Journal of Maps

ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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JOURNAL OF MAPS, 2016
http://dx.doi.org/10.1080/17445647.2016.1167785

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SCIENCE

Snow gliding susceptibility: the Monterosa Ski resort, NW Italian Alps

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ABSTRACT
Snow gliding, though a slow process, should be considered as important as the faster snow avalanche flows, as it can similarly produce severe damage to buildings and infrastructure. Snow gliding depends on snowpack properties, land cover and terrain parameters. Among these driving factors, in this work, we focus on stationary factors, that is, those that are considered features related to terrain and land cover, in particular those that could be derived from a Digital Elevation Model or land use/cover maps: slope angle, aspect, roughness and land cover. We propose a geographical information system-based procedure to create a snow gliding susceptibility index and to produce a related snow gliding susceptibility map. We tested this procedure in the Aosta Valley (NW Italian Alps), where the Monterosa Ski resort is located. The map covers an area of about 338 km^2 at a scale of 1:50,000. The proposed procedure is seen as a valuable tool to help safety personnel at ski resorts as well as in other scenarios (e.g. road management) in the identification of areas most prone to snow gliding.

ARTICLE HISTORY
Received 23 October 2015
Revised 10 March 2016
Accepted 15 March 2016

KEYWORDS
Snow gliding; susceptibility index; risk management; North-western Italian Alps; GIS procedure

1. Introduction

Snow gliding is the downhill motion of snow on the ground (In der Gand & Zupancic, 1966). The most recent review on snow gliding and glide avalanches (Höller, 2014a) summarizes all research carried out since the 1930s on the predisposing factors related to these processes. The studies of several authors (see Höller, 2014a for extensive literature) show that snow gliding is closely related to the topography of the terrain. The intensity of gliding depends on slope inclination, aspect, temperature and water content of the snow, temperature at the snow/soil interface and roughness of the surface.

Snow gliding, though a slow process, should be monitored within ski resorts just as avalanches are, as it can produce greater damage than the faster snow avalanche flows. Snow gliding can put great pressure on buildings, trees and masts and cause significant damage (Höller, Fromm, Leitinger 2009; Margreth, 2007a) which has led to specific guidelines being drawn up for the building of structures in areas prone to snow gliding (Margreth, 2007b). Leitinger, Hoeller, Tasser, Walde, and Tappeiner (2008) identified, from experimental data, the main predisposing factors leading to snow gliding and developed a spatial model to predict snow glide distances in order to create snow glide maps.

In this work, among all the predisposing factors to snow gliding, we focus on site parameters, that is, those that are considered features (rather invariable with time) related to terrain and land cover, in particular those that could be derived from a Digital Elevation Model (DEM) or land use/cover maps. We propose a geographical information system (GIS) based procedure to create a snow gliding susceptibility index (SI) and to produce a related snow gliding susceptibility map for a ski resort located in the Aosta Valley (NW Italian Alps).

2. Study area (07.65E, 45.93N)

The study area is located in the Aosta Valley in the North-Western Italian Alps, south of the Monte Rosa massif and covers an area of roughly 338 km^2 (Figure 1). The altitude ranges from 1200 to 4400 m asl, with a prevalent southern aspect (48% on SE-S-SW aspects). The vegetation cover is characterized mostly by grassland (33%), forest covers 20% of the area, dwarf shrubs and bushes respectively 5% and 9%, while the remaining 33% is represented by unvegetated areas (e.g. coarse scree, villages, rivers, glaciers).

