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Transboundary Storm Risk and Impact Assessment in Alpine Regions

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D3.3 REPORT ON CASCADING EFFECTS OF STORM-RELATED LAND COVER CHANGE ON ALPINE NATURAL HAZARDS

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AUTHORS:	Matthias Plörer, Michaela Teich, Fabrizio Tagliavini, Roberta Dainese, Matteo Cesca, Christopher D'Amboise, Marc Adams, Massimiliano Pittore		

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1 INTRODUCTION

Storm events frequently induce damages to forest vegetation and are often accompanied by other natural processes such as heavy precipitation. Land cover changes and heavy precipitation can potentially increase the susceptibility for and/or trigger further hazard processes (Kaltenböck et al. 2009). Different hazard processes that are connected are called cascading effects. Cascading effects are characterized by, e.g., a mutual amplification of different potentially damaging processes (Pöppl & Sass 2019) as single (single-hazard) or multiple (multi-hazard) processes leading to hazard amplification over several stages or process chains. The European Commission (2011) defines event cascades with coinciding hazard processes as: "Coinciding hazards […, which] are also referred to as follow-on events, knock-on effects, domino effects or cascading events."

Westen et al. (2014) distinguish, depending on the degree of interaction, between coupled events (simultaneous process combinations) and events that change the predisposition, i.e., the basic prerequisite or susceptibility, for further events (process chains) (Pöppl & Sass 2019). Coupled events are triggered simultaneously, e.g., windthrow and falling trees can lead to the detachment of rock blocks that were stabilized by root plates and consequently lead to rockfall. Process chains are also interrelated, but various natural hazard processes occur one after the other, e.g., windthrow → deforestation → changes to the protective effect against snow avalanches → changed predisposition through the establishment of new avalanche release areas after clearing → damaging avalanche events. In this process chain, months to years can lie between the storm and the avalanche event. Windthrow itself does usually not trigger avalanches, but if the damaged vegetation is removed, changes their predisposition, and leads to an increased probability of damaging avalanches in areas that were previously less susceptible.

In the current literature (e.g., Glade et al. 2019), cascading effects are discussed a lot, but rarely in relation to forest cover loss. Some process combinations and historical examples related to severe storm events are of particular relevance for Alpine regions include:

- River channel or lake damming mass movements → displacement of water → tidal wave (e.g., Italy - Vajont / Longarone in 1963)
- Heavy or long-lasting rain fall, rain on snow events or incoming sirocco winds → flooding and frequent occurrence of slope movements (e.g., Austria - Sellraintal in 2015)
- Windthrow → bark beetle infestation → changes to the protective effect of forests against alpine natural hazards (e.g., Austria, Italy – storm Vaia in October 2018)
- Heavy snowfall → frequent occurrence of damaging avalanches (e.g., southern Alps of Italy and Austria – winter storm Xunav / Wenke / Yvonne in December 2020)

Considerations of reliable statistical trends about future developments and systematic overall considerations of cascading effects in hazard and risk management in affected regions are challenging due to the still insufficient knowledge and data about past events as well as the complex interactions involved. Current management strategies and previous scientific publications primarily address single events, which is also a reason for the sparse data availability. Furthermore, due to the unique character of different cascading effects (simultaneous process combinations and process chains), it is challenging to provide concrete recommendations for actions.

Several authors cited previous studies and stated in Glade et al. (2019) that future research activities should focus more on integrating different processes and their interactions in models to predict their outcome and support decisions (e.g., Wornie et al. 2014, Brierley et al. 2006, Bracken et al. 2013, Pöppl et al. 2017, Rascher et al. 2018).

In the framework of the project "TRANS-ALP," we addressed cascading effects of storm events focusing on land cover changes and their impacts on the alpine natural hazards snow avalanches and landslides.

However, in this report we also introduce potential effects of storm-related land cover changes and therefore changes in the protective effects of forests on other important natural hazards, i.e., rockfall and torrential floods. Windthrow can result in breakage of branches, treetops, stems, and tree uprooting (Brang et al. 2003). Large-scale events can demolish whole forest stands and the protective forest can be completely lost (Schönenberger 2002). Therefore, we further considered potential cascading effects in exposure and risk analysis exemplified in the two TRANS-ALP study regions East Tyrol (Austria) and Cordevole Valley (Italy) based on field records in combination with process simulations and determination of new elements at risk. The TRANS-ALP developed methods and tools for in-situ observations for hazard analysis as well as including potential cascading effects in risk are described in this report. To support a coordinated recording after storm events including multiple cascading effects such as bark beetle infestation, snow avalanche and landslide susceptibility, recommendations are provided that will be further evaluated in practice. Finally, we synthesize the gained knowledge and experiences to provide recommendations for a trans-boundary exchange and management of cascading events related to storm induced land cover change.

