

A support tool for avalanche warning services has been developed

Quantifying the release propensity

A geographical model for visualising and calculating avalanche hazard

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Abstract

Avalanche bulletins use text, graphics and icons to provide information about avalanche hazard, but they lack a topographical visualisation of the really dangerous areas. In order to overcome this limitation, an extended model was developed to support the avalanche forecasters. The model, which is an extension of an existing algorithm, calculates the release propensity of slab avalanches according to snow cover conditions. Its parameters were partially derived from a survey addressed to practitioners and include snowpack stability, dangerous aspects and altitudes, as well as a snow cover mask and a forest one. Furthermore, the model calculates the amount of dangerous steep slopes in a given area. This model does not take into account loose snow avalanches and avalanches dynamics. Hence, future research should focus on the coupling of these two additional factors within the algorithm. By improving the parameters definition and performing a final validation, the model may eventually be considered fully reliable as a support tool for avalanche forecasting.

Keywords: avalanche, Geographic Information System (GIS), hazard, snowpack, modelling

1 INTRODUCTION

Avalanche bulletins (a.k.a. *avalanche reports*) generally present both figures and text. The verbal section, for instance, provides information about critical altitudes, geographical aspects and terrain morphologies which are prone to avalanche release. However, the danger zones are merely expressed in a qualitative way. Furthermore, the danger level of the European Avalanche Danger Scale is homogeneously distributed over wide areas in the bulletins; thus, it is not able to localise the truly dangerous areas. As a matter of fact, the bulletins provide with no geographical evidence of the potentially dangerous slopes, aspects and altitudes. Moreover, the danger zones are not numerically quantified. Due to these considerations, the avalanche service of the Autonomous Region Friuli Venezia Giulia (Italy) expressed the need to calculate and geographically visualise the danger zones to support the avalanche forecasters.

Several other models were developed for similar purposes in the past. For example, LAWIPROG (Leuthold et al., 1996) was used to visualise the verbal section of the Swiss avalanche bulletin by using numerical indexes. However, they still had a qualitative meaning. Other models assess the avalanche danger within ski resorts (Brabec et al., 2001; Stoffel et al., 2001) by using a mix of real-time data (Cookler and Orton, 2004; Gruber et al., 2009) and physical-statistical approaches (Pozdnoukhov et al., 2011).

Nevertheless, these models approach the problem using a *discrete* perspective and are used to express the results mostly with qualitative indexes. Besides, they cannot identify the Potential Release Areas (PRAs) of avalanches on very large-scale maps (i.e. with high spatial resolution).

There are also several further models to identify PRAs for engineering purposes, e.g. for danger mapping and long-term land management. They are based on some DTM-derived topographical parameters, such as slope, aspect, terrain curvature (Maggioni and Gruber, 2003; Peitzsch et al., 2014; Vontobel, 2011), terrain roughness and on forest cover as well (e.g. Blahut et al., 2017). Some authors use a *discrete* approach (Boltižiar et al., 2016; Selçuk, 2013), other ones the *continuous* approach of fuzzy logic (e.g. Ghinoi and Chung, 2005), but the majority adopts a

Boolean approach (i.e., the output value is either 0 or 1), which sharply distinguishes the potentially dangerous areas from the safe ones.

The cited models identify the total amount of PRAs, though. They do not consider the snowpack current condition and, consequently, calculate the worst-case scenario.

Recently, Veitinger et al. (2014) have suggested considering the influence of snow depth and its distribution patterns for the calculation of the PRAs. Snow cover smooths out the surface terrain roughness and the same roughness influences, in turn, localisation and width of the PRAs: for this reason, Veitinger et al. (2016) developed a new method for the definition of different release scenarios by taking into account snow depth. This method, however, does not consider the real, current snowpack stability.

Therefore, the algorithm of Veitinger et al. (2016) was extended in order to include the critical parameters which avalanche services deal with. The final purpose of this study is letting the avalanche services to visualise the most dangerous areas in accordance with the current snow and weather conditions and providing them with a support tool to determine the danger level within the avalanche bulletins.

2 FORMER MODEL

We hereby propose an extension of the model of Veitinger et al. (2016). Their model identifies the slab avalanches' PRAs by calculating the release propensity for each cell of an input DTM. The release propensity value ranges between 0 (no release propensity) and 1 (high propensity); thus, it may be considered as a *probability* value and be used as index of avalanche danger.

The former model adopts the so-called *fuzzy logic* (Zadeh, 1965). It is worth noting that this kind of logic can allow the practitioners to express mathematically their practical experience. The model employs a generalised bell membership function as given by the following equation:

$$\mu(x) = \frac{1}{1 + \left(\frac{x-c}{a}\right)^{2b}} \quad (1)$$

where a , b and c are the variables of the equation. The parameters are modelled by using this equation, which assigns them a membership value to the class *Potential Release Areas* (PRAs). The higher the membership value of a parameter within a DTM cell, the higher the release propensity.

There are three parameters which determine the final value of release propensity, i.e. slope, roughness and a wind shelter index.

SLOPE. It is well known that slopes between 35° and 45° are highly prone to release slab avalanches (Selçuk, 2013; Stoffel and Margreth, 2012). Therefore, the model of Veitinger et al. (2016) gives that slope range the highest value of release propensity. The values tend to zero for steeper (until 60°) and less steep (until 25°) slopes. Figure 1a shows the fuzzy curve that mathematically formalises these concepts. This model employs the *multi-scale quadratic parametrization* (Wood, 1996) to compute the slope value. This technique enables to calculate a topographic parameter at different scales, without changing the DTM resolution.