The Monterosa Ski resort, which is located within the study area, covers an area of about 140 km^2; it extends over three different valleys south of Monte Rosa massif, from an elevation of 1500 m up to roughly 3500 m asl. The long-term mean annual precipitation recorded at the manual weather station of Lago Gabiet

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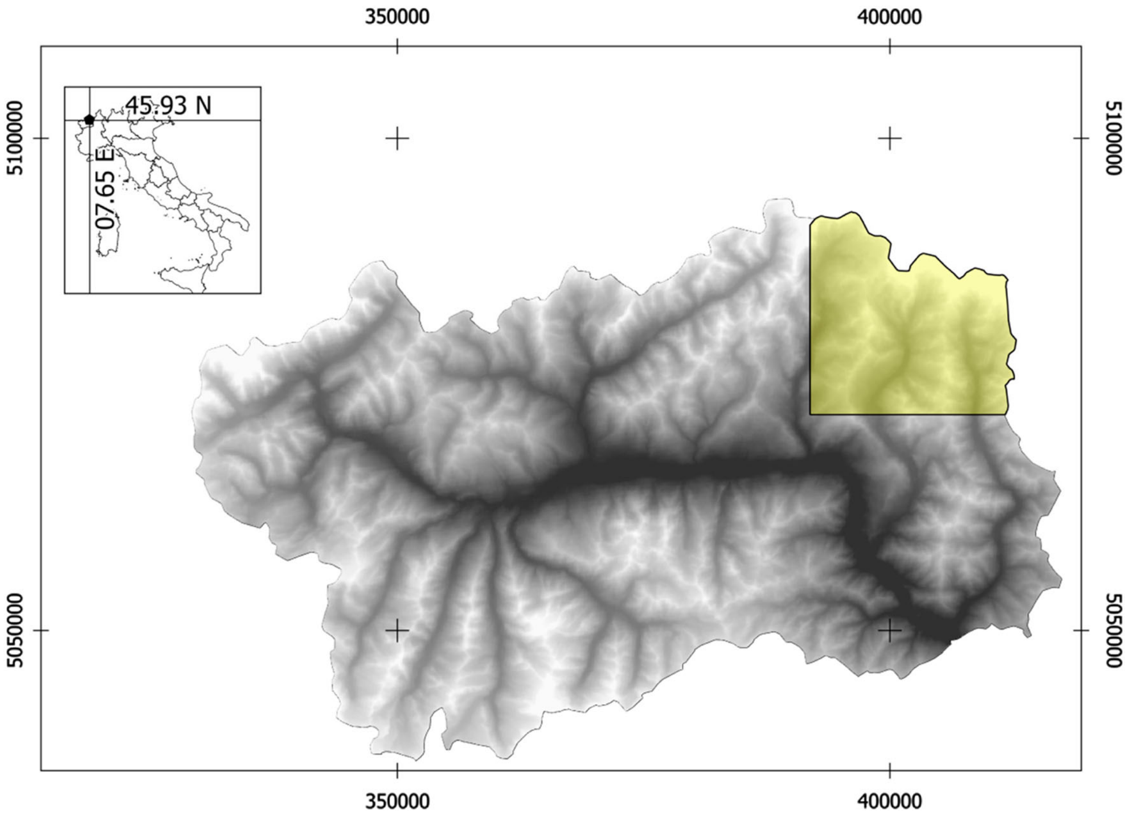

Figure 1. Location of the study area. The yellow polygon represents the extent of the study area.

(2340 m asl, Servizio Idrografico e Mareografico Nazionale – Ufficio Idrografico del Po) is 1066 mm year^{-1} (time series 1919–2001) and the mean annual air temperature is −0.2°C (time series 1978–2001). The average annual cumulated snowfall is 631 cm (time series 1928–2001) with 49 days of snowfall and 228 days of snow cover on average (Mercalli et al., 2003).

3. Methodology

The procedure was developed within a GIS and uses a DEM as the main input. From the DEM, different parameters, known to be causative factors in snow gliding, were derived and later combined to produce a SI which characterizes each pixel of the DEM (a procedure similar to those used by Stanchi et al., 2013). The spatial resolution of the DEM was 2 m. In the following sections we show the classification and the weighting criteria of the different parameters with respect to their driving importance to snow gliding, mainly following the indications of Leitinger et al. (2008) and Newesely, Tasser, Spadinger, and Cernusca (2000). We finally describe the procedure to generate the SI used to build the snow gliding susceptibility map.