2 Cascading effects of storm-related forest cover change on alpine natural hazards – State of the art

2.1 Snow avalanches

Increased surface roughness influences avalanche formation and propagation

The protective effects of forests against snow avalanche release and propagation are primarily provided by the presence of live evergreen trees and their canopy. Forests modify snowpack properties through the interception of falling snow by tree crowns, the reduction of near-surface wind speeds, and changes to the energy balance beneath and around trees (Schneebeli and Bebi 2004). Together these processes lead to a highly variable snow stratigraphy (the characteristic microstructural layering within seasonal snowpack), preventing the formation of homogeneous weak snow layers that are key to avalanche formation (Schweizer et al. 2003).

After windthrow, the forest canopy is often completely removed; however, downed trees, stumps and root plates increase the surface roughness significantly, which affects snow distribution and re-redistribution, stabilizes the snowpack, and can prevent weak layer formation and avalanche release (Viglietti et al. 2010, Teich et al. 2019). That is, downed trees can provide residual protection against snow avalanches (Schönenberger 2002). This is especially important for smaller avalanches with lower release depths (McClung, 2001), since very large snow depths can bury the obstacles and therefore smoothen the surface, resulting in potentially larger release areas (Veitinger and Sovilla 2016, Veitinger et al. 2016). Furthermore, downed woody debris can act as a barrier and obstacle for downslope mass movements (Teich et al. 2012, 2014). The presence of dead wood increases surface roughness and can prevent the gliding of the snow cover (Feistl et al. 2013), which also protects young plants from being uprooted (Bebi et al. 2015). Several studies have shown that density, height and heterogeneity of the ground vegetation and surface roughness are crucial for this anchoring effect hindering snow gliding (Feistl et al. 2014, Höller 2001, 2013).

Leaving downed trees, stumps and root plates in protective forests after a windthrow event may thus offer protection against snow avalanches until the post-disturbance regeneration is sufficiently high (Frey and Thee 2002, Kupferschmid Albisetti et al. 2003, Wohlgemuth et al. 2017). However, after years of decomposition, the remaining dead wood becomes less supportive, because it decreases in height, moves or even decomposes completely (Bebi et al. 2015, Wohlgemuth et al. 2017). Schönenberger et al. (2005) and Wohlgemuth et al. (2017) analyzed the characteristics and evolution of damaged forest such as dislocation of logs and their stability, stem height above ground and the regeneration rate at different experimental sites up to 24 years after storm Vivian in Switzerland. However, despite that they reported a considerably small number of observed snow avalanches from these sites, a critical "protection gap period" with reduced overall protection against natural hazards may occur, if snag fall and decay rates of logs are faster than the establishment of sufficiently advanced regeneration (Figure 1). In addition, the establishment of new seedlings and saplings on decaying logs may be hindered by the presence of brown-rot-causing fungus (Bače et al. 2012).

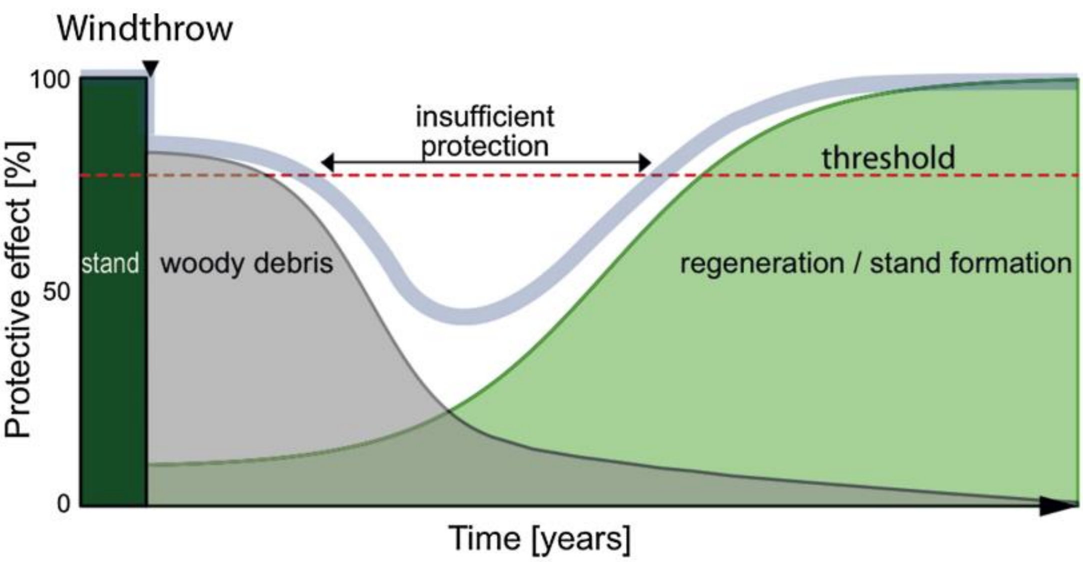

Figure 1: Development of the protective effect as a function of time after windthrow in wind-damaged mountain forests. A hypothetical threshold indicates the minimum protective effect against avalanches in times of considerable snow accumulation. Source: Wohlgemuth et al. (2017)