ROUGHNESS. Roughness influences release, localisation and width of avalanches (McClung, 2001; Schweizer et al., 2003), and is thus a very important parameter for this model. Recently, Veitinger et al. (2014) and Veitinger and Sovilla (2016) showed that roughness changes on the basis of snow depth and its spatial variability. The model of Veitinger et al. (2016) calculates the roughness values through the input

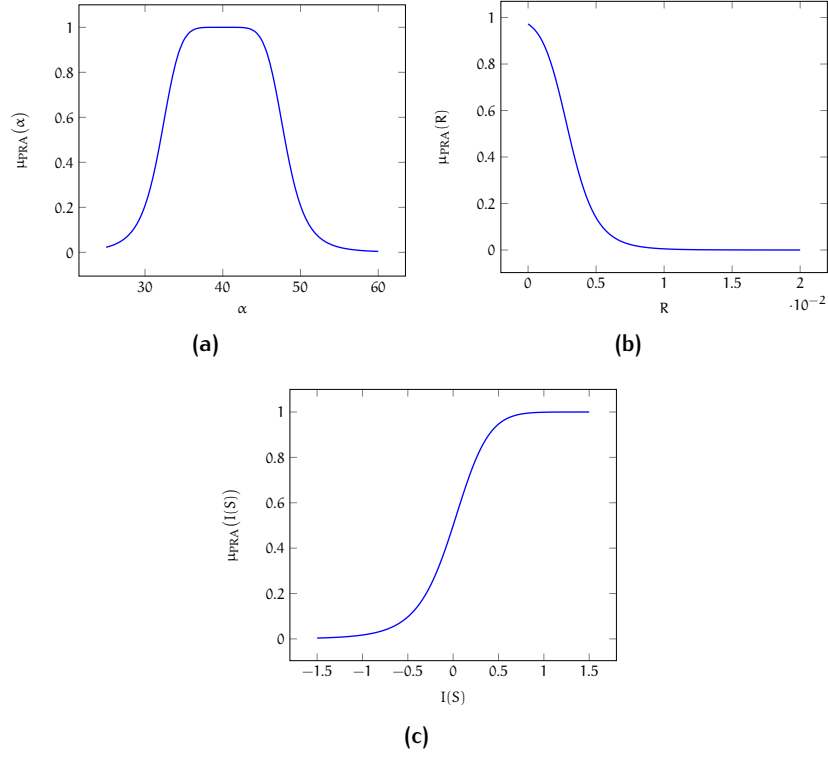


Figure 1: Fuzzy membership functions of the model parameters of Veitinger et al. (2016), computed by Eq. (1). Its parameters are (a) $a = 8$, $b = 3$, $c = 40$ for slope α , (b) $a = 0.01$, $b = 2$, $c = -0.005$ for roughness R and (c) $a = 2$, $b = 5$, $c = 2$ for the wind shelter index $I(S)$. μ_{PRA} stands for the membership degree to the class **PRA** of each parameter.

of a summer **DTM** and a mean value of snow depth: for this reason, it is possible to identify different roughness scenarios according to the value of snow depth. Numerically, for computing the roughness value, the *vector ruggedness measure* R of Sappington et al. (2007) is used. Its value ranges between 0 (smooth terrain, favourable for avalanche release) and 0.02 (rough terrain, avalanche release is improbable). Figure 1b shows the respective fuzzy membership function. The final roughness value is computed by considering two input parameters set by the user: the mean snow depth (as previously stated) and its spatial variability.

WIND SHELTER INDEX. Veitinger et al. (2016) assume that the wind-sheltered (i.e. leeward, downwind) slopes are more prone to avalanche release than the wind-exposed (windward, upwind) ones. The model adopts the *wind shelter index* (Plattner et al., 2006; Winstral et al., 2002) to model this sheltering effect. Given an input wind direction and its tolerance degree, the index value ranges between -1.5 (wind-exposed terrain) and 1.5 (wind-sheltered terrain). The respective membership function gives the highest membership degree to the wind-sheltered slopes (Fig. 1c).

Finally, a fuzzy logic operator processes the values of slope, roughness and wind shelter parameters, leading to a final **PRA** map where each cell is given a computed value $\mu_{PRA}(x) \in [0, 1]$ (Fig. 2).

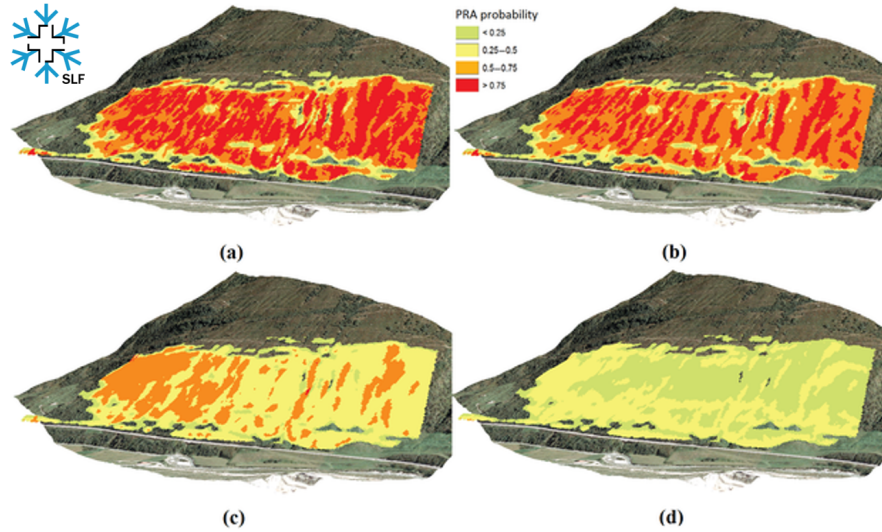


Figure 2: Output map of the former model for the Böschen avalanche (Canton Uri, Switzerland) on a north-west-facing slope. The colours graphically represent the membership degrees to the class [PRA](#). Snow depth is set to 1.2 m. Wind comes from (a) south, (b) south-west, (c) west e (d) north-west. Figure from [Veitinger et al. \(2016\)](#).