3.1. Predisposing factors

The considered predisposing factors to snow gliding are: slope angle, land cover, roughness and aspect. The initial assumption is that all the considered parameters have the same weight with respect to causing snow gliding: the weight ranges between a minimum of 0 and a maximum of 10.

3.1.1. Slope angle

Gliding only occurs when the slope angle is at least 15° (McClung & Schaerer, 2006); at a greater angle, the downslope component of the gravitational force acting on the snowpack is larger than the combined frictional forces from the snow/ground interface and the internal frictional forces within the snowpack (Jones, 2004). Leitinger et al. (2008) developed a spatial snow gliding model derived from field data of slope angles in the range 15–44°; the model simulated the largest glide distances (of more than 1500 mm) for an inclination of 35–45°. Newesely et al. (2000) collected data for 2 winter seasons at 5 sites with roughly 150 glide shoes (the measuring principle with glide shoes is described in In der Gand and Zupancic (1966)) to measure snow gliding rates and found the largest gliding distances on inclinations between 35° and 40°.

In the proposed procedure, the slope angle was derived from the DEM using the algorithm described in Burrough and McDonell (1998). The range 0–90° was initially divided into seven classes (first column in Table 1). The class 35–45° was considered the most prone to snow gliding (Newesely et al., 2000).

The seven classes were weighted according to the intensity of gliding which is dependent on sin ψ, where ψ is the inclination of the slope. We first

Table 1. Classes and weights for the parameter 'slope angle'.

Slope angle (°) [a]	sinψ	Weighting factors	Definitively used weighting factors
00–15 (7.5)	0.130	2.0	0.0
15–25 (20.0)	0.342	5.3	5.3
25–35 (30.0)	0.500	7.8	7.8
35–45 (40.0)	0.643	10.0	10.0
45–55 (50.0)	0.766	12.3	9.0
55–75 (65.0)	0.906	14.4	0.0
75–90 (82.5)	0.991	15.5	0.0

[a]Values in brackets were used to calculate sinψ.

calculated sin ψ for the original seven classes (second column in Table 1) and then determined the weighting factors for the slope angle taking into consideration these values and the existing literature. We set a weighting factor of 10 for the range 35–45° (most prone to snow gliding) and calculated the remaining factors (third column in Table 1) by using the corresponding ratios of sinψ. We corrected these values as follows: a weight of 0 was given to the classes 0–15° and 55–90° as snow gliding cannot occur (McClung & Schaerer, 2006) due to either insufficient inclination (0–15°) or to the inability of snow to accumulate (55–90°); the class 45–55° was given a weight of nine as slopes with such steep inclination consistently tend to unload snow, which means that gliding will not increase to the expected extent when considering just sin ψ (this choice is also in accordance with Newesely et al. (2000), who found that gliding decreases on slopes with an inclination of more than 40°). The definitively used weighting factors are reported in the fourth column of Table 1, reducing the initial seven classes to five: 0–15° together with 55–90°, 15–25°, 25–35°, 35–45° and 45–55°.

3.1.2. Land cover

Snow gliding and glide snow avalanches mostly occur on smooth surfaces, smooth rocks and grassland (Mitterer & Schweizer, 2013). Long grass is more favourable than short grass in facilitating snow gliding; Newesely et al. (2000) found that on abandoned pastures the gliding distances increased compared to managed pastures. Feistl, Bebi, Dreier, Hanewinkel, and Bartelt (2014) always found smooth terrain beneath long compacted grass and measured a compaction below the snowpack of one tenth of the initial vegetation height for long grass while the compaction was only a quarter on areas with short grass. Snow gliding can also occur within sparse forest, but only if the distance to the surrounding anchors is more than 20 m (Höller, 2001; Leitinger et al., 2008; Viglietti, Maggioni, Bruno, Zanini, & Freppaz, 2013). A dense forest generally inhibits snow movement.

