Aznar-Siguan and Bresch (2019), expressing risk as the probability of a consequence resulting from a hazard and its severity:

$$\text{risk} = \text{probability} \quad \text{severity} \tag{1}$$

, where

$$\text{severity} = F(\text{hazard intensity, exposure, vulnerability}) = \text{exposure} \quad \text{vulnerability function}(\text{hazard intensity}) \tag{2}$$

Figure 1. A schematic illustration of the applied IPCC risk concept with the used input components for generating the base information on exposure, hazard and vulnerability, used to create risk maps and perform risk analyses.

Since the consideration of risk requires the three components of The methods chapter is organised into subsections explaining all components of the risk framework from Hazard hazard, Exposure exposure and Vulnerability , see Fig. 1, we vulnerability to risk, and its application to the case study region (Section 2.2) in detail. These subsections contain the information on how the respective components were de ned and generated in this study and how they are used to calculate the spatially distributed monetary terms of risk. Before going into detail, we will give a brief introduction to this overview of those components: The Hazard (Section 2.3) class is obtained by avalanche hazard mapping using the "RAMMS:LSIHM" (Rapid Alpine Mass Movement Simulation:: Large Scale Hazard Indication Mapping) method. For this purpose, a protection forest layer (Section 2.3.2) is generated that de nes where protection forest is located. Using this layer, potential release areas (PRA) can be identi ed with an automatic algorithm (Bühler et al., 2018). Using extreme value statistics, maximum 3-day snowfalls are analysed and three avalanche scenarios with return periods (rp) of 30 years, 100 years and 300 years are de ned (Section 2.3.1) integrated into the release area calculation and also protection forest created take these scenarios into account. With the de ned potential release areas and an assigned amount of snow, the RAMMS (Section 2.3.4) avalanche simulations can now be carrie

out and a hazard indication map showing avalanche impact pressures can be generated for a hazard class.

The Exposure (Section 2.4) is a data set that defines the exposed monetary values. The exposed consists of statistical data on the resident population called STATPOP (number of persons per building) and the economic data STATENT (location of places of business) and economic data. These are available in a GIS data set with coordinates. Furthermore, Swiss building zones and a 3D building data set are used. Monetary values are then assigned using the Swiss standard risk methodology "EconoMe" (FOEN, 2021) (Section 2.4.1). Thus, a new exposure dataset is created that shows the geographical distribution of the monetary values on a map (Section 2.4.2). The third component is the Vulnerability (Section 2.5) class, which defines the damage sensitivity of an object that is exposed to a certain avalanche pressure. The EconoMe risk methodology specifies values for building damage in percentage caused by a certain avalanche pressure. These values are adopted in steps and define the step function as a assets' sensitivity to damage from avalanches with certain impact pressures by using a so-called impact or vulnerability function (Section 2.5.1). According to EconoMe, these functions can be assigned to a certain building type by means of an ID and thus be used in the risk framework. To express these components in numbers in the context of the Risk concept (Section 2.1), the CLIMADA (Section 2.1.2) (Climate Adaptation) risk model is used. This model allows us to express the risk in monetary terms such as the expected annual impact (eai) as well as the aggregated average annual impact (aai agg.) and depict them on spatial risk maps (Section 3.1) the considered region. These values can also be presented in damage frequency curves (Section 3.3) to show which return period the return period at which monetary losses would be expected. A sensitivity and uncertainty analysis (Section 2.6.1) completes the risk assessment and shows the limitations of the framework. The methods chapter is organized into subsections explaining all components of the risk framework from hazard, exposure and vulnerability to risk, and its application to the case study region (Section 2.2) in detail. These subsections contain the information on how the respective components were defined and generated in this study and how they are used to calculate the spatially distributed monetary terms of risk

2.1.1 Damage frequency curves

Similar to exceedance-frequency curves, which are a standard method in in natural hazard risk analysis for plotting losses against a specific exceedance-frequency for historic events (Vogel et al., 2007), the damage-frequency curve plots the calculated damage against the return period. We use these curves to show synthetically generated avalanche risk scenarios and to draw conclusions between calculated damages. Therefore, we show possible outcomes at other return periods that have not been specifically calculated but estimated through interpolation. These curves thus provide a more complete picture and give decision-makers a wider range of available interpretations of the results.

