Chapter

Avalanche Protection Forest: From Process Knowledge to Interactive Maps

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Abstract

In order to prioritize protection forest management, it is essential to know where forests have an effect on avalanches and which criteria the forests have to meet to avoid avalanche releases and reduce avalanche runout distances. This contribution outlines how the current assessment of effective protection forest can be improved by combining process knowledge on forest-avalanche interactions with newly available remote sensing data, large-scale numerical modeling and cartographic visualization techniques. Within the scope of a practical application in the Canton of Grisons (Central Swiss Alps), we showcase how scenario-specific avalanche protection forest maps have been developed and implemented into natural hazard indication maps in collaboration with avalanche modelers and practitioners. We outline further developments of such combined information towards interactive, web-based decision support tools based on resulting maps of effective avalanche protection forests.

Keywords: hazard indication maps, snow avalanches, interactive maps, remote sensing, protection forest

1. Introduction

Large scale hazard indication maps of avalanche protection provide an overview of areas potentially endangered by snow avalanches [1]. Such hazard maps serve in Switzerland also as a basis to define the extent of avalanche protection forests [2]. The first available hazard indication maps of avalanche protection at the beginning of the 21st century [2, 3] were based on a relatively coarse 25-m digital elevation model and simple forest vs. non-forest scenarios. In the meantime, we have increasingly advanced remote sensing data such as airborne LiDAR data and, in particular, highly resolved digital elevation models [4, 5], and additional and refined knowledge on avalanche-forest interactions [6, 7]. In this contribution we outline how we can take advantage of newly available process knowledge, refined spatial data and numerical modeling to improve avalanche protection forest maps, related applications and visualizations.

2. Process knowledge: avalanche protective effects of forest

The main effects of avalanche protection forests are that avalanches do generally not release in sufficiently dense forest and that smaller avalanches can be slowed down or stopped by forest [6–8]. These effects are not only influenced by the forest structure but also by topographical factors and the properties and thickness of the snow cover. Critical thresholds for the spontaneous release of avalanches can be different inside the forest compared to the open field. For example, avalanches in forests mainly occur on slopes with an inclination of at least 35° [9], whereas in open areas, they may also occur in less steep terrain below 30° [10]. The surface roughness of the terrain is a crucial factor, at least as long as the snow cover thickness in the forest does not exceed the effective height of the dominant objects such as trees, root plates, logs or deposited rocks [11].

There are essentially four physical processes that contribute to the stabilization of the snow cover in forests: (1) Interception of falling snow: snow is partly intercepted on branches and sublimated back into the atmosphere [12]. Intercepted snow, which is not sublimated, enters the snowpack in the form of snow lumps or meltwater [13]. (2) More balanced radiation regime: the duration of solar radiation and the long-wave radiation during the night are reduced in forests compared to open field [14, 15]. (3) Reduced wind speeds: within the forest, near-surface wind speeds are lower than in the open [16]. (4) Direct mechanical support: standing trees, but also lying dead wood, stumps, and root plates help to stabilize the snow cover with their reinforcing effect and increase the roughness of the terrain [6, 17].

As a result of these four processes, crown coverage, gap sizes and slope angle are considered the most essential characteristics for avalanche prevention in forests (see also chapter [18] of this book). Critical thresholds can be estimated from the retro analysis of events in relation to the topographical factors and snow properties [19, 20]. Based on such studies, critical lengths of forest gaps in the fall line are usually given in the range between 25 and 60 m, depending on slope inclination [18, 21]. Some authors also propose to use the height of the trees for defining the length and width of these gaps [22]. The size of gaps is also decisive in determining whether a small-medium scale avalanche (< 10′000 m^3) that starts in the forest can potentially develop into a large avalanche (≥10′000 m^3). The minimum gap width required to form avalanches is generally smaller in deciduous forests (approx. 5–10 m) than in evergreen forests (approx. 15–20 m), with considerable variation depending on steepness, terrain roughness and snow conditions. Smaller avalanches, which start in the forest or 100–200 m above the forest line, can come to a stop depending on the forest structure, topography and snow characteristics in the forest. The braking effect of the forest is a consequence of various interactions between avalanches and trees [6, 7] but is for large-scale hazard mapping usually simplified and modeled with a friction approach [8].