In contrast, salvaging and removing damaged and downed trees reduces surface roughness immediately, resulting in reduced protective effects of forests (Brang et al. 2006, Teich et al. 2019; Figure 2). Therefore, to promote surface roughness in potential avalanche release areas, it is recommended that lying tree stems and high stumps (>1.3 m) are left after logging (e.g., Berger et al. 2013).

Figure 2: Reduction in forest cover and surface roughness after salvage logging storm-damaged forest (Vaia 2018) on steep slopes in East Tyrol, which could create new potential avalanche release areas. Photo: Plörer, 2022

In general, natural disturbance events can have positive or negative consequences, no effect or an unclear effect on the protective effect of forests against natural hazards. The spatial extent of a disturbance event is a crucial factor that will influence these changes, i.e., while small-scale disturbance events might not be as important in altering the protective effects of forest, large-scale events can have devastating consequences. In Table 1, changes in protective effects are described for large-scale, high-severity disturbance events through the changes of individual forest stand parameters that are important for the protecting against avalanches, summarized by Oven et al. (2020) based on few available studies.

Table 1: Influence of windthrow compared to other natural disturbances on forest stand parameters important for protective effects against snow avalanche. Symbols present different effects: + positive effect (increase), - negative effect (reduction), 0 no effect, ? effect unclear. Source: Adapted from Oven et al. (2020)

AVALANCHE PROTECTION FOREST							
stand parameter → / **natural disturbance ↓**	**canopy cover**	**species composition**	**surface roughness**	**tree size relative to snow depth**	**stem density**	**gap size**	**dbh distribution**
windthrow	-	-	+	-	-	-	-

forest fire	-	-	-	-	-	-	-
ice and snow breakage	-	-	+	-	-	-	-
avalanches	-	-	+	-	-	-	-
rockfalls	-	-	+	-	-	-	-
insects	-	-	o, +	-	-	-	-
pathogens	-	-	?, o	-	-	-	-

dbh = diameter at breast height

Table 1 also shows that increased surface roughness is the most important factor, if not the only one, that has a positive effect on avalanche release and propagation. Therefore, developing methods for mapping and quantifying post-disturbance surface roughness in natural hazard process area is currently being addressed in several studies, especially with the development of unmanned aerial systems (UAS) to gather data fast and remotely (e.g., Brožová et al. 2021, Baggio et al. 2022; see also Section 3.4.1)

2.2 SHALLOW LANDSLIDES

Decreased soil stabilizing effect and changed hydrological system

The presence of trees on hillside slopes and in mountain terrain has a known soil stabilizing effect protecting against landslide release, as addressed in the Swiss guidelines for the strategic use and appropriate management of protective forest (Losey & Wehrli 2013), formally recognizing the beneficial contribution to shallow landslide, soil erosion, rockfall and avalanche protection.

The presence of trees has both a mechanical and a hydrological effect, with stabilizing and destabilizing consequences. Regarding shallow landslides, the presence of tree roots has three main mechanical effects (Cohen & Schwarz 2017):

1. Basal root reinforcement: when roots cross the slipping surface, they act as anchors, fastening the unstable soil mass to the underlying soil. This reinforcement is highly effective but is absent or weakened, if the failure surface is deep within the ground, or if roots are too shallow or not dense enough.
2. Lateral reinforcement: the tensile strength of roots is activated by the deformation consequent to the soil movement. The contribution of lateral reinforcement is highly dependent on the type of deformation of the landslide mass.
3. Roots stiffening the soil mass: roots immersed within the soil matrix act as a composite material that increases the stiffness of the ground, favoring the previous two effects.

The main hydrological effects include (Dorren & Schwarz 2016):

1. Rainfall interception: modifying the amount and timing of water reaching the soil surface,
2. Modification of soil's hydraulic conductivity due to change in porosity and soil structure related to the presence of roots (both mechanic and biochemical effects),

3. Root water uptake for evapotranspiration with higher water removal from deeper levels of the soil; compared to evaporation from bare soil, evapotranspiration in a forested area can be 5-10 times higher.