2.1.2 CLIMADA

CLIMADA is an open-source and -access Python package for probabilistic risk assessment (Aznar-Siguan and Bresch, 2019). It allows for the computation of the impact computation of natural hazards, modelled as intensity maps, on exposures, modelled as value maps, considering the vulnerability of the exposures, modelled as impact functions using intensity maps considering exposure and its vulnerability. It is possible to compute the risk today and in the future current and future risk,

including climate change that modifies the hazard and socio-economic development affecting the exposures and vulnerability. Finally, one can compute the reduction in risk and cost from adaptation options to perform a cost-benefit analysis (Kropf et al., 2021). For all the model outputs, CLIMADA provides a module to perform uncertainty and sensitivity analysis (Kropf et al., 2022) using global (quasi-)Monte-Carlo sampling.

In this project, we use CLIMADA to compute the risk of avalanches to more than 13,000 individual buildings, from each of the 40,000 simulated avalanches using the hazard intensity maps described in Sect. 2.3, the exposures distribution described in Sec. 2.4 and the impact functions introduced in Sec. 2.5. As defined in the CLIMADA tool (Aznar-Siguan and Bresch, 2019), the impact is expressed by the following risk quantities:

- the expected annual impact for each exposure (affected building) expressed in monetary terms per year (Swiss Francs (CHF) per year). It combines the hazard intensity with its expectation (= return period) and the damage degree from the impact functions;
- the average annual impact is the average of the expected annual impacts over all exposures, expressed in monetary terms per year (CHF per year);
- the average annual impact aggregated is the sum of the average annual impacts for each scenario or all scenarios combined expressed in monetary terms per year (CHF per year). The average annual impact aggregated corresponds to the overall risk.

~~To show general patterns of risk and to look at the overall risk of all scenarios, we adjusted the three scenarios for the combination with regard to the return period by $p_{30} = p_{30} \quad p_{100} = 1 = 30 \quad 1 = 100 = 0{:}0233$ and $p_{100} = p_{100} \quad p_{300} = 1 = 100 \quad 1 = 300 = 0{:}$ and $p_{300} = 1 = 300 = 0{:}0033$. This allowed us to combine the hazard scenarios and recalculate the overall impacts such as the expected annual impact (= eai) for single objects over all hazard scenarios in the entire study region as it is shown in the result section. In a further step, the uncertainties and sensitivity of the risk framework will be derived as described in Sec. 2.6.~~

2.2 Case study region

For this study we focus on a case study area of an area in the Gotthard region (Fig. 2), in central Switzerland between Altdorf and Göschenen in the Swiss Canton of Uri (Canton Uri), one of the most important north-south transit corridors in Europe. The Gotthard area is one of the snowiest regions in Switzerland and characterized by many steep, forested unforested slopes of different orientations making the region highly exposed to avalanches with high avalanche activity. Steep meadows or rocky slopes form avalanche release areas with 28° to 50° slopes in the upper catchment area of the main Reuss valley and reach from an altitude range from an elevation of approx. 1700 m 1700m a.s.l. up to almost 3000m a.s.l. At heavy snowfall events. During heavy snowfall, avalanches start in the backcountry release zones and sometimes flow down to valley bottom, where the snow masses are deposited in the bed of the Reuss river. Reuss river bed. To perform avalanche risk analyses we use snow depth increase data from the SLF-station Meien ME2 (see Fig. 2). This station has a 66 year record and includes extreme snowfalls (e.g., winters 1950/51 and 1998/99), making the data basis more reliable for extreme events.

It is located in the centre of the study area at an elevation of 1320 m a.s.l. and thus provides a good database for avalanche assessment.

Figure 2. Illustration of the case study area of the Gotthard region in central Switzerland with the avalanche prone slopes visible. a) Overview of the region with a map panel of Switzerland. b) Detail of the village Göschenen with the well known Rientalbach avalanche path. c) Hazard hot-spot Wassen. d) Altdorf and its surrounding slopes. Forests are shown in green and buildings in red. Map base data source Swiss Federal Office of Topography (map.geo.admin.ch)

2.3 Hazard - Avalanche hazard indication mapping with RAMMS::LSHIM

Hazard indication mapping of snow avalanches at scales of 1:5,000 to 1:10,000 has been carried out for backcountry users (Harvey et al., 2018) and exposed communities in Switzerland (Bühler et al., 2022), Italy (Maggioni et al., 2018; Monti et al., 2018), and other regions worldwide (Bühler et al., 2018). To cover all possible avalanches affecting the region, every hydrological catchment stretching from the main valley up to the mountain ridges of the side valleys was assessed for potential