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Transboundary Storm Risk and Impact Assessment in Alpine Regions

D5.3 INTEGRATED METHODOLOGY FOR THE IDENTIFICATION OF SURFACE ROUGHNESS IN STORM-AFFECTED AREAS.

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AUTHORS:	Fabrizio Tagliavini; Roberta Dainese; Matteo Cesca	

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1 Introduction

The TRANS-ALP project is funded under the European Commission's DG-ECHO programme for civil protection activities, and in the programme's mission is expected a close connection between project partners and stakeholders. The programme provides for the development of methodologies that are useful to the civil protection system and that can be applied equally to the different countries of the Union. What is presented here follows this approach perfectly. Thanks to fruitful discussions with stakeholders over the two years of the project, it was possible to understand the needs of a community hit by a major storm such as VAIA and the resulting cascading effects. When the effects of a storm in an alpine context are to generate large windthrow areas in a forest, one of the most likely cascading effects is that of increased avalanche risk. The avalanche risk can be mitigated by the construction of mitigation works, for the implementation of which, in a context where suddenly a multitude of new avalanche sites have been created, it is often necessary to wait several years. Until mitigation works are implemented, the risk can therefore be managed through specific civil protection plans. For a civil protection plan to be effective, in addition to mitigating the risk, it must be sustainable in terms of the resources needed, both economic and human, to apply it. In the Cordevole valley, study area of the TRANS-ALP project, such civil protection plans were implemented with the support of the Arabba Avalanche Centre after the VAIA storm, and in deliverable 3.3 a methodology was proposed, with the development of appropriate GIS tools, to speed up the assessment of cascading effects and the elaboration of the corresponding plans. The application of civil protection plans has often proved to be hardly sustainable for the volunteers involved in the various monitoring and surveillance operations, especially during very snowy winters such as those of the 2020/2021 winter season where the action relating to surveillance has been too often necessary. The stakeholders' request was therefore to identify a methodology capable of setting the initiation thresholds of the monitoring activity that would be more sustainable for the volunteers involved, without, however, reducing the effectiveness of the plan in terms of avalanche risk mitigation.

In the following chapters, in addition to a general description of the dynamics of avalanche triggering and the state of the art of existing techniques for assessing surface roughness, a methodology that is designed to discriminate, for each windthrow area, the threshold of snowpack height necessary for the monitoring activity in the civil protection plans to be started is presented.

2 Surface roughness

Surface roughness is an inherent property of topography and is commonly measured using land-surface parameters extracted from digital elevation models (DEMs) (Tian et al. 2011; Lindsay, J.B. et al. 2018). A range of DEM-derived surface roughness indices have been widely applied in geosciences and environmental research (Stambaugh, M.C. et al 2008; Grohmann, C.H.et al. 2010).

For example, topographic roughness maps have been used to delineate large-scale geological units and their age (Frankel, K.L. et al. 2007). Roughness maps have been used to delineate landslides (Glenn, N.F. et al 2006; Li, X. Et al 2015). Surface roughness has also been widely applied to the study of surface processes in planetary science (Wu, J. Et al 2018). Two related topographic properties are often conflated in common usage of the term roughness:

First, roughness can denote local elevation variability, commonly called ruggedness. Landscapes can be characterized along a ruggedness gradient from flat to variable relief. Elevation range (i.e., local relief), standard deviation in elevation, and standard deviation of topographic residuals are common metrics used to characterize landscape ruggedness (Wu, J. Et al 2018).

The second dimension of roughness is surface complexity, a measure of topographic texture. Topography can vary from smooth to irregular texture. Roughness metrics that characterize surface complexity either

use surface area, or variability in the surface normal vectors (or components of normals, e.g., slope and aspect). Vector dispersion and standard deviation of slope have been used previously to characterize surface complexity (Grohmann, C.H.et al. 2010). Ruggedness and complexity are orthogonal concepts because areas of complex texture can exhibit relatively low relief (e.g., the rough micro-topography of hummock and hollow peatlands) and vice versa.

Roughness maps are derived by measuring ruggedness or complexity related land-surface parameters within the local neighborhood surrounding each grid cell in a DEM. Therefore, roughness is commonly mapped using the same roving window approach used for measuring many of the common topographic attributes. The size of the local neighborhood dictates the scale at which surface roughness is characterized. Ideally, roughness is assessed at a scale that is meaningful with respect to the scale of landforms, geomorphological processes, and the specific application (Hani, A.F.M. et al. 2011).

With the increasing availability of high-resolution remote sensing data, it is increasingly possible to quantify surface roughness over larger areas and to estimate how related ecosystem services and climate feedbacks change over time. Surface roughness has effects on one of the most relevant ecosystem services in mountain regions: gravity-driven natural hazards. In particular, the occurrence and runout distance of rockfall, debris flows and snow avalanches are influenced by terrain roughness and land cover (Baroni et al., 2007; May, 2002; Michelini et al., 2017; Teich et al., 2014). In naturarl hazard studies roughness is a parameter that is being taken into account more and more when assessing the hazard of a certain phenomenon.

In the following chapters a methodology, easily replicable in any mountain environment, for assessing roughness in avalanche release areas in order to better structure specific civil protection plans for avalanche risk mitigation will be described.

3 Snow Avalanches

Snow avalanches are a well-known natural hazard type and are defined as a sudden release of snow masses and ice on slopes, sometimes containing portion of rocks, soil, and vegetation; and by definition the downhill trajectory exceeds 50 m (McClung and Schaerer P., 1996).

A snow avalanche path consists of a starting zone, a track, and a runout zone where the avalanche decelerates and the snow is deposited (McClung and Schaerer P., 1996).

The starting zone is where the initial snow mass releases and the following paragraphs will examine the parameters that contribute to triggering the avalanche phenomenon

3.1 Avalanche formation

Avalanche release is the result of a series of mechanical actions involving terrain, snow cover and meteorological conditions and the understanding of avalanche release at the level of the single mechanical processes is unbelievably complex. Schweizer et al. (2003) describes five essential factors: terrain, precipitation (new snow), wind, temperature and snow stratigraphy as parameters that contribute to determine avalanche release. It is important to acknowledge that avalanche formation is the result of the complex interaction of such factors.

As a prerequisite to understanding the formation of avalanches, it is important to recognize that the winter snowpack consists of layers of different density or cohesion as a result of intermittent snowfall periods and changing meteorological conditions. From a mechanical point of view, slab avalanche release requires a chain of processes to occur within a wide range of scales. It is widely accepted that properties of slab and weak layer are crucial for failure initiation and crack propagation. A so-called weak zone can be recognized

as a weaker part within the weak layer, where the failure initiation propensity is higher and could lead to the release of a slab avalanche. Our understanding of the processes driving slab avalanche release have improved significantly during the last two decades. Among the various factors influencing the formation and size of an avalanche, it is now evident among the scientific community that avalanche release area size is rather controlled by topographic than by some dynamically critical phenomena.

Terrain is an essential parameter for avalanche formation. The strong link between terrain and the occurrence of avalanches is obvious. The concept of hazard mapping, as well as the planning of structural protection measures, relies on the fact that avalanches occur at specific locations on the mountain, whereas other areas are not affected. Generally, slab avalanches release on slopes between 28° and 55°. The frequency distribution of avalanches peaks between 35° and 40°, and symmetrically decreases for flatter and steeper slopes, respectively (Veitinger, 2015).

Other terrain parameters, such as aspect, roughness or distance to ridge, also have an effect on avalanche formation. Aspect is relevant as it reflects differences in exposure to radiation and wind, leading in general to different snowpack layering. Distance to ridge (Maggioni and Gruber, 2003) refers to wind exposure close to ridges, which hinders snow accumulation. The microtopograhy (roughness) of a slope has several effects on avalanche release areas: it provides mechanical support (anchoring effect), influences the evolution of the snowpack (metamorphism), and stability as a result.

During and after a snowfall event, wind, snow gliding and avalanches redistribute snow and accordingly smooth the geomorphology of the terrain by filling irregularities. During the snow accumulation season, terrain features successively disappear, leading to the progressive smoothing of the terrain surface. The evaluation of snow's influence on surface morphology has always been an important task in avalanche hazard assessment, and has been widely discussed in the literature, together with surface roughness.

For a shallow snowpack, terrain roughness can have a stabilising function, hindering the formation of continuous weak layers (Schweizer et al., 2003) as well as providing mechanical support to the snowpack. However, when the snowpack is deep enough to form a smooth surface, the stabilising effects of terrain roughness disappear or even reverse.

3.2 AVALANCHE HAZARD MAPPING

Hazard mapping is an important long-term land-use planning instrument, preventing humans from building in avalanche-prone terrain. A hazard map consists of different zones, corresponding to different danger levels. The danger level is based on the frequency of the events (return period) and their magnitude. The return period (T) is technically the mean time (usually in years), separating two events of a given intensity, assuming independence and the same probability distribution for the successive events. Several measures for the magnitude or intensity of an event exist, such as run-out distance, velocity, or impact pressure (p). Avalanche hazard mapping mainly focuses on large avalanche events reaching valley floors and villages.

Producing a hazard map is a complex task and requires a great deal of experience to be held by the individual in charge. The main points to be considered are as follows:

Consultation of historical avalanche events in avalanche cadastre;

- Analysis of terrain characteristics;
- Field survey to recognize old avalanche traces;
- Assessment of snow climatological conditions;
- Expected type of avalanche and its return period;

• Definition of release depth and potential release area;

• Evaluation of avalanche dynamics parameters and calculations.

Based on these criteria, design events are defined as a function of return period, which is related to a certain magnitude. Gradual hazard levels are then defined based on these design events. Many countries worldwide recognise hazard mapping procedures, yet the danger levels, return periods and intensity thresholds vary from one country to the next.

Snow avalanche hazard mapping has a long tradition in the European Alps. Hazard maps delineate areas of potential avalanche danger and are only available for selected areas where people and significant infrastructure are endangered. They have been created over generations, at specific sites, mainly based on avalanche activity in the past.