3 EXTENDED MODEL

The model of [Veitinger et al. \(2016\)](#) has been extended recently. For doing this, the verbal section of the avalanche bulletins was analysed and a questionnaire-based survey was addressed to the Italian avalanche practitioners and the Tyrolean Avalanche Service. The survey was intended to discover the main factors that forecasters consider appropriate to determine the critical slopes, aspects and altitudes for avalanche danger.

The results of this survey led to determine the following input data for the model: snowpack stability level, most dangerous aspect (optional), snow depth, wind direction (with tolerance), altitude limit due to wind influence, altitude limit due to snow cover and altitude limit due to avalanche danger.

These data take part in calculating the model's parameters, which are:

1. slope
2. roughness
3. weighted wind shelter index
4. altitudes of the potential avalanche danger
5. snow cover

The user can also provide with a forest cover mask to include the sole unwooded areas for the following [PRAs](#) calculations.

SLOPE. The results of the aforementioned questionnaire suggested that the assessment of the critical slope is highly linked to the current snowpack stability. Thanks to experts' judgement, there were thus defined five fuzzy membership functions for slope (Fig. 3): A (stable snowpack), B, C, D (intermediate conditions), E (highly unstable snowpack). These functions are intended to model the different snowpack stability levels as similarly done by the European Avalanche Danger Scale with the information about *snowpack stability*.

The functions, except for Function E, reach their maximum between 35° and 45° . It has been observed that artificially-triggered avalanches do release on similar slopes, indeed, regardless of the danger level ([Harvey, 2002, 2015](#)). The functions

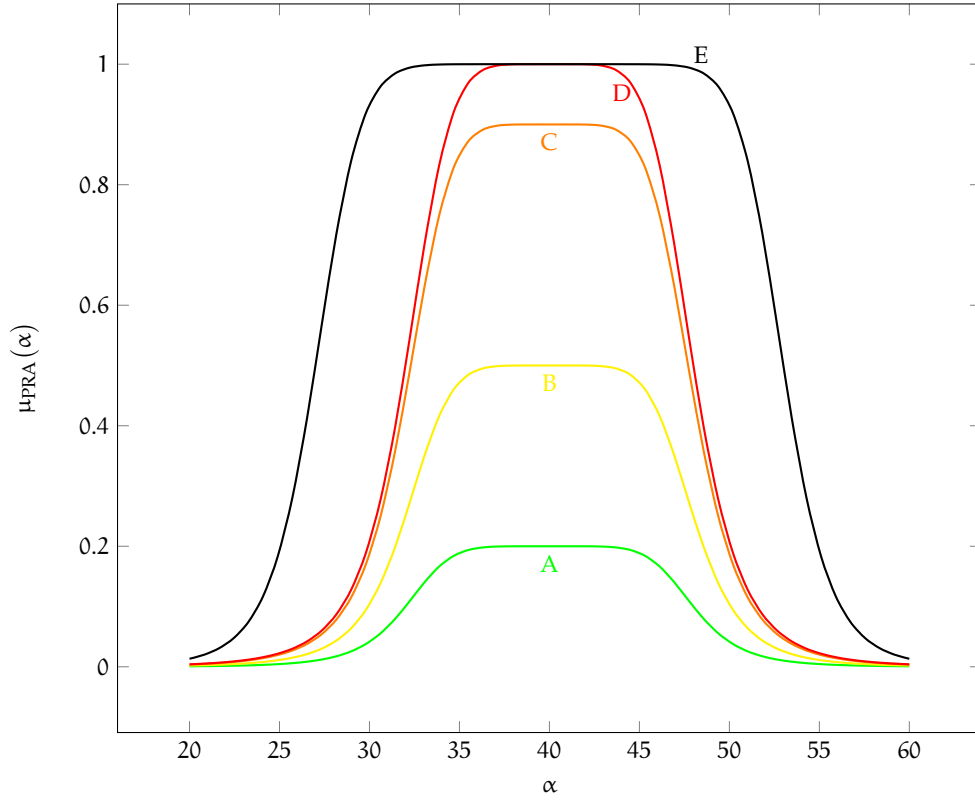


Figure 3: Fuzzy membership functions for slope α for each snowpack stability level: green for level A, yellow for B, orange for C, red for D, black for E. $\mu_{PRA}(\alpha)$ stands for the membership value of slope to the class [PRA](#).

are intended to provide different membership degrees in order to model the release propensity on the basis of snowpack stability. They have been determined using the method suggested by [Veitinger et al. \(2016\)](#) and by changing the curves parameters (see Eq. (1)). Specifically, Function D is identical to the one of [Veitinger et al. \(2016\)](#), whereas the parameters of Functions A, B, C and E have been modified. For instance, setting snowpack stability to the A level, a [DTM](#) cell with a slope of 30° gets the membership value 0.04. That is, that cell is a [PRA](#) to 4 % in respect to the slope. Using the D level on the same slope, the membership value becomes 17 %. Moreover, the extended model allows the user to set a weaker snowpack stability to a given aspect. For example, if the snowpack stability level is B and the user declares that the north-facing slopes are more dangerous than the other ones, for the different aspects Function B will be used, whereas for the northern aspects Function C.

WEIGHTED WIND SHELTER INDEX. The membership degrees to the class [PRA](#) of the wind shelter index are still computed using the function of [Veitinger et al. \(2016\)](#). However, this method does not consider the increment in wind velocity due to altitude. For this reason, and in order to partially model the altitudes of the major danger, the wind shelter index has been weighted with a function. Given two altitude values set by the user, this function linearly increases from 0 to 1: below the lower altitude limit, the wind is supposed to not have any effect on snow (weight factor 0) and above the upper limit one has a full wind effect (weight factor 1).