The final effect of such contributions to stability are dependent on the geometry of the landslide (i.e., depth of shear surface, volume, etc.), the characteristics of the soil and the pore water pressure distribution (Leung et al. 2015), and on the characteristics of the root system (root density and depth, roots tensile strength depending on the species, etc.) (Stokes et al. 2009, Cohen & Schwarz 2017). Potential destabilizing effects are due to the additional weight of trees and the magnified effect of wind that can be applied to the soil through the tree. Furthermore, the increased porosity of the soil, due to cavities created by root growth and decay and biochemical reactions that change the structure of the soil, may lead to higher infiltration rates. The increase in water infiltration may cause an increase in pore-water pressure within the soil (Fredlund 1979), which leads to a weakening of the soil shear strength, causing, in extreme cases, the triggering of a landslide (Fredlund 1987, Iverson 2000).

The beneficial effect of forests against landslides is usually agreed upon, firstly due to the increased occurrence of landslides observed in deforested areas (O'Loughlin 1974). A study by Rickli & Graf (2009) obtained a general lower density of shallow landslides in forested areas compared to open areas with similar characteristics and subjected to similar precipitations intensities, even if the difference in landslide occurrence was not so remarkable. The difference was explained by the status of the forest, where the presence of windthrow areas and trees damaged by bark beetles could significantly affect the soil stability (Rickli 2001).

Of interest is the specific problem of the creation of large windthrow areas after an extreme event like the Vaia storm in October 2018. Similar events have occurred in the past in Europe, such as the storms Vivian (1990) and Lothar (1999) in Switzerland (Wohlgemuth et al. 2017) and the event of 2013 in Poland (Strzyżowski et al. 2021). Field investigations in the years following those events have shown how the damage to the forest has led to an increased occurrence of shallow landslides, but only a few years after the events. It is possible that the disappearance of trees may have had at first even a beneficial effect, reducing the load of trees and their amplifying effect of the wind on the soil (Brown & Sheu 1975). However, after 3-5 years, the natural decay of the roots plays a decisive role with a fading tensile effect and a modified hydrology of the system (increased infiltration during rain events, absence of water depletion due to evapotranspiration (O'Loughlin 1974)). To assess the extent to which this phenomenon is also present in Vaia-affected areas, the different sites should be monitored for several more years. The Veneto Region has started a monitoring campaign based on Permanent Scatters to assess any reactivated or new landslides.

2.3 Rockfall

Increased rockfall activity and reduction of the protective effect against rockfall

Forests are the most effective biological protective measure against rockfall processes. Trees act as a shield against rockfall impacts. A favorable forest structure can a) prevent rockfall and b) significantly reduce the kinetic energy, velocity, and runout length of falling rocks by absorbing their impact energy and deflecting them. Most of the impact energy (at a single tree) is absorbed by the root-soil system through rotation and translation of the root-soil plate (Kalberer et al. 2007). Based on various measurement methods, a spruce with a diameter of 45 cm can absorb energies between 200 and 450 kJ (Dorren et al. 2017). In comparison, a 0.5 x 0.5 x 0.5-meter boulder develops an energy of about 105 kJ at a transit velocity of 90 km/h (BMLRT, 2020). The maximum velocity of single rockfall can be up to 125 km/h (BMLRT, 2020).

According to rockfall simulations, about 30% of the kinetic energy can be absorbed during the fall process in forested areas compared to non-forested (cleared) areas. Rockfall velocities are reduced by an average of 24% (Oswald 2019). In a field experiment along a 220 m long slope in France (Dorren et al. 2005), 5% of falling rocks came to rest in forest-free paths, while 66% stopped in forested areas. According to Dorren et al. (2017), forests can exert such a braking influence against boulders up to a volume of 20 m³ (Figure 3); however, against boulders of larger volumes even an intact forest has no protective effect.

An ideal rockfall protective forest has a multilayered vertical stand structure (including shrub layer), a dense horizontal stand structure (only few gaps in the fall line), a high number of stems, a wide diameter distribution (dbh, diameter as breast height), a mix of tree species (deciduous and mixed coniferous forests), and a high basal area (sum of basal areas of trees per hectare [m²/ha]) (BMLRT 2020 & Dorren et al. 2017). Thus, entire settlements and transportation routes situated at the foot of steep slopes are naturally protected from rockfall as long as the forest stand is intact.

A storm with windthrow damages abruptly reduces the protective effect against rockfall (Bebi et al. 2015), especially if the damaged areas are cleared immediately after the event (Wohlgemuth et al. 2017). However, during a windthrow event, rockfall initiation is also common (Gruner 2008). Trees often grow their roots into open joints and cracks of the bedrock. Strong winds and the associated swaying can lead to leverage effects and dynamic rock loosening (Gruner, 2008), and tree roots can sometimes push even large boulders out of the ground and cause them to release (BMLRT 2020, Frehner et al. 2005). During storms, which even lead to the toppling of trees including root plates, rocks from the soil and root zone can be pulled out and subsequently fall downslope. This results in a simultaneous, cascading effect / process chain of windstorm – windthrow/forest damage – rockfall.