The problem arises when new territory with no or an incomplete historical record is to be developed. It is an even larger problem when trying to predict the effects of climate change at the state scale, where the historical record may no longer be valid.

In order to close this gap, numerical models of avalanche dynamics, are well-established tools in the current engineering practice of hazard mapping. They allow the assessment of an avalanche's velocity, low-height or impact pressure. Numerical models are especially important when historical data is sparse or completely lacking. The input parameters for numerical avalanche simulations are a detailed digital elevation model (DEM), the release volume and the friction parameters in the avalanche path. Although the procedure of running such simulations is relatively simple, the choice of input parameters is crucial and requires an experienced user. The release volume is particularly important, as it is the parameter with the highest degree of freedom for the user. The release volume comprises two complementary parameters, the release area and the fracture depth. In order to determine fracture depth for a given return period, empirical formulas exist. Fracture depth is mainly based on the 3-day new snow sum, which is statistically interpolated for different return periods (Salm et al., 1990).

3.3 Influence of roughness in defining avalanche release areas

Location and extent of avalanche starting zones are of crucial importance in order to correctly estimate the potential risk that avalanches pose to villages and infrastructures. To date, release area assessment is based on terrain analysis, combined with expert judgment. In alpine terrain, the snow-covered winter surface deviates from its underlying summer terrain due to the progressive smoothing caused by snow. It is assumed that this may change the potential release area size and location (Maggioni M. and Gruber U. 2003).

In the trans-alp project (Deliverable 3.3) an algorithm capable of automatically identifying the Potential Release Areas (PRA) of an avalanche has already been presented.

The tools developed by the technicians of the Arabba Avalanche Centre of ARPA Veneto and tested in the framework of the TRANS-ALP project, allow not only to define the PRA but also to assess the avalanche runout in an entire basin on a geomorphologic basis, as well as to evaluate which vulnerable elements may be affected by avalanche in order to implement specific civil protection plans.

The avalanche release area is an important parameter to be estimated for the avalanche hazard mapping procedure. While parameters like runout distance or deposition height are usually easy to measure, the PRA is often difficult to determine, due to terrain inaccessibility and/or severe weather conditions in the upper areas of an avalanche track.

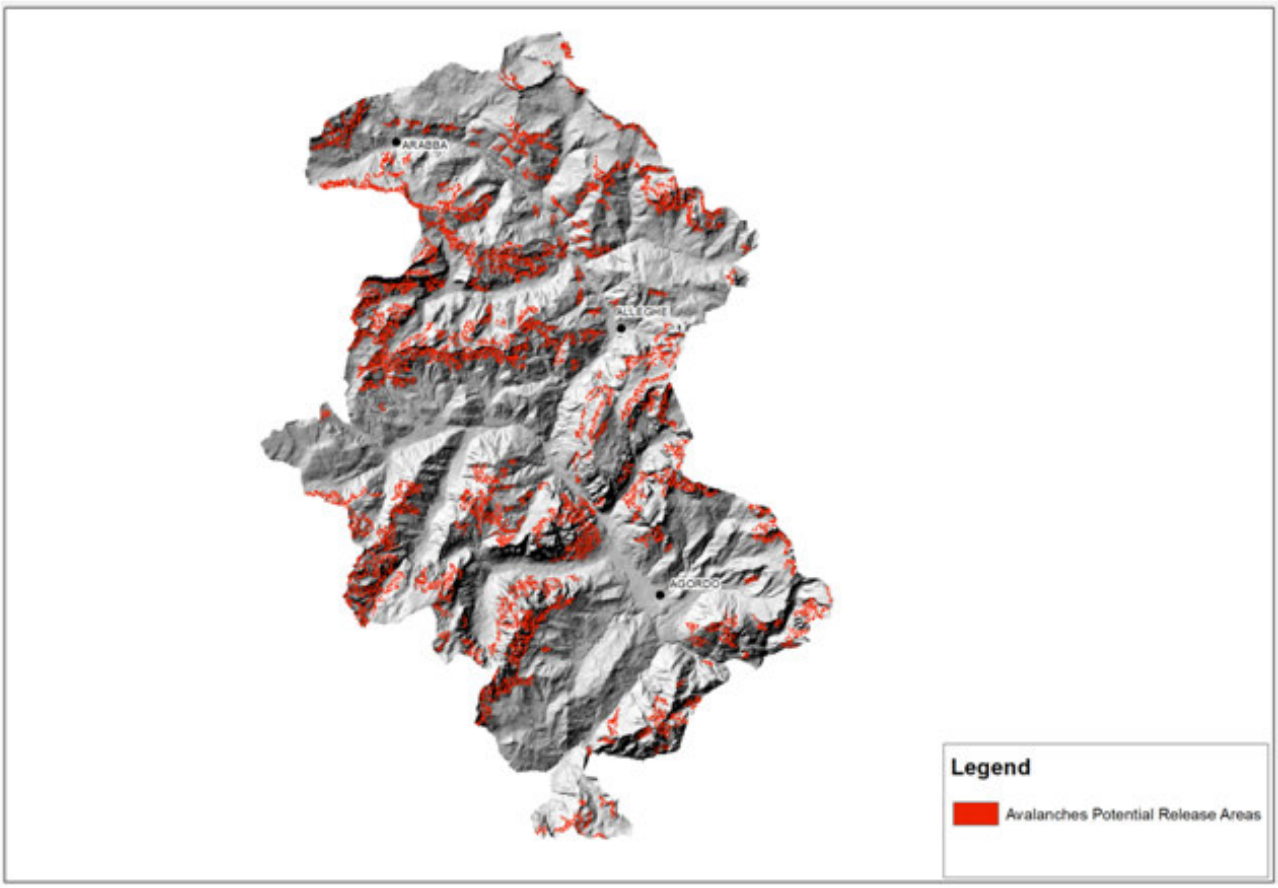

Figure 1: Potential Release Areas of the Cordevole Valley (for more detailed informations see deliverable 3.3)

Once the PRAs have been defined, however, it is necessary to assign a correct avalanche fracture height to each PRA. For the calculation of PRAs, a key parameter is the presence or absence of the protection forest.

Protection forests are forested areas with designated protective functions against natural hazards. As well described in deliverable 3.3, in the Alpine region, forests protect against different gravitational hazards, such as snow avalanches, rockfalls, shallow landslides and debris flows. Regarding snow avalanches, forests reduce the formation of homogeneous snowpack and the potentially weak layers with altered microclimates and stabilize snowpack using the tree stems (McClung and Schaerer P., 1996). However, once protection forests are significantly disturbed, their protective function may decrease or become eliminated if the forest is severely disturbed (Berger and Rey, 2004). As a result, disturbed forests may not provide sufficient protection against cascading effects. Furthermore, since forest disturbances are expected to increase in the future due to climate change the interactions between natural hazards and disturbed forests will be a topic of high relevance in mountainous regions (Bebi et al., 2017; Paine et al., 1998). Wildfires, snow avalanches, shallow landslides, insect outbreaks and storms are common natural disturbances for European forests (Baggio et al. 2022).

The tool developed in the TRANS-ALP project for the automatic determination of PRAs is extensively described in deliverable 3.3 and highlights how windthrow areas substantially changed the extent of avalanche sites.

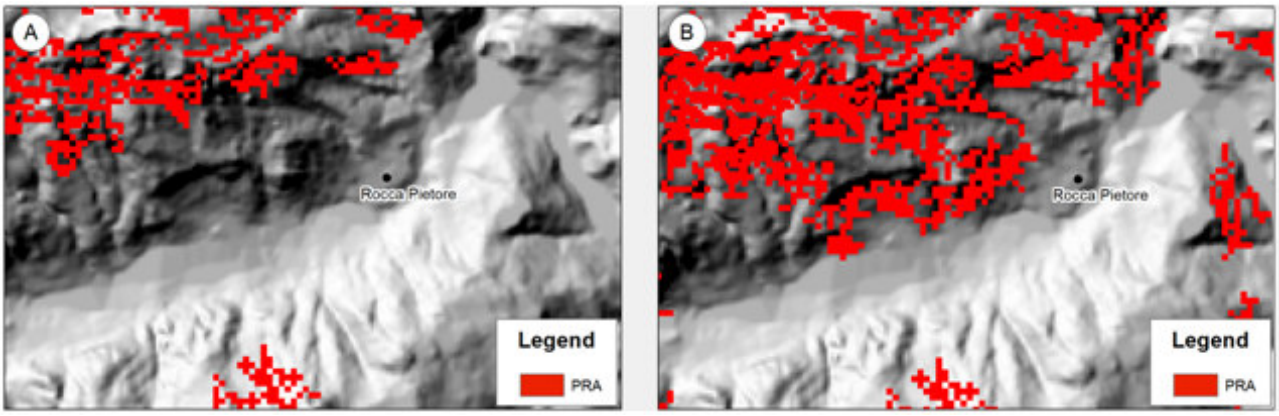

Figure 2: The Potential Release Areas evaluated by the tool developed by the Arabba Avalanche Center (ARPAV). A) with the pre-storm Vaia forest condition; B) with the post-storm Vaia forest condition. (for more detailed informations see deliverable 3.3)

Nevertheless, until now the roughness of the trees in the windthrow areas had not been taken into account when assessing how much snow should be considered dangerous for triggering avalanche phenomena.

After a windthrow event, fallen trees can provide residual protection against natural hazards, Such protection gradually decreases due to breakage processes and wood decay. Identification of the residual protective capacity and its temporal evolution together with natural regeneration are major processes for hazard evaluation and management of disturbed forests in populated mountain areas. The assessment of residual protection, the time of minimum level of protection and the period of forest recovery is particularly significant in case of protection forests mitigating snow avalanches. The spatial quantification of the protection capacity of forest biomass disturbed by a storm event is of crucial importance for hazard mapping. The resulting irregular surface is characterized by spaces between trees where a variable snow volume could be stored, contributing to snow cover stabilization and therefore hindering the release of snow avalanches.