In the proposed procedure, the land use map of the Aosta Valley Region (ISPRA, 2007) was first clipped to the study area and the original 56 classes reclassified into six classes (first column in Table 2) to create a land cover map. The class 'grassland' was considered the most prone to snow gliding. The distinction between 'dwarf shrubs' and 'bushes' was made on the basis of vegetation height and flexibility, with soft dwarf shrubs being more predisposed to snow gliding than stronger lignified shrubs. In the class 'other' villages, caves, rivers, glaciers were included; we assumed that the process does not occur on such terrain.

The criterion for weighting the land cover was based on the calculation of the relative glide velocity starting from the equation $N = (1 + 3\ n)^{1/2}$ where N is the glide factor and n the relative glide velocity. The glide factor N expresses the increase in snow pressure with movement of the snow cover along the ground (Salm, 1978) while the relative glide velocity n is defined as the relationship between the movement on the ground and the movement on the surface (Haefeli, 1948). By considering the values of N reported by Margreth (2007b) for different land covers (second column in Table 2) we calculated the relative glide velocity n (third column in Table 2). We set a weighting factor of 10 for the class 'grassland' (the class where snow gliding is most frequent) and calculated the remaining weighting factors (forth column in Table 2) by using the corresponding ratios of the relative glide velocity n. Although not considered in Margreth (2007b) we also took into account forested areas, where snow gliding, though to a minor degree, is also possible. We set a weighting factor of 0.3 for those areas, taken from the work of Höller (2014b). The definitive values of the weighting factors are shown in the last column of Table 2.

3.1.3. Roughness

Smooth surfaces are the most favourable for snow gliding (In der Gand & Zupancic, 1966; Mitterer & Schweizer, 2012) as basal friction is low. McClung and Clarke

Table 2. Classes and weights for the parameter 'land cover'.

Land cover	Glide factor N[a]	Relative glide velocity n	Weighting factors	Definitively used weighting factors
Grassland	2.6 (N) or 3.2 (S)	3.08 (S) or 1.92 (N)	10.0	10.0
Dwarf shrubs	2.0 (N) or 2.4 (S)	1.59 (S) or 1.00 (N)	5.16	5.2
Bushes	1.6 (N) or 1.8 (S)	0.75 (S) or 0.52 (N)	2.43	2.4
Coarse scree, terrain covered by smaller or larger boulder	1.2 (N) or 1.3 (S)	0.23 (S) or 0.15 (N)	0.74	0.8
Forests				0.3
Other				0.0

[a]N assumes different values on aspect North (N) and South (S), from Margreth (2007b).

Table 3. Classes and weights for the parameter 'roughness'.

Roughness	Relative extent of gliding	Weighting factors
Low	1.00	10.0
Medium	0.25	2.5
High	0.10	1.0

Table 4. Classes and weights for the parameter 'aspect'.

Aspect	Relative extent of gliding	Weighting factors
South (112.5–247.5°)	1.0	10.0
East, West (67.5–112.5°, 247.5–292.5°)	0.6	6.0
North (292.5–67.5°)	0.2	2.0

(1987) reported a linear relationship between surface roughness and glide velocity.

In the proposed procedure, roughness was derived from the DEM implementing in R (R, 2014) the method proposed by Sappington et al. (2007). Three equidistant classes were defined from the range of values computed by Sappington et al. (2007) and the class with lower values for roughness (smoother terrain) was considered the most predisposing to snow gliding.

The criterion for weighting the parameter 'roughness' was based on Höller (2012) who determined the intensity of gliding for different terrain roughnesses by considering stagnation depth and the height of mounds. The stagnation depth (d') is directly proportional to the glide velocity and, according to Salm (1978), can be estimated as:

$$d' = 1/(2\pi)^3(\lambda_0/A)^2\lambda_0, \tag{1}$$

where λ_0 is the wavelength (m) and A is the amplitude (m) of the bed topography.