3. From process knowledge to maps

In order to create large-scale and applicable maps of forests with a protective effect and/or protective function (protection forest maps), it is necessary to deduce criteria from existing process knowledge and combine them with appropriate remote sensing and other available GIS-Data. For a hazard indication mapping project in the Canton of Grisons (Eastern Switzerland) we consequently aimed at the following criteria for the delineation of avalanche protection forest (**Figure 1** and **Table 1**):

1. Based on existing data: We used data on 150 avalanches released in forested terrain of the Swiss Alps and deduced a logistic regression model to quantify the effect of topographical and forest structural variables ([19, 20], **Table 1**).

2. Comprehensive and automatized: We aimed for a completely automatized and comprehensible delineation of the protection forest for the whole area of the Canton Grisons. Thus, it is necessary that all variables and criteria used to delineate the forest with an avalanche protective function and effect could be spatially deduced from newly available remote sensing data and/or additional GIS data, which are available for the whole Canton of Grisons and can potentially be repeated later with updated forest data.

3. Verified and optimized: The delineation of the avalanche protection forest had to be verified and further adapted by knowledge from scientists and local natural hazard and forest experts. In order to verify the effect of the forest structure on avalanche runout, an additional optimization loop had to be conducted after the simulation with the avalanche simulation software RAMMS [8, 23].

A central component within this framework is the logistic regression model calculated with the most important variables "slope inclination", "percentage of crown cover" and "gap width", adapted from [20]. Those variables were implemented within a GIS approach. The algorithm is described in detail in **Table 1**. Based on spatial input data sets (e.g., vegetation height model [VHM] and digital terrain model [DTM]) [24] and various GIS operations, we calculated an "avalanche disposition" between 0 (no disposition) and 100% (very high avalanche release probability). To minimize the calculation time, a forest mask was used to delimit the calculation domain of the model. This forest mask consists of a combination of forest areas defined by the Federal Office of Topography (Swisstopo) and the Swiss National Forest Inventory, NFI [4, 25]. We defined different threshold values for tree heights to assign forest gaps ("Gap-threshold") and forest cover ("Forest cover-threshold") for different avalanche scenarios (frequent scenario vs. extreme scenario according for regionally expected snow-heights snow heights according to [28]). Additionally, we accounted for two factors which could not be quantitatively deduced from the original logistic

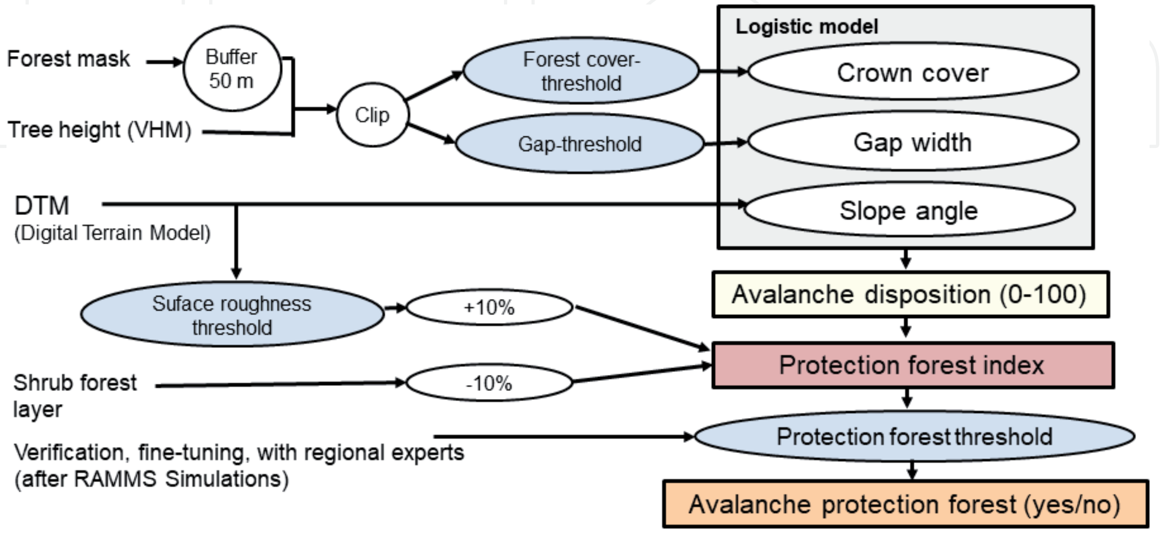

Figure 1.
Schematic structure of the model for calculating the spatial extend of avalanche protection forest. The core of the disposition model is a logistic model based on avalanche releases in forested terrain [23]. A vegetation height model (VHM) [3], a digital terrain model (DTM) [24], a forest mask [3, 25], a shrub layer [26] and a surface roughness layer according to [27] were used as input GIS-data.