ALTITUDE OF THE POTENTIAL DANGER. As for the weighted wind shelter index, a function has been defined for weighting the very final value of release propensity. This function linearly increases from 0 to 1 on the basis of two limit altitudes set

by the user: a lower one under which avalanches are extremely improbable (0) and an upper one above which they can release (1). In other words, a *buffer* of release propensity has been implemented, whose width (as altitude values) is determined by the user (Fig. 4a).

SNOW COVER. Melted areas (i.e. with no snow cover) do not contribute to PRAs. In order to exclude those areas, it has been therefore implemented a snow cover mask with changeable boundaries according to the main aspects. For a more realistic mask, the algorithm allows giving four different altitude limits of snow cover to the main four aspects (Fig. 4b).

3.1 Percentage of dangerous steep slopes

Lastly, the model outputs the *percentage of dangerous steep slopes*: that kind of percentage is often used by avalanche forecasters in order to assess the danger level for the avalanche bulletins. However, this number has been estimated by the sole forecasters' experience so far: the proposed model outputs a computed value instead.

It has been assumed that a slope can be defined as 'steep' if its angle has a value between 30° and 60°; and that is 'dangerous' if it is more prone to avalanche release rather than not (i.e. $\mu_{PRA}(x) > 0.5$). Calculating the total area of the 'dangerous' cells and dividing it by the area of the 'steep', snowy and unwooded cells, one can obtain the ratio p as follows:

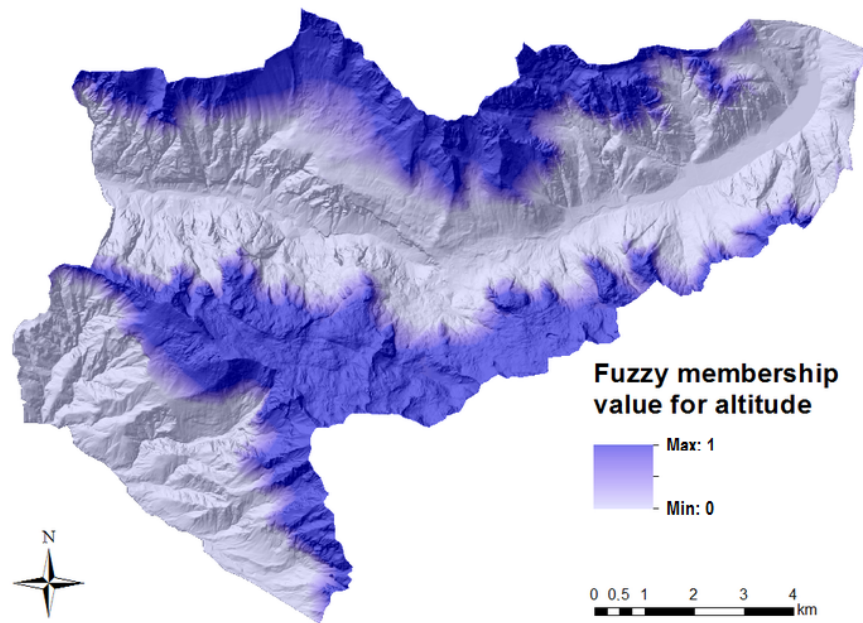
$$p = \frac{\text{number of dangerous cells}}{\text{number of steep cells}} \quad (2)$$

It is the fraction of the 'steep' cells having a release propensity greater than 50 %, and can be expressed by percentage. Therefore, we are used to referring to it as the *percentage of dangerous steep slopes*.

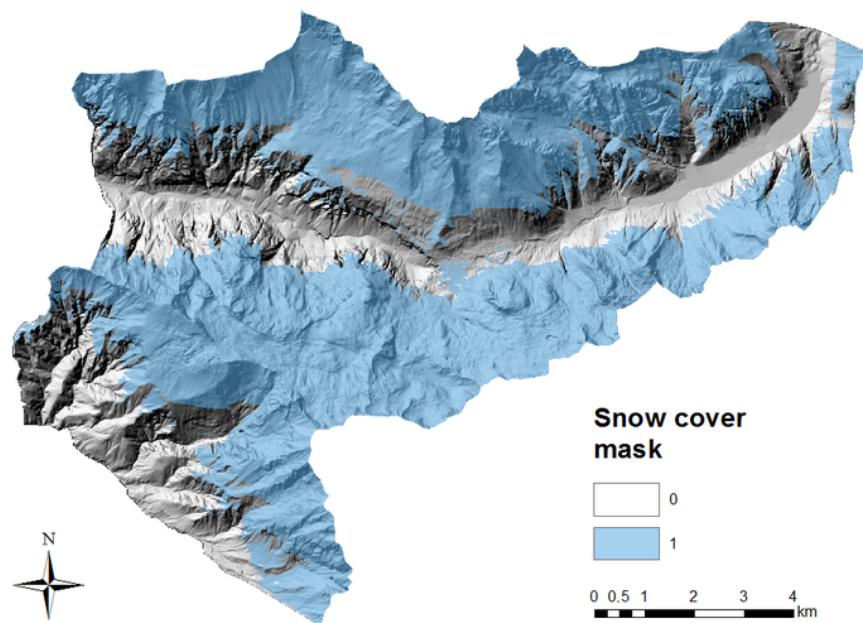
The algorithm then processes the model parameters and the final results of the calculations are as follows (Fig. 5):

- a *raster* map of the PRAs, which has been corrected in accordance with the current snow and weather conditions;
- the percentage of dangerous steep slopes.

The model of Veitinger et al. (2016) on equal main wind direction and snow depth can output just a single scenario (Fig. 6a). The extended model can identify multiple ones instead, thanks to combinations of parameters allowed by the new algorithm. Some examples are shown in Figures 6 e 7. The open-source algorithm was programmed in language R using the software with the same name (version 3.3.2, <https://cran.r-project.org/>). If you would like to get this software, please do not hesitate to contact us by email at the address luca@iacolettig.it. Figure 8 shows its flowchart.