If the broken and damaged timber is left in windthrow areas, the surface roughness still has a positive effect for rockfall protection for the next 20 years (Wohlgemuth et al. 2017). However, the deadwood decays gradually and the surface roughness and the strength of the remaining stems decrease. The stand should already have an appropriate regeneration by then or supplemented by combinations of reforestation and technical rockfall protection measures which become necessary (Bebi et al. 2015).

Figure 3: a) left: freshly damaged timber by a rockfall event, b) right: boulders stopped by tree stems. Source: Plörer, 2020.

2.4 Floods

Increased rainwater runoff and higher flood risk below unforested catchments

The hydrological protective effects of forests include runoff retention and, subsequently, flood control. The current literature indicates a broad consensus that smoother land surfaces show more rapid runoff concentrations (higher flow velocities, reduced soil infiltration). Engler already recognized in 1919 that forests with intact vegetation cover play a key role in attenuating flood peaks on torrents and receiving streams. An example from 1965/66 in Austria is also known to have been the cause of catastrophic floods due to the lack of forest cover (Kleemayr et al. 2019).

A multi-layered forest stand with pronounced ground vegetation (shrub layer), an intact humus layer and deadwood has a higher roughness and therefore leads to a slower runoff of precipitation water, i.e., a lower or delayed surface runoff (Markart et al. 2014, Klebinder et al. 2014). Depending on the vegetation (tree species), up to 6 mm of precipitation is retained in the canopy during a storm event. Furthermore, the kinetic energy of raindrops is refracted by the vegetation. In this way, the drops are dissipated into the ground in delayed via the tree canopy and underlying vegetation layers (Markart et al. 2017). After an area wide storm damage, this intercepting effect by the canopies is no longer present.

The delayed runoff formation (initial abstraction) by forest was proven in experiments in the Austrian Zillertal, near East Tyrol. In a comparative precipitation/runoff modeling simulation (ZEMOKOST), it was found that the catchment area of the "Hundsbach", which was already forested in 1950, showed no changed runoff response in 2003 (Figure 4). However, the neighboring catchment "Taleggbach" had been remarkably improved by silvicultural measures during 50 years, which had resulted in a 50% lower and significantly delayed runoff peak (Markart et al. 2017).

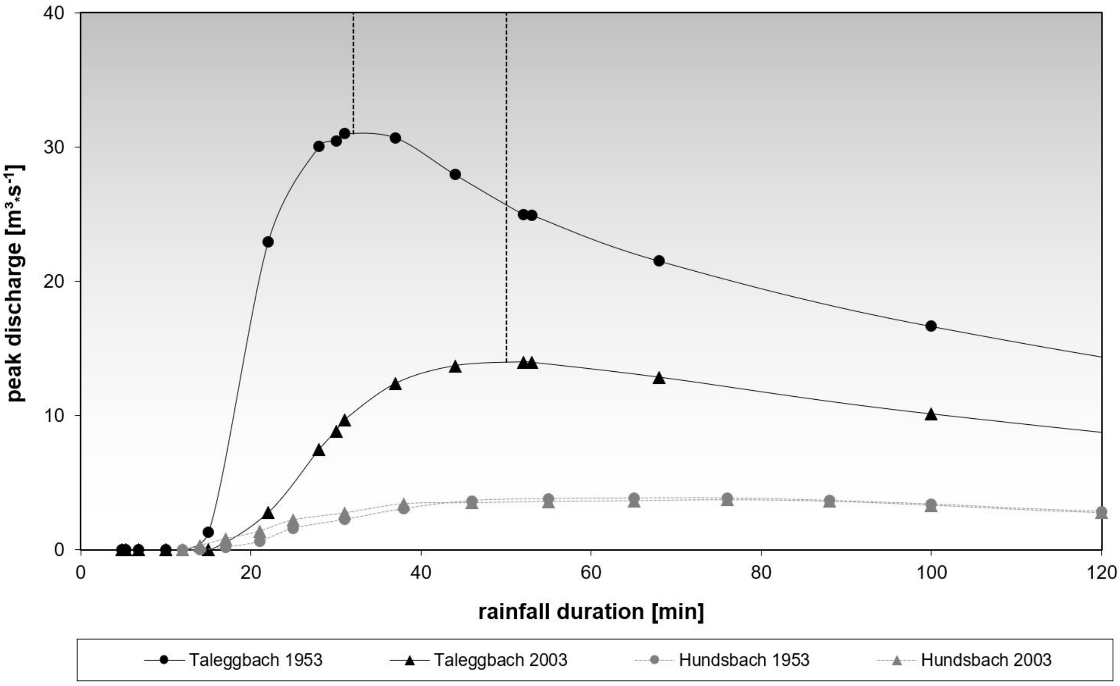

Figure 4: Modelled discharge in the continuously forested "Hundsbach" catchment and the silvicultural improved catchment of the "Taleggbach". Source: Kohl, 2004.