Considered variables and threshold	Definition
Crown cover	The higher the crown cover, the lower the likelihood of an avalanche release. The crown cover is calculated based on a percentual proportion of pixels with a higher VHM value than the crown cover threshold. This procedure is done within a 5 m and 25 m environment, and the arithmetical mean is calculated.
Gap width	Pixels that have a lower VHM value than the Gap-threshold (see definition below) are considered as a gap. If multiple gap pixels are adjacent to each other, a polygon is drawn, which represents the gap. The gap polygon is intersected with the contour lines to extract gap width. The length of the contour line represents the width of the gap. Gaps smaller than 500 m^2 were neglected after verification of avalanche runout with RAMMS simulations. To get homogeneous results, the mean over a 10 m environment is calculated.
Slope angle	The angle of the slope was calculated based on a 10-m DTM. Values lower than 28° and higher 48° are considered as constant. In the range within 28 and 48° an increase of inclination is expected to lead to a higher potential for an avalanche release.
Forest cover-threshold	In order to take into account the coverage at different spatial scales and to optimize the detection of trees, especially in a critical range between 3 and 5 m, the following VHM limits have been set: • Frequent event: 4 m for 5 × 5 m and 3 m for 25 × 25 m environment • Rare event: 5 m for 5 × 5 m and 4 m for 25 × 25 m environment
Gap-threshold	The local snow depth for a 100-years event was calculated according to [28] and corrected by a factor of 0.85 for frequent and 1.14 for rare events. The calculated snow heights multiplied by the factor 1.5 according to Protect-Bio [29] results in the respective tree height limit. To compensate for underestimations of tree heights within the VHM, a constant height was subtracted from the VHM raster value.
Surface roughness	The surface roughness influences the likelihood of an avalanche release, especially when the snow height is low. The roughness was calculated with the “Vector Ruggedness Measure” (VRM) according to [27] based on a 2-m DTM (SwissAlti3D) and a moving window of 5 × 5 m. Based on empirical comparisons, areas with a value > 0.02 are considered as rough. For rough areas that do not show lateral convex curvature an increase of 10% of the avalanche disposition is accounted for.
Shrub forest	Shrub forests tend to protect less against an avalanche release. Trees such as green alder *Alnus viridis* (Chaix.) DC. or the shrub form of mountain pine *Pinus mugo* have more flexible stems than upright trees of the same size. Thus, they are pressed down by snow. We address the limited protection capability of shrub forests by assigning a decrease of 10% of the avalanche disposition for all areas classified as shrub forests according to [26].
Avalanche disposition	Statistically deduced disposition of each pixel to be part of an avalanche release area, given as a value from 0 to 1 according to a logistic model with following formula: $\text{Logit}_{(\text{release } 1/0)} = -6.17 + 0.18 * \text{slope angle } [°] - 0.03 * \text{crown cover } [\%] - 0.05 * \text{gap width } [\text{m}]$.
Protection forest index	Index calculated from avalanche disposition and additional parameters (roughness, shrub forest) (may have values from −10 to 110)
Protection forest-threshold	The threshold for the protection forest index, based on validation in well-documented areas. Threshold values for fulfilled protective effect were: • Frequent scenario: forest with a protection forest index < 65 • Extreme scenario: forest with protection forest index < 85

Table 1.
Variables, threshold values and definitions for delineating avalanche protection forest for a frequent (ca. 10–30 years event) and extreme (ca. 100–300 years event) scenario.

model, but which turned out to be of additional relevance and for which spatial data were available for the whole canton: (1) a scrub forest area layer [26] helped to assign an adequately higher avalanche disposition to areas covered by shrubs. (2) We delineated areas with a high surface roughness from a high resolution DTM, and which do not show lateral convex curvature. With this combined requirement, we could exclude vertical gullies with high terrain roughness, as they are known for frequent avalanche release. Based on (1) and (2), we assigned higher values to the protection forest index for areas with considerable terrain roughness and lower values for areas that are covered by shrub forests (**Figure 1**). The resulting "protection forest index" builds the basis for the protection forest maps. The exact threshold values defining a sufficient protection forest index for frequent (ca. 10–30 years return period), and extreme (ca. 100–300 years return period) scenarios could then be defined in an iterative process after validating avalanche simulations with former avalanche events and after discussing different scenarios (with and without forests) together with the responsible regional natural hazard experts [23].