4 Civil protection plans for avalanche risk mitigation

The following paragraphs describe the existing civil protection plans and how a proper assessment of the roughness on the windthrow areas can be a fundamental tool to improve such plans and make them more affordable from a executive point of view.

4.1 Definition of the civil protection procedure thresholds

Regarding the avalanche risk in the Cordevole valley, extraordinary civil protection plans were made to ensure adequate safety conditions to infrastructures and buildings, since preventive avalanche control measures, such as the artificial avalanche release, cannot be considered due to the presence of vulnerable elements potentially subject to damages. Such plans were developed based on simple snow height measurements and the comparison of the measured data with predefined alert thresholds, which allows the preventive evacuation of buildings and/or road closures in case of considerable risk.

Dynamic avalanche modelling using the RAMMS software has been used for risk calculation. For each area threatened by new avalanches, the risk was classified into three distinct levels:

- **Low risk** (areas outside the avalanche runout perimeter with return period TR>100 years, impact pressure P<0.3 kPa);

- **Medium risk** (risk at buildings/roads that can be disposed of preventive closure, such as holiday houses, roads with alternative routes, etc.);
- **High risk** (risk at permanently inhabited buildings, along roads with no alternative routes, etc.).

the methodology applied was the one proposed by Salm (1990) and already described in detail in deliverable 3.3.

Different thresholds were then identified, site by site, corresponding to the risk levels described above. The thresholds correspond to snow height increase values at which avalanches could be released and affect the differently vulnerable elements downslope. Descriptive and data collection sheets were therefore created for each site.

SCHEDA DESCRITTIVA - Sito 021 – Andraz
Comune di Livinallongo del Col di Lana

Fotografia 1 :

Fotografia 2 :

Caratteristiche del sito valanghivo:
*area complessiva** ***173778*** *m²*
quota m s.l.m. ***media*** *1433* *max* *1640* *min* *1382*
esposizione ***sudest***
**(comprendente aree di potenziale distacco scorrimento e accumulo fino alla soglia TR100)*

Beni potenzialmente interessati per soglia di rischio

SITO	SOGLIE		IMMOBILI INTERESSATI n° progressivo	STRADE
021 - "Andraz"	1	55 cm	30	SI
	2	100 cm	37	SI
	3	140 cm	41	SI
	TR100	193 cm	45	SI

Note
Sito ampio di dislivello medio (circa 250 m). Il sito interessa la S.R. 48 "Delle Dolomiti, l'abitato di Andraz e la relativa viabilità comunale di accesso. Interferisce con siti valanghivi censiti (n. 99 e 349 CLPV) nella zona di distacco di uno dei quali si erano realizzate, in passato, opere paravalanghe metalliche.
Ora il fronte di potenziale distacco si è allargato minacciando gran parte della frazione di Andraz; in particolare l'esbosco in corrispondenza del sito n.°99 può ampliare l'effetto dei distacchi, a spese soprattutto del nucleo meridionale dell'abitato di Andraz. Attenzione che la carta tecnica non è aggiornata e mancano degli edifici a rischio.

Campo neve di riferimento

CAMPO NEVE: LIVINALLONGO - 1

QUOTA: 1530.2 m s.l.m.
COORDINATE GAUSS BOAGA FUSO OVEST (EPSG 3003)
EST = 1729311 NORD = 5152843

Sito di osservazione di riferimento: n.°16 (prima del bivio di Cernadoi salendo da Caprile)

Schede grafiche di riferimento: 7A – 7B – D021

Figure 3: example of a descriptive sheet of the civil protection plan of the municipality of Livinallongo del Col di Lana

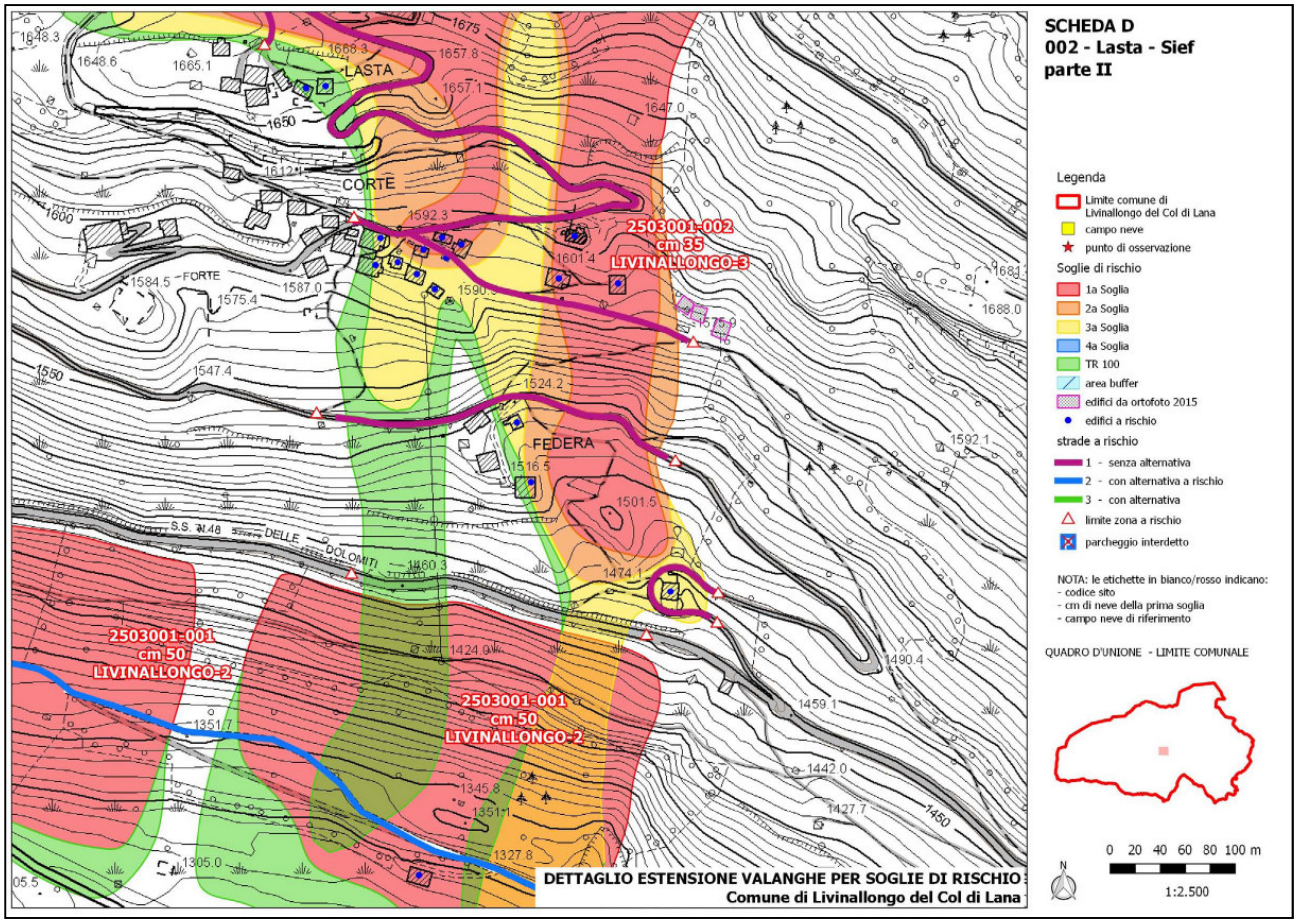

Figure 4: example of one of the maps annexed to the plan. The legend shows the road closure points and the houses to be evacuated according to the snow height thresholds shown in table 1

site	thresholds		property units affected	roads
021 – "Lasta Sief"	1	35 cm	7	yes
	2	70 cm	9	yes
	3	120 cm	17	yes
	Tr100	199 cm	21	yes

Table 1: snow height thresholds identified for the different measures foreseen in the plan

Table 1 shows the threshold values corresponding to the low, medium and high risk levels described above. These values are, as mentioned, the result of a dynamic avalanche simulation and were identified without taking into account the roughness due to the trees laying on the ground on the windthrow areas. Following the VAIA storm, in fact, an ordinance issued by the special emergency commissioner, stated that the removal of collapsed vegetation in areas that had become new avalanche sites that could affect built-up areas was conditional on the site being made safe by mitigation works. The threshold values above are valid from the moment the vegetation is buried by snow on the ground, thus ceasing its mitigating influence against new snowfall.

4.2 OPERATIONAL MENAGEMENT OF THE CIVIL PROTECTION PLAN

The operational management of the plan includes monitoring and surveillance activities, verification of the achievement of alert thresholds from which to evacuate houses threatened by potential avalanches, as well as keeping the mayor constantly informed of the evolution of the potential risk situation.

The technicians of the Arabba Avalanche Center of ARPA Veneto have trained the people involved in monitoring operations with specific courses in the snow field, so that they can collect the necessary data in the best possible way.

In relation to possible use for many consecutive years, the plan must be updated with particular reference to the following aspects:

- Refinement of the areas no longer forested as a result of wind damage, also by acquisition of aerial/satellite photographs;
- Reporting on avalanche phenomena of a size exceeding the parameterization of the plan;
- New hazard map following the eventual removal of the felled vegetation;

forecast data

On the basis of the forecast data issued by the Arabba Avalanche Centre, the surveyor will update every day at 2 p.m. the amount of new precipitation expected (expected HN). The forecast for the current day is relative to a 10-hour interval (period 14:00 - 24:00); for the two subsequent days it refers to 24 h (period 00:00 - 24:00). The forecast snowfall data are referred to the altitude of the reference monitoring field.

Snow field data

Surveys at the snow monitoring field identified in the plan must be carried out daily, at 08:00 and 14:00, and the data collected must be entered into the system immediately. The Arabba Avalanche Centre provides a platform on which to enter data that can then also be evaluated by ARPA Veneto technicians in support of civil protection operations.