Model calculations show that disturbances of the mountain forest, such as windthrow or related bark beetle infestations in a watershed area, can directly influence the runoff pattern and therefore significantly exacerbate flood runoff (Hildebrandt, 2006). New forest roads that are often created for salvage logging and timber removal from large-scale windthrow areas further exacerbate surface runoff. This is because water that escapes as intermediate runoff from artificially created road embankments is conveyed much more rapidly to the receiving water body (Markart et al. 2017).

The condition of the forest soils also plays a central role. Forest disturbances or area wide forest removal (e. g. through windthrow) results in a successive loss of the positive forest soil properties (Hildebrandt, 2006). However, pre-moistening also has a decisive influence on runoff behavior. Appropriate pre-moistening (several precipitation events in a short period of time) accelerates or increases runoff. Thus, the forest effect is also dependent on the precipitation type. In the case of short intense storm events (convective), the forest can develop its retentive effect better than in the case of continuous precipitation (advective), which leads to high pre-moisture / a high degree of water saturation over time and a forest site nearly approaches the runoff behavior of non-forested areas (Figure 5). Similarly, the forest effect seems to play a minor role at the macroscale (large catchments), as runoff formation becomes more complex and does not depend mainly on forest cover (Hegg 2006, Markart et al. 2014 & Kohl 2018).

The deadwood management seems to be somewhat contrary. Deadwood still provides effective avalanche and rockfall protection up to 20 years after windthrow (Wohlgemuth et al. 2017). Regarding protective effects against floods or against flood cascades caused by windthrow, deadwood must be considered in a different way: Deadwood left lying in or near river channels can lead to a significant increase in hazard potential due to the risk of blocking outlets. Thus, how to treat deadwood from windthrow must be decided at site-specific or on a local scale.

According to Kohl et al. (2008), improvement of the hydrological protective effect of forests has occurred in many places since the 1950s. But the increased, nation-wide soil sealing (traffic areas, residential and commercial areas, ski slopes, etc.) has more than equalized the positive effects of forests. Severe storm events such as "Vaia" in 2018, which can lead to large-scale destruction of intact forests, could increasingly intensify the already negative trend due to soil sealing. A forest loss of a 1-hectare area (due to windthrow, clearing, ski slope construction, road construction, etc.) requires an intensive improvement of 5 hectares of forest area to maintain the hydrological beneficial effects in a watershed (Kohl 2018).

Figure 5: Flood discharge after a short & heavy precipitation event in a high-alpine, sparsely forested catchment. Source: Plörer, 2021

3 Improving harmonized and trans-boundary identification and mapping of potential cascading effects of storm-related forest cover changes

3.1 Six steps for identifying, mapping and assessing the impacts of storm-related cascading effects

After a storm event that damaged forest areas, few steps must be taken to consider the consequences of the damaged forest for potential cascading effects. Considering the cascading effects related windthrow can be fulfilled by different methods or tools, some of which are dictated by the type of cascading effect being investigated:

1. Identify areas where the forest has been damaged,
2. Identify potential cascading effects and the key variables controlling it,
3. Measure the key variables that may have changed due to forest damage,
4. Assess the new scenario with a simulation tool or model,
5. Develop new mitigation plans based on the new state of the system,
6. Implement a monitoring plan and evaluate mitigation plans following future disturbance events.

To identify areas where forests have been damaged (Step 1), several methods can be applied. Some of the factors to consider when choosing the appropriate method are the size of the forest damage and how difficult it is to access or move in the terrain. Methods that could be used to identify damaged forest areas are visual inspection, unmanned aerial systems (UAS) or manned aircrafts collecting aerial orthophotos or satellite images. For very large regions it may only be feasible to assess the forest damage via remotely sensed data, where in small regions ground sampling distance of the satellite imagery may be too coarse to detect the damaged forest.

Step 2 is to identify what the possible cascading effects are that could result from the forest damage. These could include gravitational natural hazards such as snow avalanches and landslides, soil erosion, or enhanced forest damage due to subsequent bark beetle outbreaks. Key variables that control the feedback between the cascading effect and the damaged forest must be identified at this step. Some of the key variables might be the area of land cover change, the volume or surface area of dead wood, the roughness of the surface/terrain, or the number of stems that have been removed.