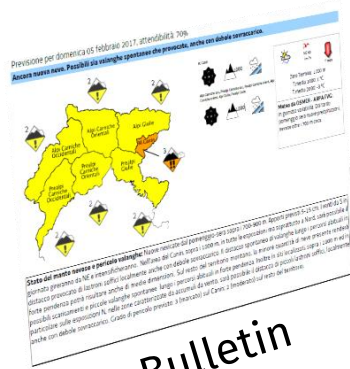


(a)



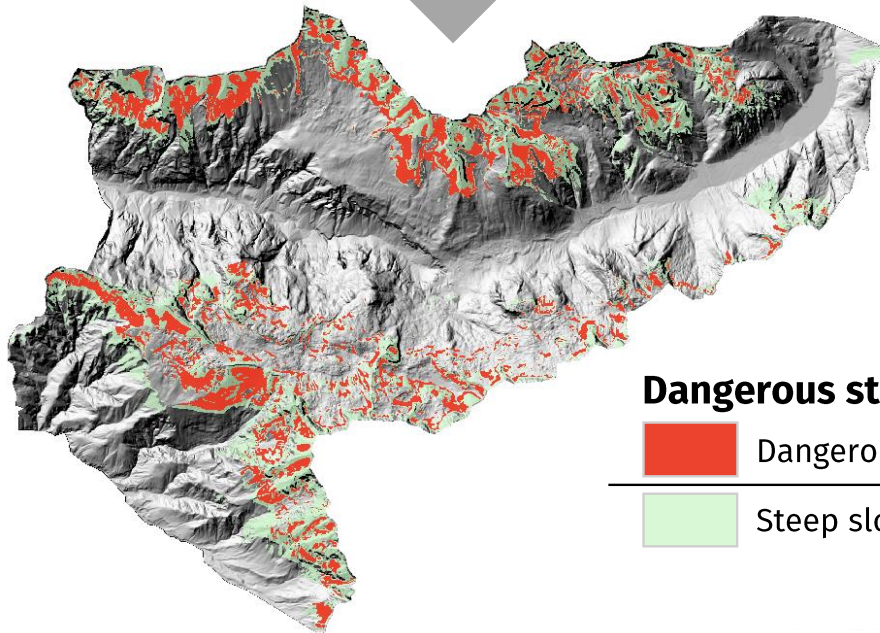
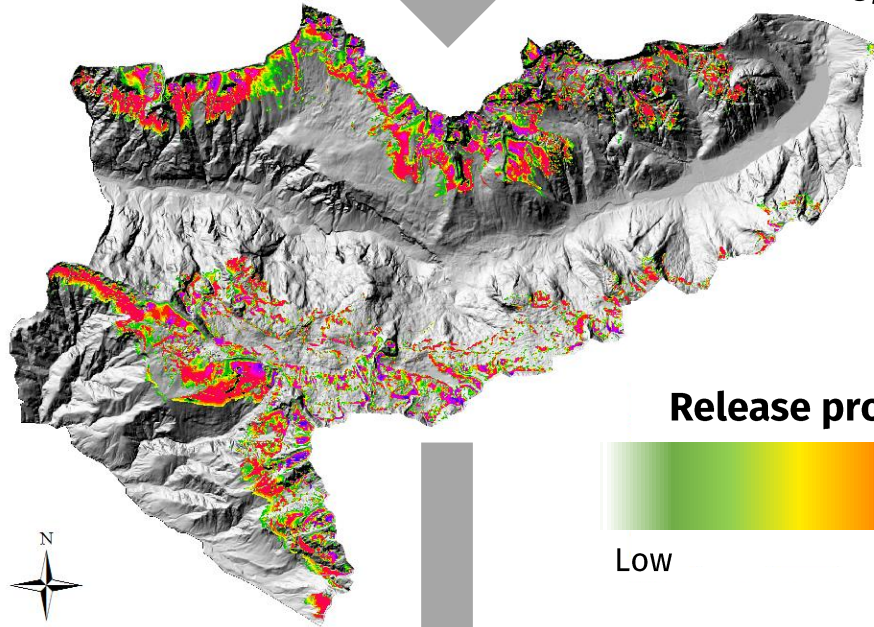
(b)

Figure 4: (a) The fuzzy function for the altitudes of potential danger displayed graphically. In this case, under 1500 m the altitudes are given value 0 (absence of avalanche danger), while above 1800 m value 1 (danger is present). The algorithm, thanks to a linear regression, calculates the values automatically for intermediate altitudes (colour gradient in the figure). (b) An example of a snow cover mask on the Mount Kanin group. If snow is present, cells are given value 1, otherwise 0. The altitude limit of snow cover may be different at different aspects: in this case, at the northern aspects, snow limit is set to 1200 m, at the southern ones to 1500 m, eastern ones 1300 m, western 1100 m. If a cell gets value 0, it cannot be a potential release area.