The avalanche protection forest map for the Canton of Grisons (**Figure 2**) is thus the result of an iterative process starting with an empirical statistical model of avalanche releases in forested terrain and was subsequently improved in several working and validation loops. The iterative process allowed us, for example, to better account for the stopping behavior of small and very small avalanches in forested terrain and how these processes are simulated with the avalanche dynamics software RAMMS [8]. In the applied model, the turbulent friction ξ (Xi) is set to a very high value, simulating the braking effect of the forest. Other adaptations introduced after validation loops included a stronger representation of surface roughness, leading to an increase in the protection forest index of forests with high surface roughness and may shift the categorization for some forests with a relatively open forest structure but a high surface roughness. Additionally, we considered differences between actual tree heights and how these tree heights were assessed with the available vegetation height models [3, 30]. Besides validating the forest cover map after the simulation of avalanches and besides the feedback of regional experts, it was also essential to validate the delineation of the avalanche protection forest maps specifically in well-investigated areas with known tree heights and avalanche history.

While all these validation procedures improved the quality and applicability of our map, more progress is possible during the following years by applying the map in practice and by introducing additional spatial data sets on forest characteristics. Therefore, the map will be updated once (i) reliable tree species maps are available

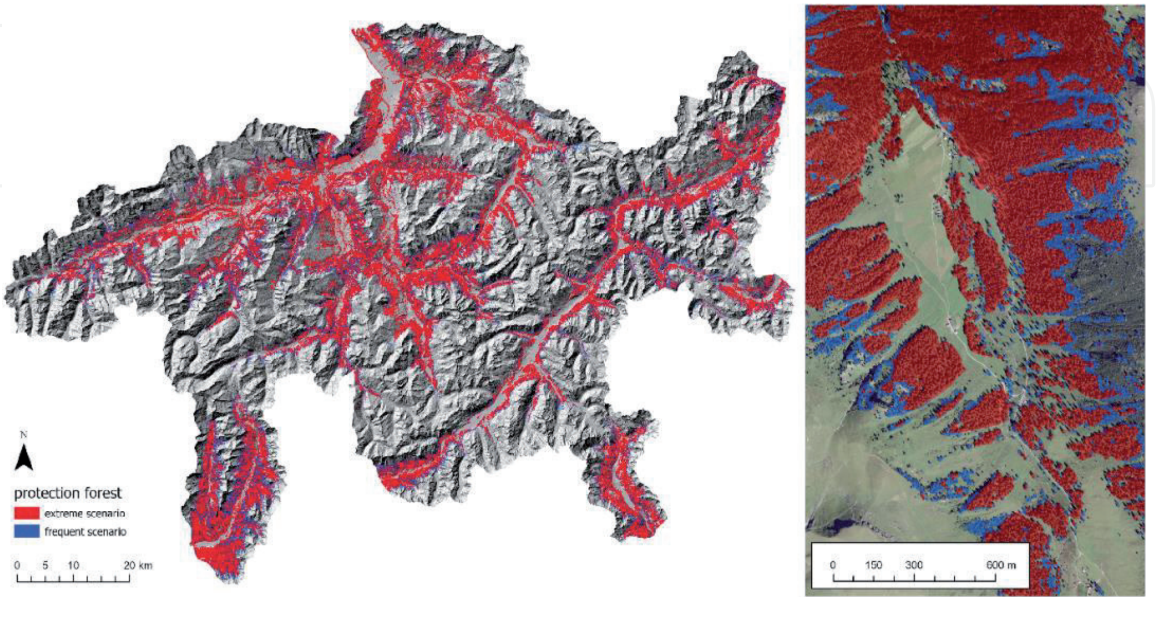

Figure 2.
Protection forest map for the Canton Grisons for a frequent avalanche scenario (corresponding to avalanche events with a 10–30-year return period, displayed in blue and red combined) and for an extreme snow cover scenario (corresponding to a ca. 100–300-year avalanche event, displayed in red).

in order for better consideration of the protective capacity of different forest types (e.g., forests dominated by evergreen coniferous trees, deciduous conifers or broadleaved trees) or (ii) after an improved understanding of the effect and the assessment of different surface roughness categories.