The key variables that have changed due to forest damage can be measured or estimated (Step 3) by several different methods, which need to be feasible for the size of the forest damage. For very large remote sensing techniques would be preferred over ground-based or close-range measurements, while smaller areas would allow a more detailed in-situ study, ranging from deriving optical or lidar data collected from different platforms to performing in-situ snowpack observations to determine its microstructure and potential susceptibility to slab avalanche formation.

Assessing the new hazard scenario by considering the new information about the key variables (Step 4), often entails some type of simulation tool or model to see how changes to the key variables are propagated to the cascading effect. Again, the size and scope of the forest damage may dictate the type of model that is applied.

Step 5 is to develop a new hazard and risk mitigation plan considering the new state of the system. This could be a temporary solution until the forest has grown back or a more permanent plan that might include technical protection or avoidance measures.

The last step (Step 6) includes the continues monitoring of changes to the system, e.g., additional cascading effects that may occur years after the windthrow event or future disturbances in undisturbed forest areas, and updating of mitigation plans.

3.2 METHODS TO IDENTIFY AREAS WITH SIGNIFICANT STORM-RELATED LAND COVER CHANGE

In recent years, the development of unmanned aerial systems (UAS) has provided a wide range of new possibilities for high-resolution monitoring and mapping of areas with significant land cover change (Sharma 2019, Colomina & Molina 2014, Aber et al. 2010). This is highlighted by the vastness of publications on diverse topics and natural hazard processes including: windthrow (Deigele et al. 2020, Mokroš et al. 2017), landslides (Turner et al. 2015, Fernandez et al. 2015), deep-seated mass-movements (Hormes et al 2020, Urban et al. 2019), forest fire (Moran et al. 2019, Merino et al 2012), or rockfall (Giordan et al. 2015, Danzi et al. 2013).

In general, UAS can bridge the gap between full-scale, staffed aerial and terrestrial observations (Briese et al. 2013, Rosnell & Honkavaara 2012). They are credited as being able to allow flexible image acquisition at an unprecedented level of detail (ground sampling distance (GSD) of few centimeters or millimeters) (Ryan et al. 2015). Additionally, the rapid development of UAS-specific payloads has further increased their versatility and range of application. In this contribution, the term UAS refers to aircraft with a typical weight of <5 kg, flight times of 30-45 minutes, optimized for easy field deployment, recovery, and transport, typically fitted with optical sensors for image acquisition.

Processing UAS imagery is usually performed with off-the-shelf or custom photogrammetry pipelines. The development of novel computer vision techniques [structure-from-motion (Koenderink & van Doorn, 1991) and multi-view stereopsis (Furukawa & Ponce, 2009)] and their implementation into a wide range of software packages, have significantly reduced the requirements for the recorded data (Vander Jagt et al. 2015, Turner et al. 2012). Standard outputs are orthophotos and digital surface models (DSMs). The latter refers to the height of the terrain, buildings, or vegetation, captured in the scene. The DSM is interpolated from a dense point cloud (DPC) generated as part of the photogrammetric workflow. For a recent, comprehensive review on available software options and mapping accuracy see Deliry & Avdan (2021). UAS can be applied to perform Steps 1 to 3 of outlined above.

In addition to what has just been described, it is in any case essential to conduct a series of onsite inspections to quantify the damage that has occurred and to foresee, based on expert opinions, potential cascading effects in the short and medium terms, contributing to Steps 2 and 3. As mentioned in the introduction to this work, however, it is essential that the approach to field surveys is a multidisciplinary one.

The onsite surveys must highlight all elements that cannot be detected by remote sensing techniques and that can affect the cascading effects related to the storm. For example, potential fractures in the ground must be identified as evidence of new landslide triggering, as well as if there are avalanche risk mitigation works or particular morphologies that preserve vulnerable elements, or considerations on the health of the vegetation left standing (see Section 5.2).

3.3 IDENTIFICATION AND RECORDING OF VAIA WINDTHROW AREAS IN EAST TYROL AND CORDEVOLE VALLEY

3.3.1 EAST TYROL (AUSTRIA)

The storm depression "Vaia" swept across East Tyrol starting on 29 October 2018 and caused considerable damages, especially to mountain ecosystems. Floods, mudslides, damage to houses and infrastructures and numerous windthrow events were triggered by this storm event. Protective forest areas were particularly affected: 61% of the damaged areas were forests with an object protective function, 59 % of the windthrow areas were located in terrain with a slope inclination of more than 30° (BMNT, 2019). Approximately 600,000 cubic meters of damaged timber accumulated. The sudden loss of the protective effect of these forests in East Tyrol is unprecedented in Austria (BMNT, 2019).

The windthrow areas were determined and recorded by the Amt der Tiroler Landesregierung (state of Tyrol) using airborne laser scan surveys. A DSM was generated, which was compared with a DSM before the storm event. By subtracting the DSM after Vaia from the DSM before Vaia ("NDSM"), it was possible to identify those areas where significant changes in vegetation cover have occurred (windthrow). The time stamp of data is January 25, 2019 (Land Tirol).