Bulletin

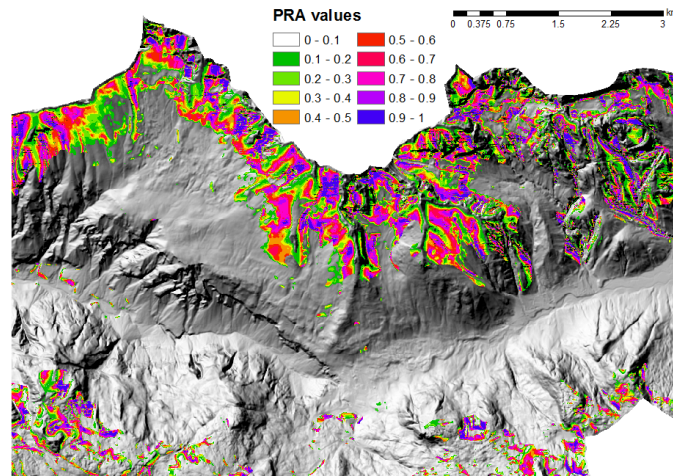
Expert judgement



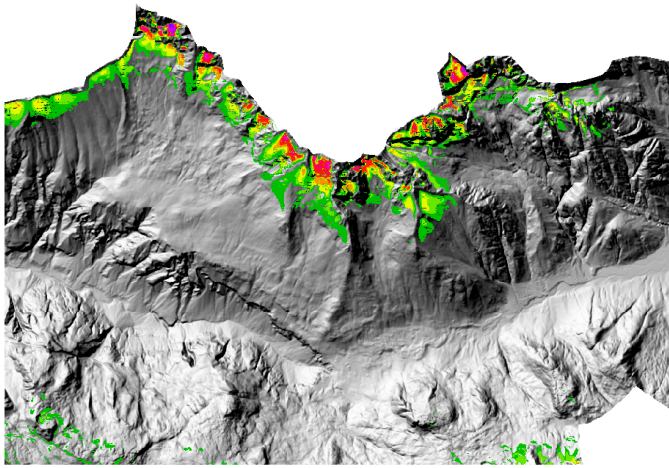
Dangerous steep slopes = 39 %



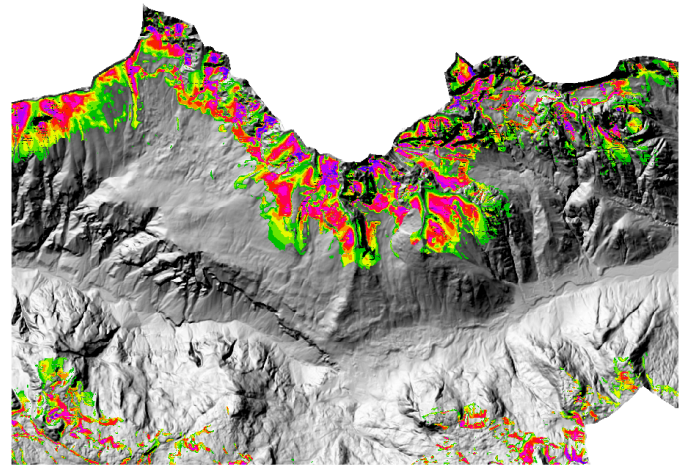
Figure 5: Graphical summary of the model. Thanks to avalanche bulletin's information and the experts' judgement, the algorithm outputs a map of release propensity whose values range between 0 (no propensity, no colour), and 1 (high propensity, dark blue). Furthermore, it calculates the percentage of dangerous steep slopes: this one is computed by doing the ratio between the area of the most dangerous slopes (red, in the bottom figure) and the area of the steep slopes (i.e. with an angle between 30° and 60°). In this specific scenario, 39% of the steep, snow-covered and unwooded slopes is significantly dangerous. The last information, if critically considered, could be useful for the forecaster to assess the danger level (here, 3 considerable). The area displayed above is the Mount Kanin group (Sella Nevea, Friuli Venezia Giulia, Italy).



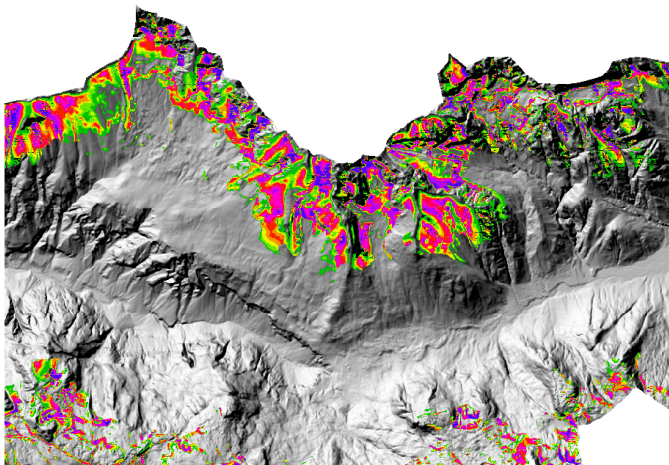
(a) Veitinger et al. (2016)