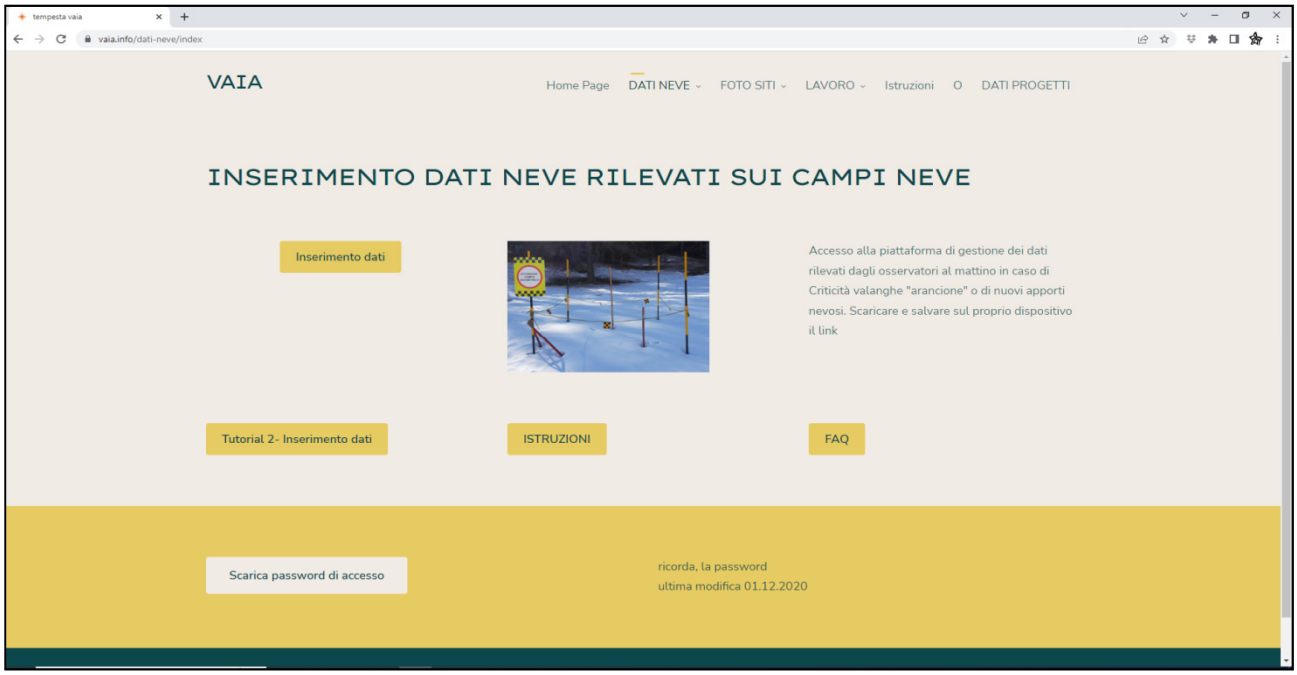

Figure 5: the web platform developed by the technicians of the Arabba Avalanche Centre for the use of civil protection plans

The data collected are as follows:

1. Total snow depth (HS) no. 2 times in one day (08:00 and 14:00)

2. Total new snow (HN) n. 1 time per day (08:00 hrs)

The snow height values read on the nivometer pole at the reference monitoring snowfield correspond to predefined avalanche release thicknesses studied (tab. 1). All the release thicknesses (measured orthogonally to the slope) were therefore adjusted to the altitude of the reference snowfield, considering an increase in new snow thickness of about 5 cm for every 100 m of increased altitude.

Monitoring must be carried out on all snow fields identified by the Arabba Avalanche Centre and include two modes of operation: observations and measurements.

Observations: Observations (e.g. avalanche activity, critical snow depth, signs of instability, etc.) should be carried out extensively over the affected area from a vantage point from which the PRA (or a large part of it) is clearly visible using binoculars, camera or video recording equipment.

Measurements: measurements (new snow depth, snowpack height, etc.) must be taken at a suitably prepared and equipped snow field with fixed instruments. The snow field, with dimensions of at least 3 x 3 m, must be located on flat or gently sloping ground, in a representative position with respect to the reference area, must be free of obstacles in the vicinity and easily accessible even in critical snow and weather conditions. A snow field can be used for monitoring several sites.

In addition to locally collected data, for the assessment of the overall hazard it is necessary to properly consider a series of products related to the general snow-meteorological situation issued by the competent authorities and, in particular, by the Arabba Avalanche Centre and by civil protection early warning system of the Veneto Region.

product	competent authority	Main contents	link
Avalanche Warning Notification	Regional Civil Protection Office	synoptic alert level (colour code) over the affected area	www.regione.veneto.it/web/protezionecivile/cfd
Snow and Avalanche Hazard Bulletin	Arabba Avalanche Center – ARPA Veneto	Avalanche hazard in the area of interest	www.arpa.veneto.it
Dolomites weather forecasting bulletin	Arabba Avalanche Center – ARPA Veneto	Weather forecast in the area of interest	www.arpa.veneto.it
Snowfall bulletin	Arabba Avalanche Center – ARPA Veneto	Snowfall forecast by area and altitude	www.arpa.veneto.it

Table 2: the different the different types of notification/bulletins that must be taken into account for the activation of civil protection plans

The products listed above are available daily throughout the winter season.

The civil protection plan also describes how often the observations and measures described above are to be carried out. In particular, there are 4 different levels of frequency of observations and measurements, corresponding to the 4 different alert levels communicated by the regional civil protection offices in the "Avalanche Warning Notification":

NO ALERT
➢ no observation/measure foreseen

YELLOW ALERT
Observation activities: ➢ checking the indications reported in the Avalanche Warning Notification; ➢ checking the indications reported in the Snow and Avalanche Hazard Bulletin; ➢ verification of achievement of critical snow depth from observation site; ➢ measurement of the total snowpack height at the reference snowfield; ➢ measurement of any fresh snow depth (in 24/72 hours) at the reference snowfield; *Actions:* ➢ if the critical snow depth has not been reached (even with fresh snow) and no further snowfall is is forecast, no further action; ➢ if the critical snow depth has been reached, or if it has not been reached but snowfall is expected in the next 24/72 hours to exceed the critical snow depth, activation of daily monitoring;

ORANGE ALERT
Observation activities: ➢ checking the indications reported in the Avalanche Warning Notification; ➢ checking the indications reported in the Snow and Avalanche Hazard Bulletin; ➢ intensification of the frequency of observations in the yellow alert scheme ➢ observation of avalanche activity in the PRA and neighbouring areas; ➢ observation of any other signs of instability (e.g. fractures and slippage of the snowpack in the PRA). *Actions:* ➢ if the critical snow depth has not been reached (even with fresh snow) and no further snowfall is is forecast, no further action; ➢ if the critical snow depth has been reached, or if it has not been reached but snowfall is expected in the next 24/72 hours to exceed the critical snow depth, activation of daily monitoring; ➢ communication to the Mayor for the purposes of confirming the orange alert and subsequent assessment of possible mitigation actions; ➢ if the critical snow depth has been reached and fresh snowfall of more than 100 cm is expected within the next 24/72 hours or even with less snowfall, but in the presence of avalanche activity in the PRA and/or in the presence of evidence of snowpack slippage or other signs of instability, communication to the Mayor for the possible local reconfiguration of the alert level from orange to red.

RED ALERT
Observation activities: ➢ checking the indications reported in the Avalanche Warning Notification; ➢ checking the indications reported in the Snow and Avalanche Hazard Bulletin; *Actions:* ➢ communication to the Mayor for the purpose of applying interdiction and evacuation measures ➢ apply the same monitoring modalities as in orange alert

If requested by the local authorities (Mayor) the eventual removal of measures (interdiction and evacuation measures) must be assessed on a case-by-case basis, taking the following aspects into priority consideration:

- recent snow settling;
- increase in the diurnal temperature range;
- End of spontaneous avalanche activity in the PRA and neighbouring areas;
- lack of other obvious signs of instability (e.g. new slip fractures);
- lack of weak layers beyond the critical snowpack height (to be assessed possibly by means of snow profiles and/or stability tests).

4.3 CRITICAL ISSUES IN CIVIL PROTECTION PLANS

identification of "threshold 0"

The civil protection plan described above provides the evacuation of houses and road closures according to specific thresholds of snowpack height identified for each site. As mentioned above, the thresholds identified do not, however, take into account the stabilising effect of felled trees left on the ground. It is therefore necessary to find a threshold, called 'threshold 0' from which to make the above considerations. This threshold must be somehow linked to the average height of the felled vegetation.

The extent of the damage created by the storm VAIA made it necessary the application of civil protection plans for dozens of municipalities in Veneto Region, and for each municipality there are multiple Potential Release Areas affecting settlements. Such a vast area did not make it possible to carry out a detailed study with field measurements of the average height of the felled vegetation, in some areas it would have been even more complicated given the inaccessibility of the sites.

The plans therefore provide for a number of observation sites where monitoring teams can qualitatively assess the state of the PRA snow cover. When at least 50 % of the PRA has the vegetation completely covered by the snowpack, then the measurements on the reference snowfield start and from that point the thresholds determining the various civil protection actions become valid.

However, the morphology of the Dolomite valleys, which are narrow and abrupt, does not always make it possible to have observation points that are accessible and meet the requirements of complete visibility of PRAs, such as visibility is not always guaranteed due to cloud cover even in sites normally visible from observation points. For this reason, the so-called "threshold 0" was arbitrarily set at 120 cm, considering this to be the average height of the trees on the ground for all PRAs involved in the civil protection plans.

Such an rough approach was initially necessary given the scarcity of information in the Potential Release Areas and the need to assess risk as the winter season approached, but it is evident, even in the image below, that not all PRAs have the same average height of the crashed trees, just as within each PRA the roughness can be variable.