In Höller (2012) and in the present study amplitude (A) is the height of mounds. The lower the amplitude the higher d' and consequently the glide velocity. In Equation (1) it can be estimated to what extent d' (and hence the glide velocity) will change if amplitude (A) is modified. Three categories of amplitudes were provided: (1) mounds with an average height of 0.1 m; (2) mounds with an average height of 0.2 m and (3) mounds with an average height of 0.3 m. We selected mounds with a height of 0.1 m as a reference (relative extent of gliding = 1, second column in Table 3) meaning that, according to Equation (1), gliding on a ground surface with mounds of 0.2 m would decrease to 0.25, and to 0.1, respectively if mounds with a height of 0.3 m are present.

We set a weighting factor of 10 for the smoothest ground surface (0.1 m terrain roughness) and calculated the remaining factors (last column in Table 3) by using the corresponding ratios of the relative extent of gliding.

3.1.4. Aspect

Mitterer and Schweizer (2013) state that results on prevailing aspects for snow gliding areas are inconclusive as most studies did not consider all aspects. However, southern aspects were found to be associated with larger gliding distances by Leitinger et al. (2008).

In the proposed procedure, the aspect was derived from the DEM using the algorithm described in Burrough and McDonell (1998). The range 0–360° was divided into three classes (Table 4): the southern aspects (SE-S-SW: 112.5–247.5°) were considered the most favourable to snow gliding, while on northern aspects (NW-N-NE: 292.5–67.5°) the snow gliding process is expected to rarely occur.

The criterion for weighting the parameter 'aspect' was based on the work of Höller (2012) who determined the intensity of gliding for different aspects using the snowpack structure. He assumed that snowpack on north-facing slopes consists of faceted crystals and depth hoar while rounded grains dominate south-facing slopes. A viscosity of 1×10^{10} Pa s was assumed for rounded grains and 5×10^{10} Pa s for depth hoar layers (deQuervain, 1979), which is five times higher than for rounded grains. Höller (2012) divided the aspect into three classes (slightly different from ours): (1) SE-SW, (2) E-SE and SW-W and (3) NW-NE. South-facing slopes were used as a reference (relative extent of gliding = 1, second column in Table 4). Considering these assumptions, it appears, as viscosity is inversely proportional to gliding (see additional papers from McClung McClung (1975), McClung, Walker, and Golley (1994) and Clarke and McClung (1999)), that glide rates on north-facing slopes (NW-NE) are only a fifth (relative extent of gliding = 0.2) of those occurring on south-facing slopes (SE-SW). For E-SE and SW-W slopes the relative extent of gliding was assumed to be 0.6.

We set a weighting factor of 10 for south-facing slopes (where snow gliding is most frequent) and calculated the remaining factors (last column in Table 4) by using the corresponding ratios of the relative extent of gliding.

3.2. Susceptibility index

The layers of the four different parameters were weighted and reclassified according to the classification

Table 5. Classification and weighting factors of the different parameters for the determination of the SI.

Slope angle	Weight	Land use	weight	Roughness	weight	Aspect	weight
0°–15°	0.0	grassland	10.0	low	10.0	South	10.0
15°–25°	5.3	dwarf shrubs	5.2	medium	2.5	East, West	6.0
25°–35°	7.8	bushes	2.4	high	1.0	North	2.0
35°–45°	10.0	coarse scree	0.8				
45°–55°	9.0	forests	0.3				
55°–90°	0.0	other	0.0				

shown in Table 5 using QGIS (CERL, 1993) in order to generate four new layers with values ranging between the minimum (0) and the maximum value (10) of the weighting factors. The four layers were then combined using map algebra and cell values summed to obtain the snow gliding SI layer with values in the range 0–40. The higher the value of SI, the higher the probability of snow gliding processes occurring.