4. From static to interactive mapping

Two-dimensional protection forest, hazard indication or risk maps are still the standard application in the administration and consulting offices. Nevertheless, modern cartographic visualization strategies go far beyond showing a static portray of reality at a given point in time. Especially new advances in web technologies and multimedia integration, known as "web mapping", make it possible to create easily shareable, user-friendly and robust web applications via different (mobile) devices such as smartphones, tablets or personal computers.

As forests undergo permanent and often abrupt changes in time, protection forest maps should be updated when more data or better process knowledge is available and after relevant changes in the forest structure. Map updates are particularly important with expected changes due to climate change and important legacies of past land use and expected increases in the frequency and severity of natural disturbances [30]. The development from static, two-dimensional maps to dynamic, interactive maps in a 3-D environment with possibilities to regularly update the visualization of protective effects in response to different forest scenarios would not only be a logical response to the increasing availability of spatial data, cartographic capabilities and computing capacity, but also a response to increasing practical needs. Compared to existing maps, dynamic maps enable to track effects of changes to the forest cover due to natural disturbances and different management scenarios on the protective capacity and other forest functions.

Based on the avalanche protection forest layer presented in this contribution, the avalanche hazard indication map for the Canton of Grisons [31] was compiled and mapped for the first time with an interactive visualization platform (maps.wsl.ch), which is currently being developed at the WSL Institute for Snow and Avalanche Research SLF in Davos, Switzerland. In a first step, the latest findings on protection forests, RAMMS simulations of various avalanche scenarios and topographical and asset data such as buildings or roads were combined into an interactive user experience.

For the implementation, basic criteria were defined for the cartographic representation and the functional scopes of the interactive maps. In addition to a traditional two-dimensional map view, the user is offered a three-dimensional, spatial form of representation. Within this 3-D representation, all functions of "traditional" web mapping and other functions beyond are available. This means that the map reacts directly to the user, attributes and geometric data are linked, and interactive legends and diagrams are available. This encompasses the well-known functions of zooming, panning, perspective, 3-D navigation and flights through digital elevation models and three-dimensional objects like buildings or snow avalanche release areas, selection, print or an extended search function. The latest functions include the individual selection of layers, the retrieval of information via pop-ups, the creation of own bookmarks for quick navigation, the measurement of distances and areas in three-dimensional space as well as the personal editing of certain layers and the integration of shapefiles. The integration of shapefiles allows the user to upload recorded field data, for instance, and thus to overlay this data with the map content for visual analysis or prints. The functionality and design of the application will be improved in the future depending on the needs of the users and the progress in avalanche modeling.

The development of interactive web maps can broadly be categorized into three parts: 1) data preparation and visualization, 2) user interface design, and 3) application development. Hence, the map itself is only one element in a more prominent programmatically framework of digital cartography. For the detailed analysis and necessary transformations of the geospatial data that will be part of the application (step 1), conventional GIS software is used. Most of the layers are also being visualized at this stage. In order to keep the application lightweight in storage, all map data is being uploaded to a cloud or, respectively, a hosting data server. The user interface design is carried out with HTML and CSS (step 2), while for most of the application development, including all the functional parts, the programming language JavaScript is the main component. Finally, the application has to be run through a web server (maps.wsl.ch) responsible for distributing all necessary files to the client's web browser (step 3).

In addition to the existing range of functions, the interactive maps are made to be increasingly dynamic. This is an updating of the map contents, which the user can also do. For example, a forester may digitize, edit and upload areas where forest disturbances such as windthrow, insect outbreaks or forest fires occurred or where a forest intervention is planned or implemented. However, providing modeling software as RAMMS via web service is neither possible nor planned so far.

Drone images or other collected data such as forest inventory data or climate data can provide additional information on selected sites (hotspots). Such dynamic, interactive maps will not only allow a user-friendly way to represent different forest scenarios or changes in forests, natural hazards or resulting risk but can also be used as a tool for (forest) planning or for consulting issues as well as for teaching and research (**Figure 3**).