Figure 6: From the image, it is possible to appreciate the different roughness of the windthrow areas

the perception of risk

The individual's perception of risk is influenced by previous habits and experiences: people tend to underestimate everyday risks and those with a low probability of occurrence. A statistical study carried out in Italy on a representative sample of citizens (Carrieri A., Fermani A. 2018), shows how the perception of risk from natural disasters varies over time and is closely related to the past experiences of individuals or communities. The conclusion of the study reports that the perception of the controllability of the event and the concern about the repetition of the disaster also have an impact on the individual's well-being in terms of the perception of the need to implement preventive actions. The participants consider the prevention activities promoted in the area to be inappropriate. In the same study, it is indicated how the perception of risk of a population that has been the victim of a natural disaster decreases as the years passed, thus creating a false sense of security.

Among the residents affected by the effects of the storm VAIA, the perception of the risk associated with heavy rainfall and strong gusts of wind is still in evidence, however, the cascading effects resulting from VAIA have certainly not been fully understood by the population and local administrators. The possibility of avalanches occurring in portions of the territory that have never previously hosted avalanche phenomena is scarcely perceived by residents. All even more so after the 2020-2021 winter season, which recorded

significant snowfalls that created hundreds of avalanches throughout the region, but no avalanches ever fell at VAIA sites thanks to the anchoring effect of trees on the ground.

This figure, from a technical point of view, confirms the validity of trees on the ground as avalanche risk mitigation, but for ordinary people it was instead read as if the Potential Release Areas were not real avalanche sites.

The great snowfalls of the 20-21 season led numerous times to the activation of civil protection plans, with men and equipment committed to the relevant actions, and the false perception of safety due to the simultaneous absence of avalanches led administrators to call for the plans to be revised and to assume a much higher "threshold 0". Some administrators declared on their own responsibility that measurements taken on site reported a height of the crashed trees of even more than 5 metres. However evidently false these statements were, it is still necessary to identify a methodology capable of objectively representing the real average height of crashed trees, so that the plans themselves can be updated by differentiating the "threshold 0" for each area.

5 IDENTIFICATION OF THE AVALANCHE INITIATION FREEBOARD

As well as in floods risk freeboard is defined as the space between the water level and the level where the river starts to overflow the bank, by avalanche initiation freeboard is meant the maximum height of the snowpack (HS) accepted before an avalanche can be triggered; that means the snow depth required so that fallen vegetation on the ground is not completely buried.

5.1 THE ROLE OF REMOTE SENSING IN IDENTIFYING ROUGHNESS AND VEGETATION HEIGHT

Over the last decades, the role of remote sensing gained in importance for monitoring applications in precision agriculture and for the evaluation of topographic surface roughness.

LiDAR or Light Detection and Ranging is an active remote sensing system that can be used to measure vegetation height across wide areas. The most common products returned by a LiDAR are the digital terrain model and the digital surface model.

The Digital Terrein Model (DTM) is a representation of the bare ground (bare earth) topographic surface of the Earth excluding trees, buildings, and any other surface objects. The Digital Surface Models, instead, is a representation of the surface captured, including natural and human-made structures such as vegetation and buildings.

It is possible to use the DTM to identify the roughness of the topographical surface, as well as the DSM to evaluate some interesting parameters related to vegetation. It is also possible to combine both models to obtain essential information on the height of vegetation, identifying the Canopy Height Model (CHM).

Canopy Height Models are a measurement of the height of trees, buildings, and other structures above the ground topography. This product is used in a variety of forestry applications including tracking vegetation and trees in a forest over time, calculating biomass, and estimating leaf area index.

A canopy height model is calculated by subtracting the digital terrain model (DTM) from the digital surface model (DSM).

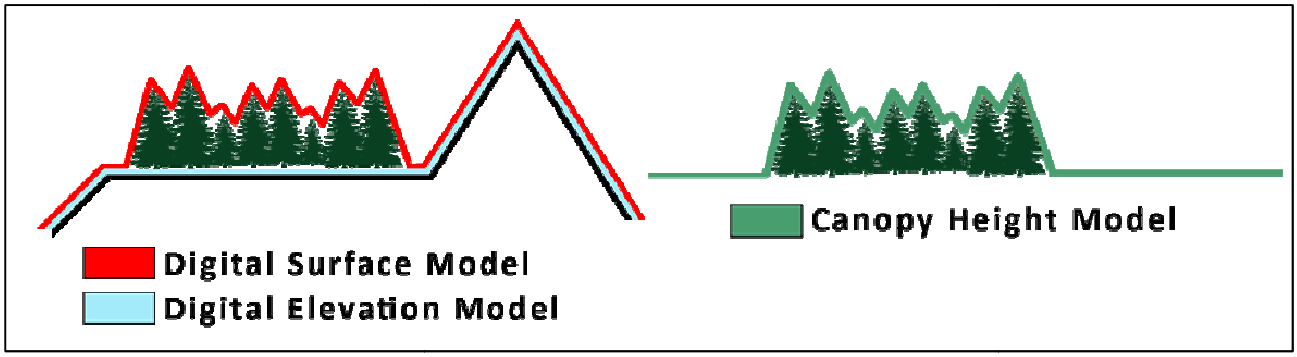

Figure 7: schematic representation of a Canopy Height Model (from http://gsp.humboldt.edu/)

Although very useful, the Canopy Height Model cannot be used to determine the freeboard generated by the roughness of the vegetation felled. In a situation like the one shown in figure 8, where the felled trees are piled one on top of the other, the avalanche initiation freeboard is not provided by the average height of the trees. In fact, as the snow falls, it would be placed on top of the trunks, filling the space between the lowest and highest trunk. A schematic representation of what has just been explained is shown in the small illustration in figure 8.

Figure 8: schematic representation of the Avalanche Initiation Freeboard. The values to be used for calculating the height of the freeboard are those representing the gap available for the vegetation on the ground not to be completely buried.

It is evident from the diagram in figure 8 that the freeboard is a parameter related to the roughness of the vegetation felled on the ground and that the CHM must in any case be calculated preliminary.

5.2 Evaluation of Canopy Height Model in the windthrow areas

For identifying the correct algorithm, it is still necessary to start from remote sensing data. Topographical data in the study area were collected with LiDAR technology using a professional remotely controlled drone. The data collected in .LAS format are representative of a point cloud with a spatial resolution of 50

cm. From the cloud of points it was then possible to interpolate the necessary rasters to create the desired maps. Orthophotos taken during LiDAR flights were used to appropriately map the windthrow areas.

In the study area, there were already two different maps of the windthrow areas: the first was carried out by the technicians of the Arabba Avalanche Centre in the days immediately following the VAIA storm by means of field surveys and then reported in a GIS system. The second was done with a semi-automatic classification using other remote sensing data by the regional agency AVEPA. Both previous maps, however, had errors, which for the purpose of this deliverable certainly needed to be fixed.

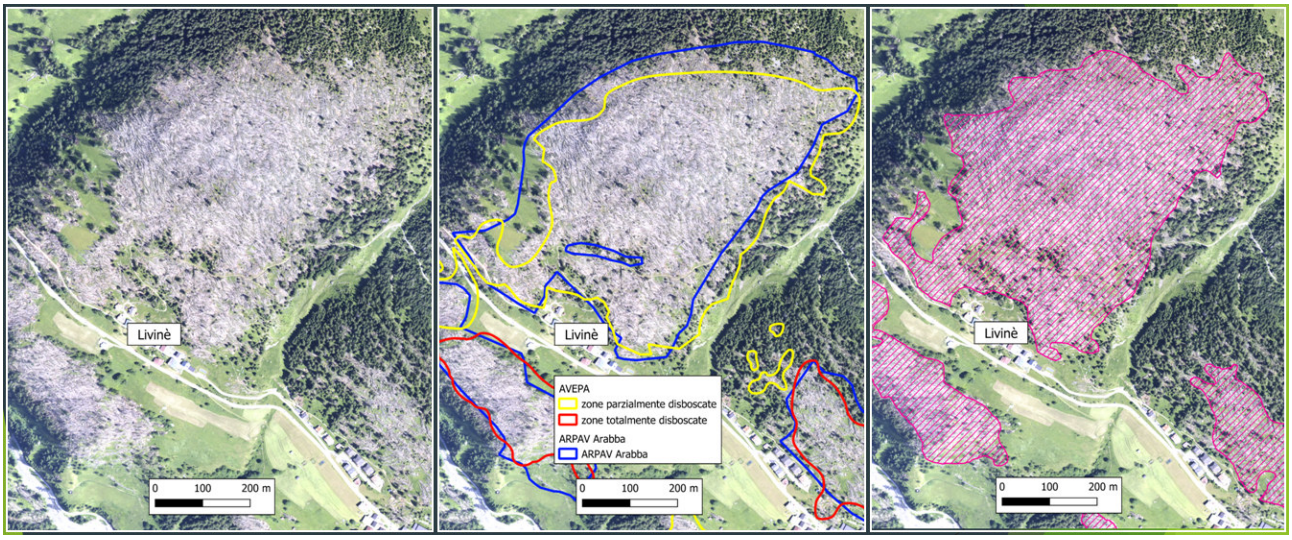

Figure 9: example of windthrow area maps. A) Ortophoto; B) previous maps available Yellow and red from AVEPA Survey, Blue froms ARPAV Survey. C) areas mapped within the TRANS-ALP project

The new map was necessary in order to exclude from the calculation those areas within the PRA that may, however, influence the calculation of roughness and the evaluation of the avalanche initiation freeboard.

Since the LiDAR flight was made after the trees obstructing the road had been removed, special care was taken to exclude all those portions of the windthrow area from the map, so that the final result would not be affected by such low roughness values (Fig. 10).