4. Results and discussion

The resulting map (Main Map) was compared with event records provided by the Monterosa Ski resort personnel. To assess the quality of the results a simple qualitative comparison with historical and more recent photos was made. The expert judgement of the ski patrollers was also used to check the quality of the results on the basis of their experience and memories (unfortunately much information is not written but only oral). We were able to identify several areas known to be affected by snow gliding and glide snow avalanches: for example, the two experimental test sites described by Frigo et al. (2014), where two pairs of glide shoes were installed to continuously measure snow gliding (in two winter seasons 11 events of glide snow avalanches were recorded). We also identified areas where those phenomena typically do not occur: for example, the Seehore avalanche test site described by Barbero et al. (2013) and Maggioni et al. (2013), a north-facing slope characterized by an extreme roughness. These areas are shown as examples in the four insets reported on the map (Main Map). While we could not apply a robust validation method as the quality of the data (oral testimonies and pictures) was not good enough, we could identify typical snow gliding areas on the map. A future goal to improve the effectiveness of the results should be to identify other areas to be monitored with georeferenced cameras or snow gliding detection equipment. With more precise data, it would be possible to use a different approach, including the analysis of the predisposing factors within designated snow gliding areas in order to assess their relative weights (an approach similar to Leitinger et al., 2008).

Our procedure is based on the assumption that an equal weight is given to the four considered parameters. Leitinger et al. (2008) found that the parameters forest stand, slope angle, winter precipitation, static friction coefficient, slope aspect E and slope aspect W have significant influence on snow gliding in a descending order of influence. However, to gene-ralize their results in terms of the relative importance of different predisposing factors, it would be necessary to apply their methodology in different areas.

It would also be crucial to apply our procedure in other areas where adequate snow gliding data are available (e.g. the areas considered by Leitinger et al., 2008; Newesely et al., 2000; Peitzsch, Hendrikx, & Fagre, 2014). Those areas could, if high resolution terrain models are available, be used to apply our procedure to DEMs at different resolutions in order to also assess the influence of the DEM resolution on the results. In the current study we evaluated the influence of using a 2 m and a 10 m DEM resolution on the final map by simply checking the percentage of area classified in one of the three different SI classes: 'low' (SI: 0–13), 'medium' (SI: 14–26), 'high' (SI: 27–40). In the case of a 2 m DEM, the class 'low' covers 22% of the whole area, the class 'medium' 65% and the class 'high' 13%. In the case of a 10 m DEM, the classes cover respectively a percentage of 13%, 55% and 32%. The difference between the two cases is relevant. The use of a more accurate DEM allows the identification of areas not detectable with a lower resolution DEM. For example, small areas with high roughness (not detectable with a 10 m DEM) are found within larger areas at low roughness; those areas could act as an anchor within the smoother surrounding areas and inhibit snow gliding. It is important for the expert to consider the resolution of the DEM when evaluating the results of the procedure.

Another issue to be discussed is the static approach we used, which only considers parameters related to the terrain, but for this reason easily derivable from a DEM. Referring to Heckmann and Becht (2006), our approach belongs to a 'basic disposition model', as it is a function of space only. More sophisticated approaches consider two components which are functions of space and also time, called 'preparatory' and 'triggering' components (Heckmann & Becht, 2006). In the case of snow gliding, these components might be the snow temperature at the snow/soil interface, snow depth or stratification which are known to be fundamental factors of the physical process of snow gliding (Mitterer & Schweizer, 2013). Such parameters vary depending on time and cannot be easily determined on a large scale; they are generally determined only locally in specific experimental test sites (e.g. Ceaglio et al., 2012; Frigo et al., 2014). Therefore, it is hard to include them in a 'preparatory' or 'triggering' disposition model, if only limited data are available. Preparatory and/or triggering factors might also be snow and weather data. Dreier, Mitterer, Feick, and Harvey (2013) characterized glide snow avalanche activity on the basis of some parameters recorded by an automatic weather station, finding a clear distinction between cold or warm events. Cold events occur at the beginning of the winter season, for which the most important driving factors are air temperature, the sum of new snow and incoming shortwave radiation; warm events occur late in spring, for which the most important driving factors are snow surface temperature, air temperature and the change in snow depth. Another example is Peitzsch, Hendrikx, Fagre, and