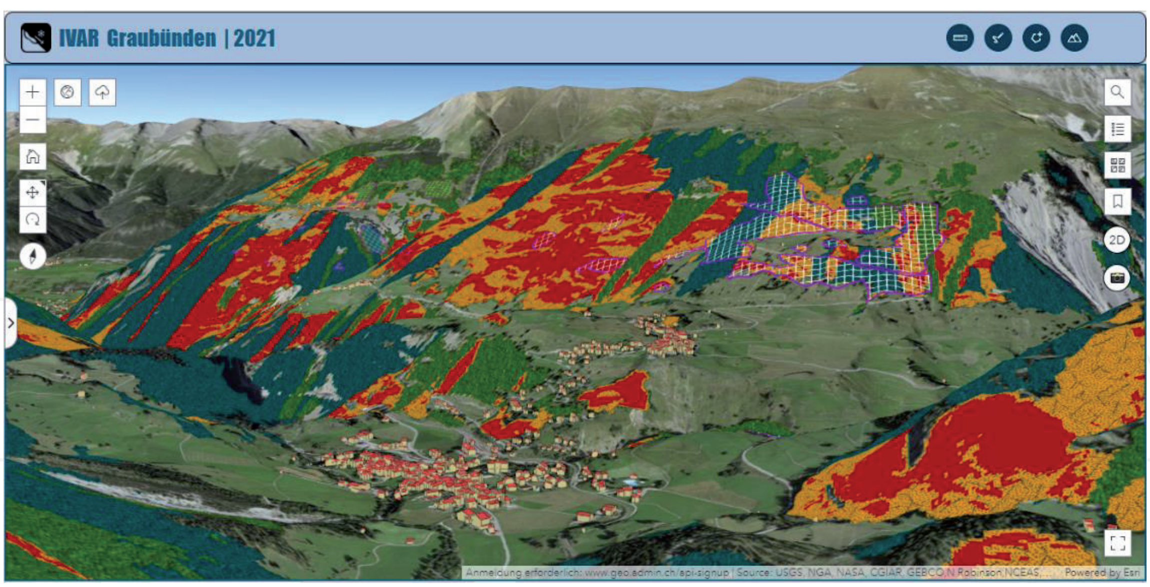

Figure 3.
Insight into the interactive map platform, which is currently being developed at WSL (maps.wsl.ch). Shown is a map section of the Bergün region, Canton Grisons, Switzerland. The example shows how remote sensing data and avalanche models are used to identify hotspots and prioritize forest management in avalanche protection forests. In the top-left and top-right corners of the web application different user interface components can be found such as functional widgets, navigational tools and elements allowing for map customization. All forest classifications have been derived from an overlay analysis between the current avalanche protection forest layer of the canton and RAMMS simulations with and without forest for a frequent scenario (approx. 10–30 year avalanche event). Forests colored in green/blue have an effect on avalanches, which do not endanger buildings. Forests colored in light orange (slope < 35°) and red (≥35° steepness) have a (building) protective function and a protective effect against snow avalanches. The threshold of 35° inclination highlights potential avalanche release areas in disturbed sites (with high surface roughness) or in forests where forest structure is not appropriate. In the area of Bergün severe storms destroyed parts of the forest in 2018 (windthrow areas highlighted with pink outline and white mesh).

5. Conclusions

Automatically produced protection forest maps (showing protective effects and functions of forests) based on a sound scientific framework and reliable spatial data are an important basis for prioritizing management interventions and for deducing hazard indication maps or even legally binding hazard maps. In view of further optimizing such maps and their application in different regions, it is important to carefully validate the mapping procedure after the simulation of avalanches with regional experts. Furthermore, as the technology to assess spatial data, and the forest cover and its ability to reduce avalanche risks are changing with time, it is necessary to regularly update such maps and calculate them for different scenarios. Thus, we propose and currently develop web-based interactive maps as a new planning and visualization tool.

Acknowledgements

The protection forest map of Grisons has been supported by the Cantonal office for forest and natural hazards of the Canton of Graubünden (Grisons). Additional funding has been provided by the WSL research program Climate Change Impacts on Alpine Mass Movements – CCAMM (ccamm.slf.ch) and by the prevention foundation of the Swiss cantonal building insurance (KGV). We thank in particular Roderick Kühne, Stephan Wohlwend, Andreas Stoffel and Stefan Margreth for support and feedback which helped to improve the maps. The map is still in evaluation. We also thank Frank Graf, Michaela Teich, Frank Perzl and Frédéric Berger for valuable comments on an earlier version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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