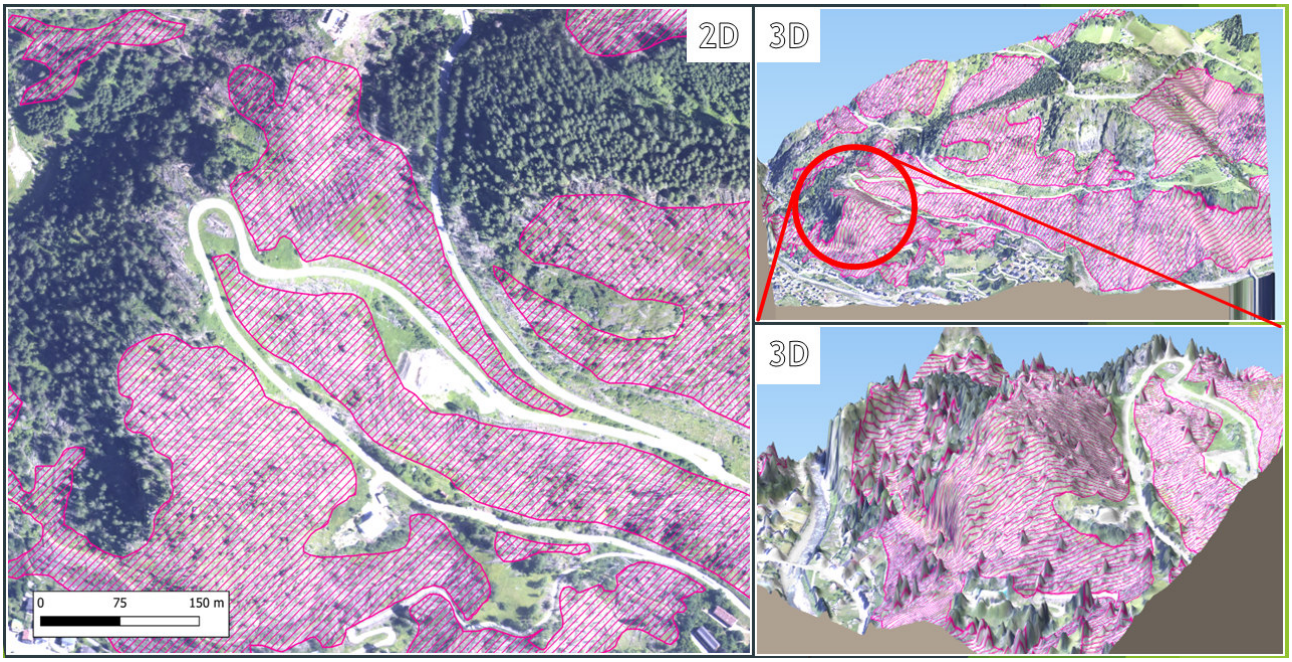

Figure 10: particular detail was given in delimiting the areas by excluding the parts where the timber had been removed, in order not to influence the final result

311 areas of damaged forest from the VAIA storm in the study area were thus mapped in detail, many of which potentially threaten vulnerable elements of strategic importance or entire villages. Once the mapping was completed, the Canopy Height Model was calculated. However, the results were not immediately satisfying, because in addition to some errors in the restitution of the point cloud, the mapped areas are not only concerned with crashed trees but also with infrastructure that affects the final result.

The main problems encountered were:

- errors in the Digital Surface Model especially in the presence of escarpments;
- Canopy Surface Model values completely offset below the power line.

In order to correctly apply the methodology proposed in this deliverable, it is absolutely necessary not to introduce any error in the data input that could misalign the calculation of the avalanche initiation freeboard.

Airborne topographic data collection requires removal of errors that arise due to surface features that obstruct the ground from the sensor. Typically, this has been based on manual correction and/or automated filtering. The latter has provided a method for identifying and removing unwanted surface obstructions in large topographic data-sets. However, the algorithms used are unintelligent in that they cannot reliably differentiate between the various types of obstructions and the ground. And it is precisely where the correction algorithm struggles to distinguish between obstacles due to vegetation and soil that an error can be introduced into the restitution of digital models. The best example is when small but deep escarpments interrupt the topography, creating depressions of tens of metres. Correction algorithms applied to the Digital Terrain Model return a correct course of topography, but such algorithms cannot be applied as effectively to the digital surface model, which is much more rarely used for planning purposes, but is of absolute importance for the creation of a canopy height model.

Figure 11 shows, by way of example, the CHM trend in one of windthrow area affected by the VAIA outbreaks. It is evident that at the escarpment the digital surface model returns absolutely overestimated

values for the vegetation, and if no manual correction is made, this error would substantially compromise the calculation of the freeboard.

Figure 11: particular of an error in the restitution of the CHM due to a data acquisition problem that can occour along the escarpments

Although the most correct procedure to apply to manual correction would have been to take field measurements of plant height and report them, even in a random manner, in the Canopy Height Model, it was decided, for a cost-benefit analysis, that portions with such errors should simply be deleted from the area on which the avalanche initiation freeboard had to be calculated. The decision to remove these areas from the calculation was motivated by the fact that, first of all, they are only small portions within the polygon to be analysed and, secondly, in the presence of escarpments the vegetation tends to be absent and therefore no values should be recorded that could substantially influence the avalanche initiation freeboard.

With regard, however, to the data of the trees felled on the ground in correspondence with the high-voltage lines, a different analysis was made. As is well known, the digital surface model returns the highest of the surveyed elements as a height value, and the power line is placed at extremely higher heights than the crashed vegetation beneath it.

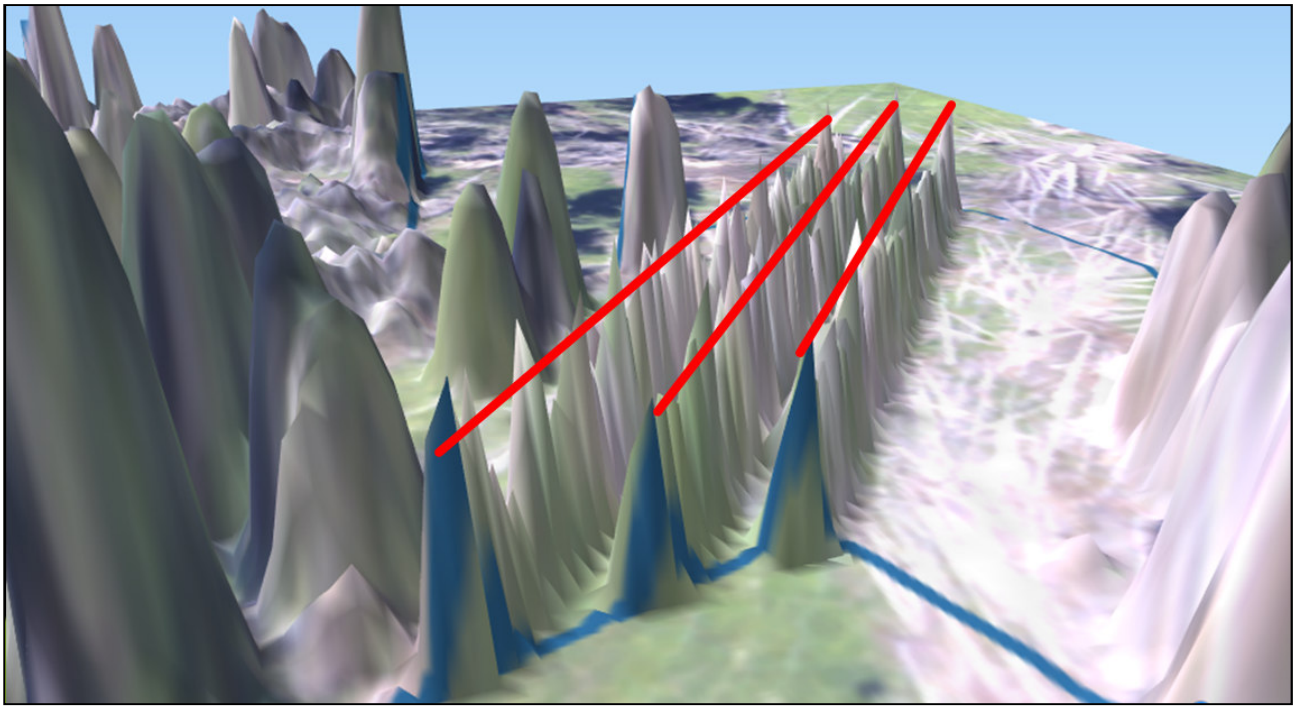

Figure 12: the red lines highlight how the CHM represents, instead of the height of the plants, the power line

Figure 12 shows how in case where the power line passes over the polygon to be analysed, the surface height is excessively offset. To solve this problem, a query was first made in a GIS environment, using data from the digital topographic map, and extracting from this all the existing power lines. The power lines were then crossed with the polygons of the VAIA windthrow areas and the results were analyzed. A survey was then carried out in some of the areas affected by this overlap and the average roughness of the ground vegetation was measured. In the Canopy Height Model, the values of these areas were then replaced with the values measured in the countryside by applying a random function that could represent the observed reality. Although this type of substitution does not correctly represent the reality, as far as the calculation of the average vegetation roughness of each polygon is concerned, it represents the best and most representative compromise of the morphology of the surface to be analyzed.