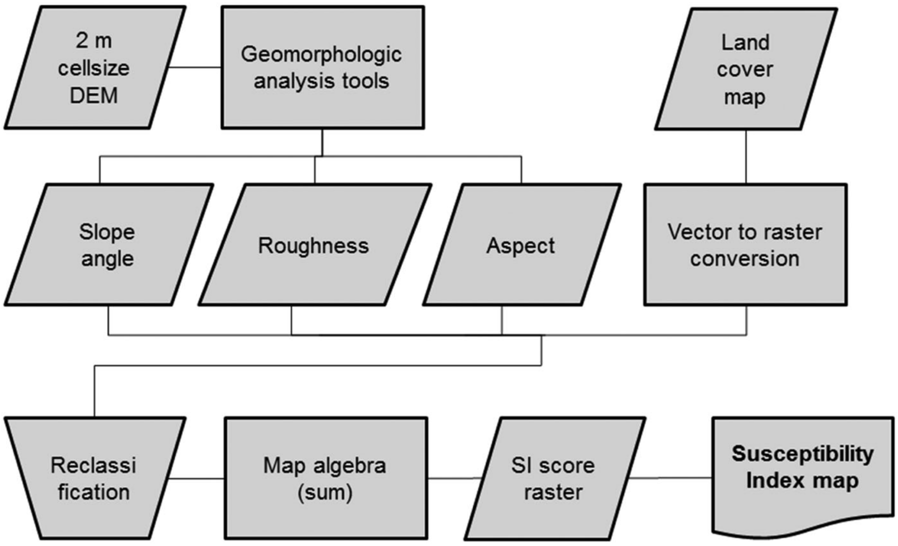

Figure 2. Conceptual model for the creation of the snow gliding susceptibility map (Main Map).

Reardon (2012), who found that air temperature and snowpack settlement appear to be the most important variables in glide avalanche occurrence.

Ski patrollers and road managers might find the most suited approaches or combination of approaches for their purposes. A snow gliding map could be used to identify the areas most prone to glide snow avalanches at a large scale while statistical models might provide threshold values for the most relevant snow and weather parameters to be used in an early warning monitoring system on the most dangerous sites shown on the map.

5. Conclusions

In this work we propose a procedure for the determination of a snow gliding SI and created a snow gliding susceptibility map for the Monterosa Ski resort in the Aosta Valley. Though validated only over a relatively small area and only using a qualitative method, we found good agreement between the areas classified with a high value of SI and the available historical data. In the future, the monitoring of the areas identified as most prone to snow gliding will be necessary in order to obtain more data to develop a robust validation of the procedure.

Maps of this nature are seen as useful tools in ski resort management; for example, masts of new cableways could be placed in those areas identified as less prone to snow gliding or be properly dimensioned. As glide snow avalanches often release where snow gliding is most intense, this map could also be used for avalanche risk management; ski runs below areas prone to snow gliding and glide snow avalanches can be protected with simple measures and/or monitored with specific systems (e.g. Frigo et al., 2014).

The proposed procedure could be extended to other applications. In villages it would be useful to identify areas where buildings are at risk from snow gliding. For viability it would be useful to identify areas at road sides that might slowly fall over the road.

It should also be noted that these maps, together with any kind of models, can serve only as an additional determining tool for avalanche experts.

Software

For the creation of the snow gliding SI we used the software QGIS (QGIS, 2013) and the programing language R (R, 2014). Figure 2 shows a flow chart that summarizes the conceptual model behind the procedure.

Aknowledgements

This work was undertaken as part of the project *Risk, Research and Innovation* of the Mountain Risk Research Team, a research unit formed for the framework of the 'Bando per la creazione e lo sviluppo di Unità di Ricerca' (D.G.R. 1988/2011 e s.m.i.), in the Operational Program 2007–2013 of the FSE and FESR – Regione Autonoma Valle d'Aosta. We thank the partners of the Research Unit, in particular Monterosa Ski for avalanche data, Fondazione Montagna sicura and Politecnico of Torino.

Disclosure statement

No potential conflict of interest was reported by the authors.

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