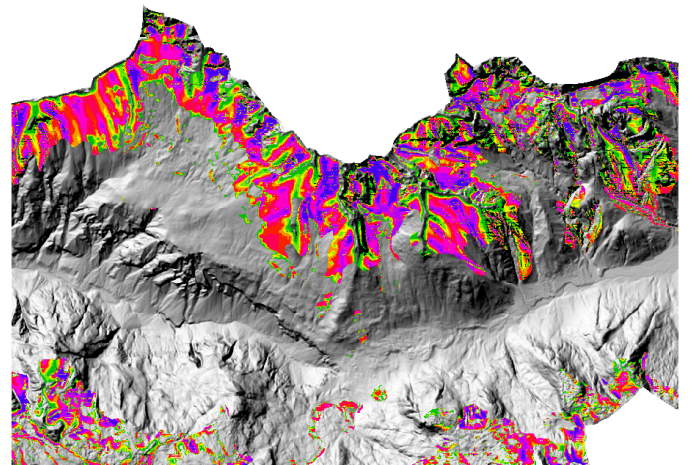
(b) Level B



(c) Level C

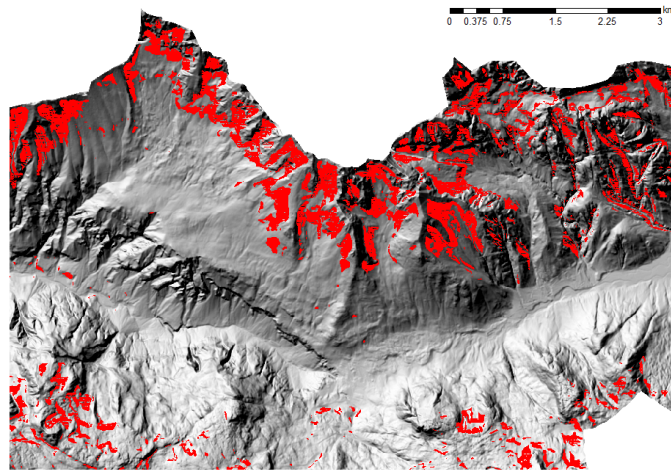


(d) Level D

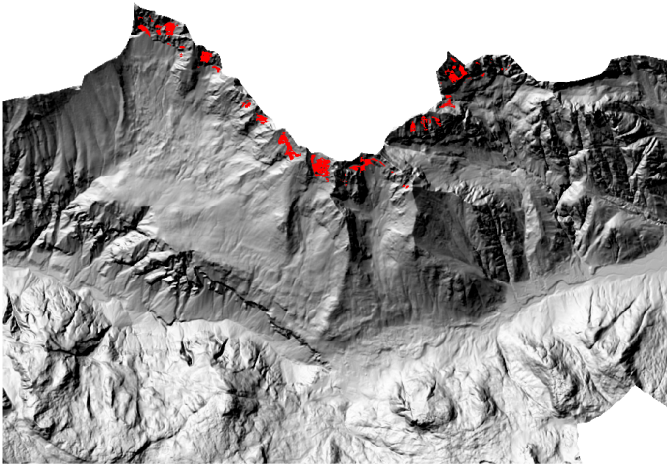


(e) Level E

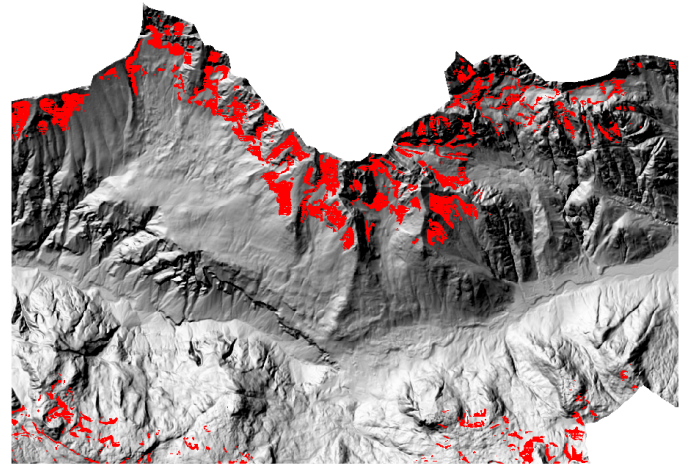
Figure 6: PRA fuzzy maps. The former model (Veitinger et al., 2016) and the extended one are compared. The common input data between the models were: 2 m of snow depth and no specific wind direction. The differences of the extended model from the former one are due to the snowpack stability levels and the combinations of the remaining parameters.



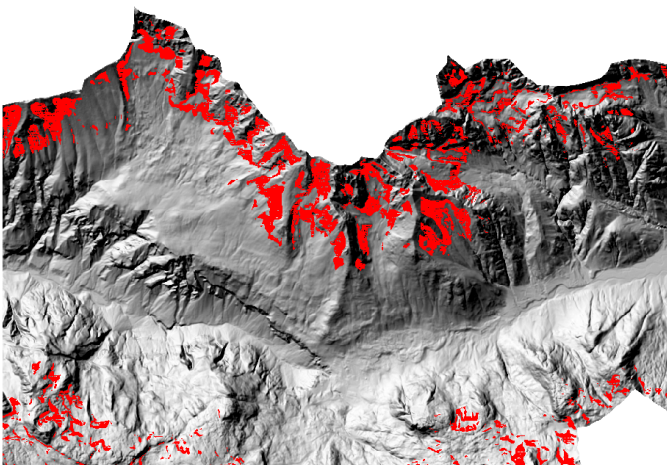
(a) Veitinger et al. (2016)



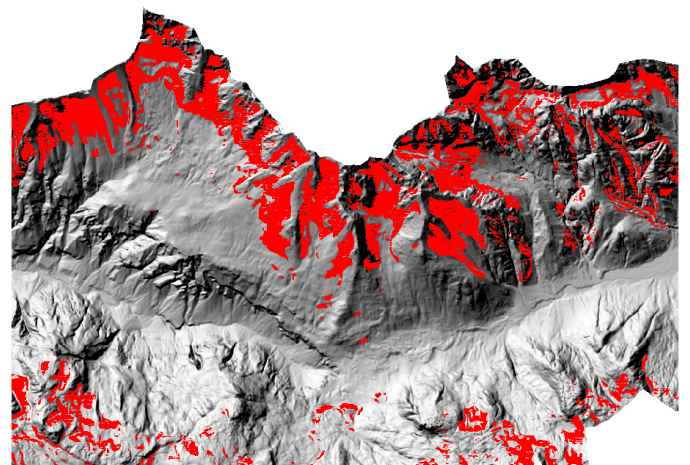
(b) Level B



(c) Level C



(d) Level D



(e) Level E

Figure 7: Boolean PRA map of the 'dangerous slopes' ($\mu_{PRA}(x) > 0.5$) extracted from Figure 6.