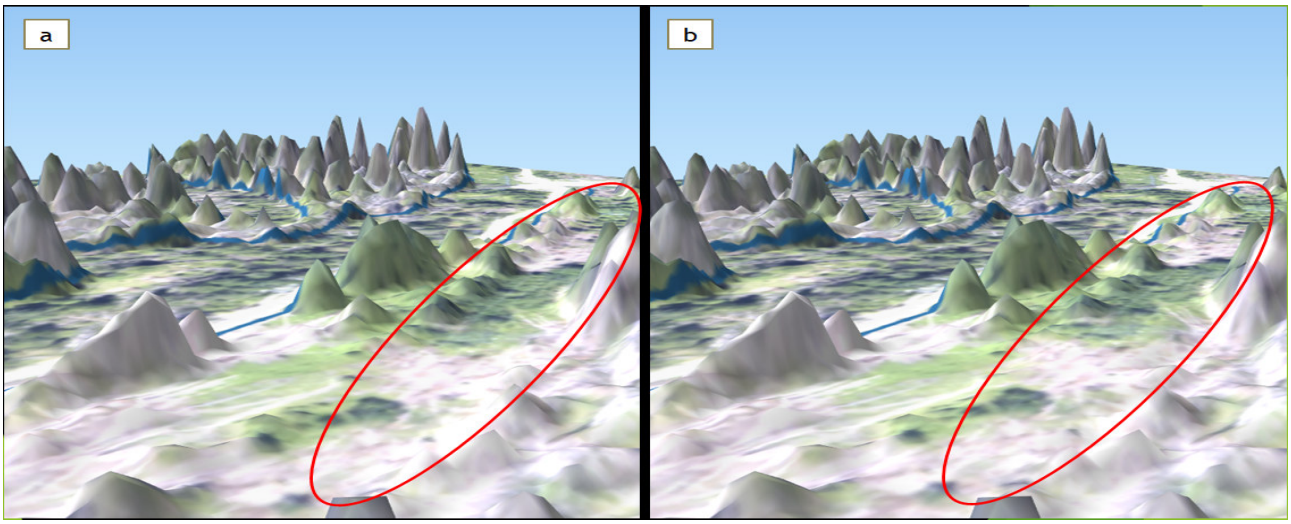

Figure 13: example of adjustment of the error due to the power line: a) the values of the power line were removed from the CHM; b) instead of the power line, the average values identified during specific inspections were added using a random function

Once all the errors have been corrected at the escarpments and the random function has been applied to normalise the roughness values un beneath the power line, the Canopy Height Model was used as input data in the algorithm to find out the avalanche initiation freeboard.

5.3 AVALANCHE INITIATION FREEBOARD

As explained in the previous paragraph, the CHM cannot represent the Avalanche Initiation Freeboard, but this can be derived from the roughness of fallen trees. Several algorithms are currently being studied to identify roughness coefficients, the most used by the scientific community is the topographic ruggedness index (TRI) developed by Riley et al. (1999) to express the amount of elevation difference between adjacent cells of a DEM.

The TRI calculates the difference in elevation values from a center cell and the eight cells immediately surrounding it. Then it squares each of the eight elevation difference values to make them all positive, sums them, and takes the square root. Basically the TRI contains the sum of the differences between the central pixel and the 8 surrounding pixels.

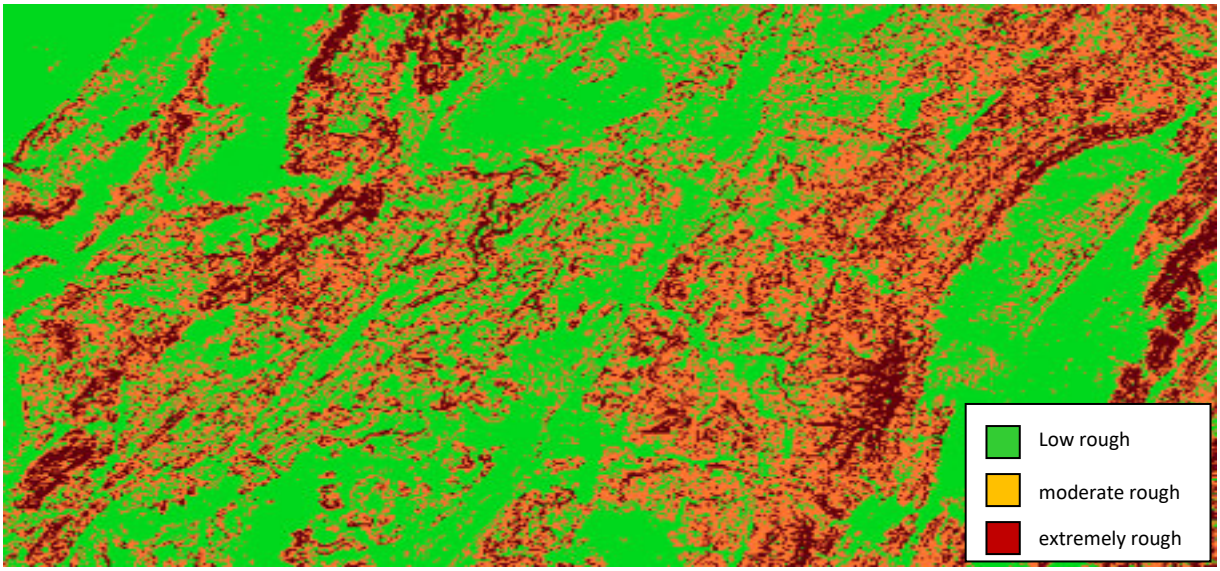

Figure 14: example of Topographic Roughness Index

Although extensively tested, and also used in the implementation of the GIS tools presented in deliverable 3.3 of the TRANAS-ALP project for the determination of PRA, the TRI, as an index, does not correctly represent the average value of the avalanche initiation freeboard. The way the algorithm works is ideal for representing a roughness index that can be reclassified from slightly rough to extremely rough, but gives no indication of how much snow can fall before the vegetation becomes snow-covered.

In order to achieve what was set out to do, we then developed an algorithm capable of returning a particular focal analysis of the Canopy Height Model. The focal analysis performs, for each pixel in the map, 8 different subtractions, one for each pixel neighboring it. The output map will represent, for each pixel, the maximum value of this difference.

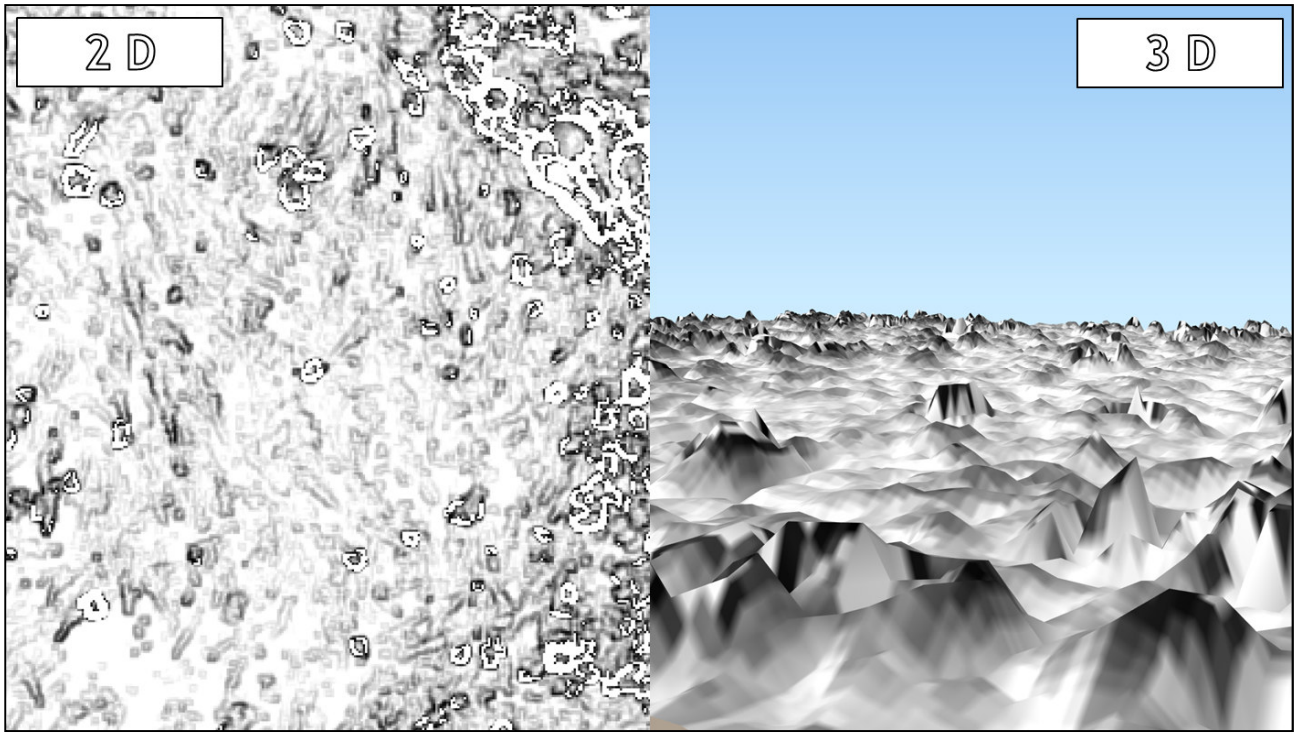

Figure 15: example of the maps obtained by the algorithm used for identifying the Avalanche Initiation Freeboard

The final result is a raster map that does not faithfully represent reality, but is perfectly meaningful for determining the average values, for each windthrow area, of the avalanche initiation freeboard.

The raster shown in figure 15 is the numerical representation of the focal analysis described above, and it therefore gives a pixel-by-pixel indication of the possible avalanche initiation freeboard, but the aim of this work is to find, for each individual polygon, a single freeboard value so as to optimise the civil protection plans.

As described in Chapter 3.2, the civil protection plans, to date, require volunteers to make qualitative observations of the PRAs, and when snowpack in these areas buries the fallen trees for at least 50 per cent of the area's extension, monitoring procedures are activated. The adopted principle was therefore the same and the results of the freeboard map were analysed in such a way that a unique value was identified for each polygon that represented at least 50% of the values present from the minima of the Gaussian curve.

To correctly apply the methodology proposed here, however, the input raster must be further corrected. When algorithms are implemented for certain types of spatial analysis, it must always be borne in mind that any model is a simplified representation of reality. In particular, the raster shown in figure 15 is the numerical representation of what appears in figure 16 and certain considerations must be done.

Figure 16: example of a windthrow area in the Cordevole Valley

From a practical point of view, some special situations must be considered before averaging the values in the avalanche initiation freeboard map and in particular:

- standing trees;
- values equal to or close to 0

From the point of view of avalanche risk mitigation isolated standing trees have no effect. It is known, in fact, that a protective forest requires, among other parameters, a density of about 250 trees/ha to be effective (Schneebeli, M. & Meyer-Grass, M.1992).