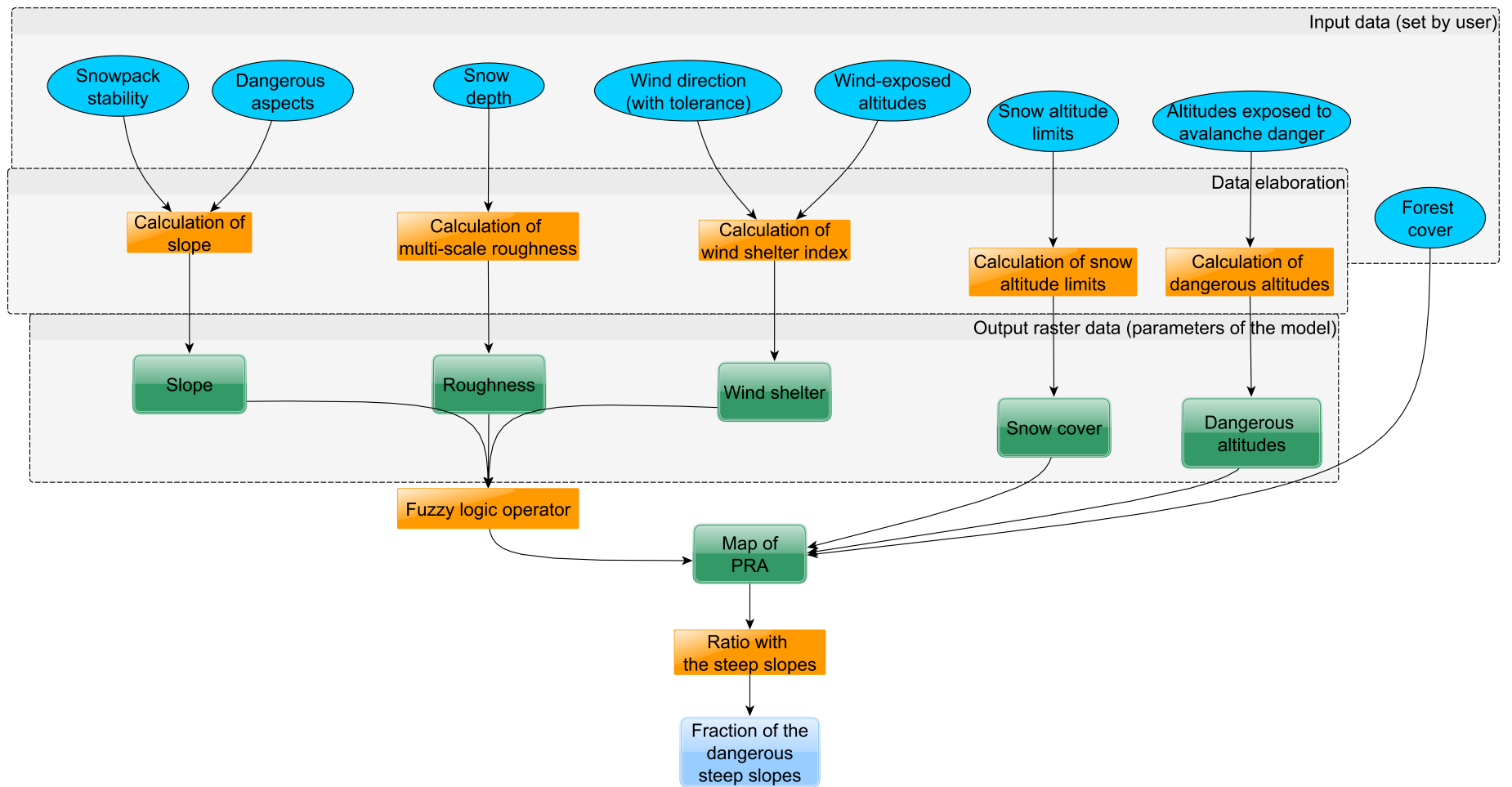


Figure 8: Flowchart of the algorithm with the input data (blue), the calculations performed on these (orange) and the output raster data (green). The last one is the aim of the model: the map of the Potential Release Areas (PRAs) in accordance with the current snow and weather conditions. The last box at the very end of the diagram (fraction of the dangerous steep slopes) is the percentage of dangerous steep slopes.

4 CONCLUSIONS

We hereby proposed an extension of the model of [Veitinger et al. \(2016\)](#) to support the avalanche danger assessment within the bulletins. Thanks to the automated algorithm, this extended model allows the geographical visualisation of the avalanche forecasting. It indeed calculates the release propensity of slab avalanches according to the current snow and weather conditions. The calculations are performed for every cell of the [DTM](#) of a given area, and the results are finally displayed through a [GIS](#) software.

The main achievements of the model are the following:

1. the modelling of the snowpack stability via slope functions;
2. the calculation of the fraction of dangerous steep slopes.

Point 1 represents the most important difference between the former model and the extended one: the variable width and colours of the identified areas show this difference graphically (Fig. 6–7). Once this parameter is included, the algorithm might be used as a forecasting tool. Point 2 is quantitative data which may be employed by the forecasters to support the assessment of the danger level objectively while drawing up avalanche bulletins.

Nevertheless, in order to provide a complete and reliable tool, more field work, experiments, and, above all, validation are needed. The following issues should be considered: the fuzzy functions were yet determined thanks to the experts' judgement, but their number was scarce. Furthermore, the extended model identifies the same width of the release areas all the time—except when using the most unstable level of the snowpack. The only varying thing is the release propensity degree, but the European Avalanche Danger Scale seems to suggest that this behaviour should be different: for instance, with a very stable snowpack, it states that the release is possible *only* on steep and very steep slopes. As far as we are concerned, this looks like a contradiction to what [Harvey \(2002, 2015\)](#) discovered: this particular issue should be further investigated by future research activity.

In addition to this, the extended model (like the former one) finds out the sole release areas of slab avalanches. The track and the deposition zones, as well as loose snow avalanches, are not taken into account.

Finally, even if the former model was validated, there is no validation of the extended one. Therefore, the extended model should be validated by performing its calculations at several avalanche warning services and investigating its reliability. Once done, the model could be useful for determining and validating the danger level of the bulletins and, for example, for providing precise hazard maps for ski-mountaineering competitions as well as for civil protection purposes (e.g. road closures).

The full work may be read in [Iacolettig \(2017\)](#).

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