In a situation such as the one illustrated in figure 16 in addition to not giving any protective function, standing trees would lead to an alteration of the average freeboard values. In an analysis that must lead to an average value among those represented in the map, in fact, having values exceeding 30 metres in height, however mathematically correct, would overestimate the avalanche initiation freeboard. It was therefore decided to give all standing trees a height value equal to that identified in some surveys to the maximum height reached by trees piled on the ground which was measured at about 3.5 metres.

A similar approach must be taken for all freeboard map values equal to or close to 0. The algorithm developed to realise the freeboard map can return values equal to or close to 0 when the 8 neighbouring pixels of a central pixel have values very close to each other. This situation in practice can be represented by two trees on the ground bordering each other and perfectly aligned, as well as in the absence of trees on the ground. With regard to the calculation of the average freeboard, these values must be removed as they do not contribute to the definition of the avalanche triggering protection height and their use would lead to an excessive underestimation of the final value. Therefore all values below 50 cm, which is the spatial resolution of the LiDAR used, were removed from the calculation.

5.4 FINAL RESULTS

Once all the corrections described above had been made, it was possible to calculate the avalanche initiation freeboard for all the windthrow areas that are focused on the special civil protection plans.

The final result shows that in the 311 areas analysed, the average heights of the avalanche initiation freeboards are different from each other. This result is not entirely unexpected, as the freeboard value is influenced both by the density of the damaged forest and the slope on which it is lying. Figure 17 shows the two extremes of the result obtained: near the village of Alleghe a specific area shows an average freeboard of 80 cm, while near the Livinè hamlet another polygon shows average values of about 2.3 metres.

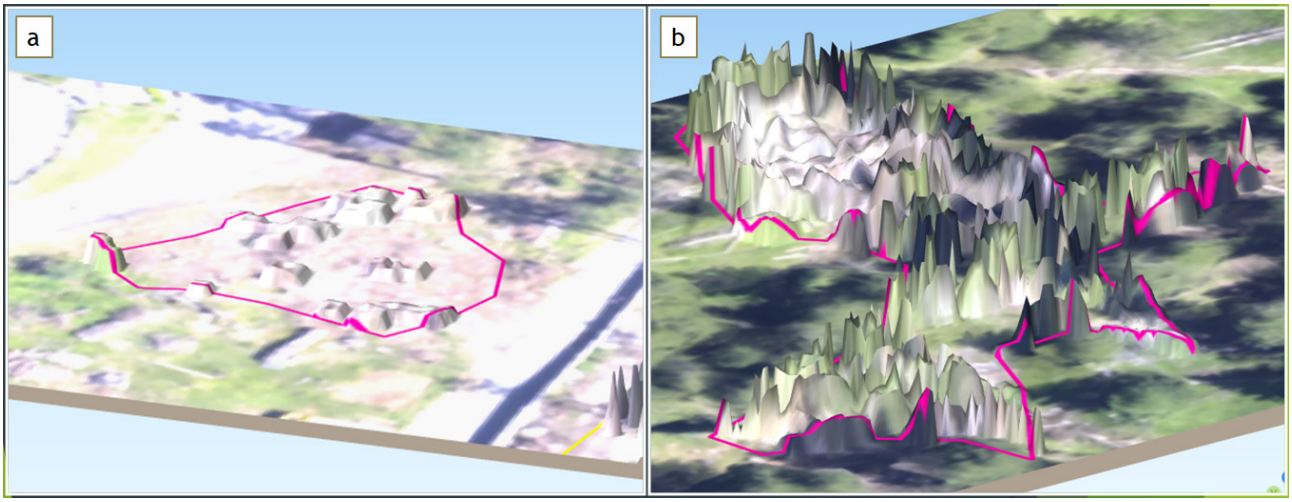

Figure 17: two examples of the Avalanche Initiation Freeboard a) an area near the village of Alleghe; b) an area near the village of Livinè

Final results are summarised in table 3

Polygons mapped	311	
Area max	937.697,4	m^2
Area min	456,7	m^2
Polygon freeboard max	2,32	m
Polygon freeboard min	0,8	m
Polygon freeboard average	1,63	m

Table 3: some statistics of the final results

As mentioned in section 3.2 the avalanche initiation freeboard in the civil protection plans was arbitrarily set at 1.2 m for all Potential Release Areas and was set as “threshold 0”. The table 3 shows that this threshold is underestimated compared to the values of many areas, according to the methodology applied. This means that, although in favour of safety, the monitoring actions of the civil protection volunteers have been activated too often, which makes the plans themselves onerous in terms of the number of hours needed to be applied for a long time. In the same way, many polygons have a freeboard of less than the “threshold 0” (1.20 m), which means that potentially the fallen trees in these areas could be completely submerged by the snow without monitoring actions being started. For the same reason, it is not meaningful, for the correct application of this methodology, to apply an average threshold (1.63 m from table 3), of all polygons as a new “threshold 0”.

As mentioned above the objective of this deliverable was to find a methodology capable of identifying the freeboard of each individual PRA to reconfigure the threshold 0 of every single area in the civil protection plans. Figure 18 shows an extraction from the GIS project in which these threshold values are highlighted.

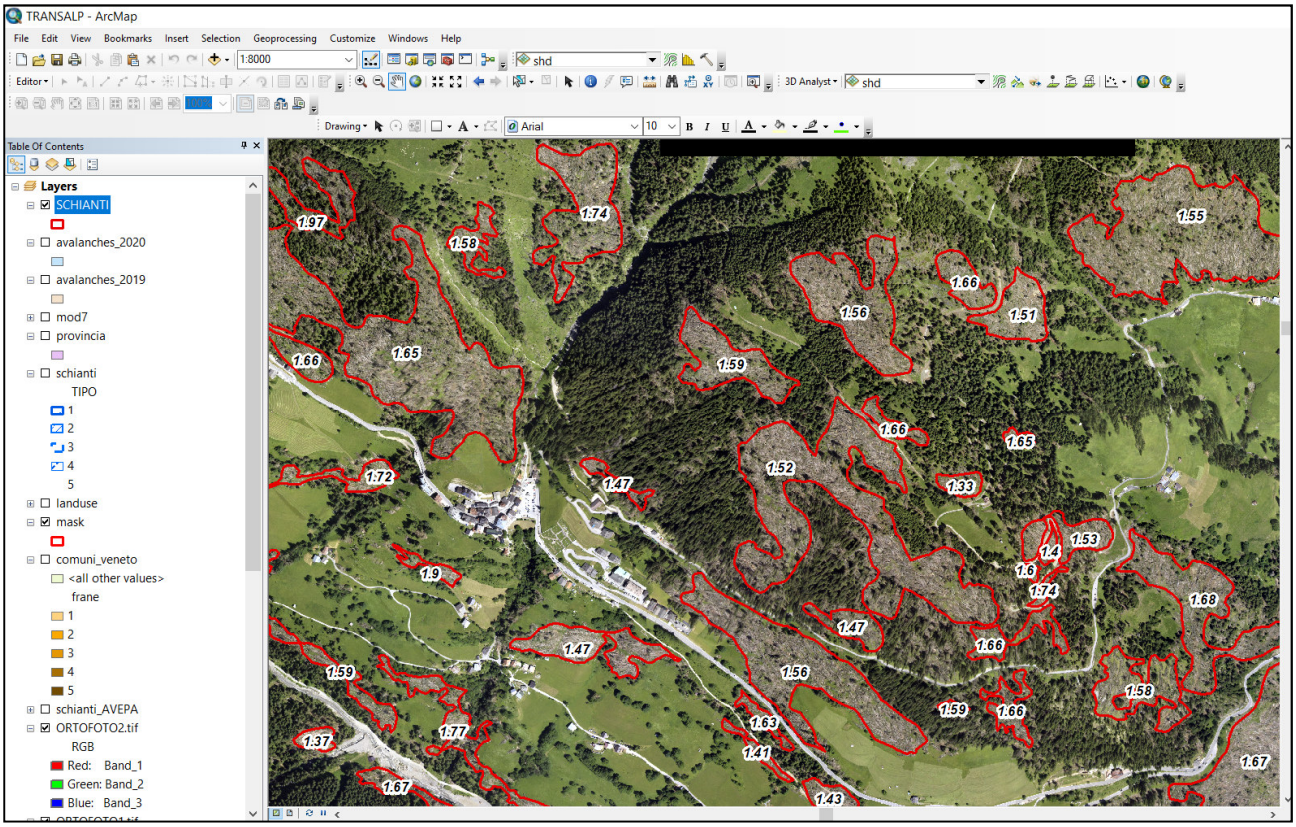

Figure 18: the label inside each windthrow area polygon represents the Avalanche Initiation Freeboard and thus the new "threshold 0" to be adopted in civil protection plans

6 Conclusions

The results of this work were possible thanks to feedback from local administrators, civil protection volunteers and personnel involved in special civil protection plans for avalanche risk mitigation in accordance with the mission of the DG-HECO programme. The methodology developed and above presented is a logical extension of what was carried out in deliverable 3.3 of the TRANS-ALP project. Together with the tools presented in the above mentioned deliverable, in fact, thanks to the methodology proposed in these chapters it will be possible, after a storm that produces large windthrow areas in a mountainous region, not only assess the avalanche risk, but also implement civil protection plans that are effective for risk mitigation and sustainable in terms of human resources required for monitoring actions.

Having said this, it is underlined that civil protection procedures, however effective, must be considered a temporary measure for risk mitigation while waiting for mitigation works to be carried out.

Finally, a methodology for avalanche risk reduction that is based on the anchoring effects of felled vegetation left on the ground, must take into account of the decay of the biomass over the years, and in the case of delays in the construction of defensive works, it is necessary to update the threshold values identified by the proposed methodology from new LiDAR surveys of windthrow areas.

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