Via the described procedure and further post-processing steps in a Geographic Information System (GIS), 1475 single windthrow areas could be identified all over East Tyrol. These areas cover 2155 hectares, which represent around 1,1% of the entire area of East Tyrol.

3.3.2 CORDEVOLE VALLEY (ITALY)

Between 28 and 29 October 2018, strong scirocco winds with gusts exceeding 200 km/h devastated large areas of the Eastern Alps, causing considerable damage to the forests in Veneto. Detailed calculations indicate a damaged forest area of 18300 hectares with 3.3 million cubic meters of timber. This event, known as 'Tempesta Vaia', was the most impactful ever known by the Veneto region. However, other similar events have occurred in Europe over the last 30 years, even more disastrous in terms of damaged forest area. On the European continent, in fact, wind is the main disturbance agent in forests causing up to three times the damage compared to forest fires (Seidl et al. 2014). There is no denying, however, that the Vaia storm represents the first event of such magnitude that has ever impacted the Veneto region, affecting populated areas and resulting in significant economic and social impacts. This may partly explain why the forestry census offices were not prepared to quickly quantify the damage that had occurred. In the early post-event phases, the different risk management offices (hydrogeological, avalanche control, forestry, etc.) were not coordinated and data collection was done individually by each office, using disparate methodologies. The lack of a multi-risk approach for data collection certainly contributed to the dissipation of valuable resources in the hectic post-event phases. To overcome the limitations of this experience, a multi-hazard survey sheet is proposed in Section 5.2, which can be used to collect useful data for hydrogeological instabilities, avalanches, and aspects of forestry interests in a combined homogenized manner.

Immediately after the event, an initial estimate of the damage was produced to manage the emergency phase quickly, but it was only after several months that remote sensing data became available to allow more precise monitoring of the forest damages. The databases used in this monitoring activity refer to Sentinel-2 satellite images (both pre- and post-event acquisitions were used), with the integration, where available, of post-event orthophotos. The following vegetation indices were compiled from satellite images: Normalized Difference Vegetation Index (NDVI), Red Edge Normalized Vegetation Index, Normalized Difference Water Index, and Green Normalized Difference Vegetation Index. For each index, the difference (post-event index) - (pre-event index) was calculated. Only more than one year after the storm event, a lidar flight acquiring data to compute a Digital Elevation Model (DEM) and DSM of all affected areas has been made available.

In the days immediately following the event, the technicians of the Arabba Avalanche Centre of ARPAV, manually mapped all the areas of downed forest connected to vulnerable elements at risk. This methodology, although unorthodox, has nevertheless made it possible to speed up the creation of specific civil protection plans to mitigate the avalanche risk to the population. Such plans were already operational in use during the winter season following the storm. In the same days, the landslide mapping office of the Veneto Region conducted a series of inspections and collected specific data on damages, including to forest, which could affect the slope stability.

3.4 METHODS TO MONITOR AND QUANTIFY CHANGES IN CASCADING EFFECTS

3.4.1 THE EXAMPLE OF POST-WINDTHROW SURFACE ROUGHNESS POTENTIALLY AFFECTING AVALANCHE RELEASE

The field site in Kals am Großglockner in East Tirol was established as an experimental field site to investigate and understand how the trees downed by the storm Vaia in 2018 affect the snowpack and, thus, the snow avalanche hazard. Therefore, not all the steps mentioned in Section 3.1 were carried out for the Kals am Grossglockner field site. The investigation started with Step 2, where terrain roughness was identified as a potential key variable. The hypothesis is that the surface roughness from tree stems laying on the ground in steep terrain will act as a temporary protection measure against the release of snow avalanches (Teich et al. 2019, Wohlgemuth et al. 2017, Frey and Thee 2002). A roughness measurement in the direction of the slope's fall line was then developed with the goal to quantify the effect downed trees have on the susceptibility of snow avalanche release. The results of this investigation should be a basis for parameterizing an avalanche Potential Release Area (PRA) model, thereby improving Step 4, which should influence the risk mitigation plan (Step 5).

The forest damage assessment (Step 1) was carried out by applying different methods. First an overview of the forest damage was obtained via high-resolution satellite and manned aircraft orthophotos in the region of East Tirol. Further investigation was done on the ground by manual inspection by a group of foresters and researchers (see Figure 6) and with UAS flights to retrieve a detailed overview of the forest damage at the experimental test site (Figure 7).


Figure 6: Visiting the study site for the first time (10 Oct 2021) (left); aerial view of the lower section of the site with Kals a.G. in the background, recorded with the UAS DJI Mavic 2 Pro on the same day (right).

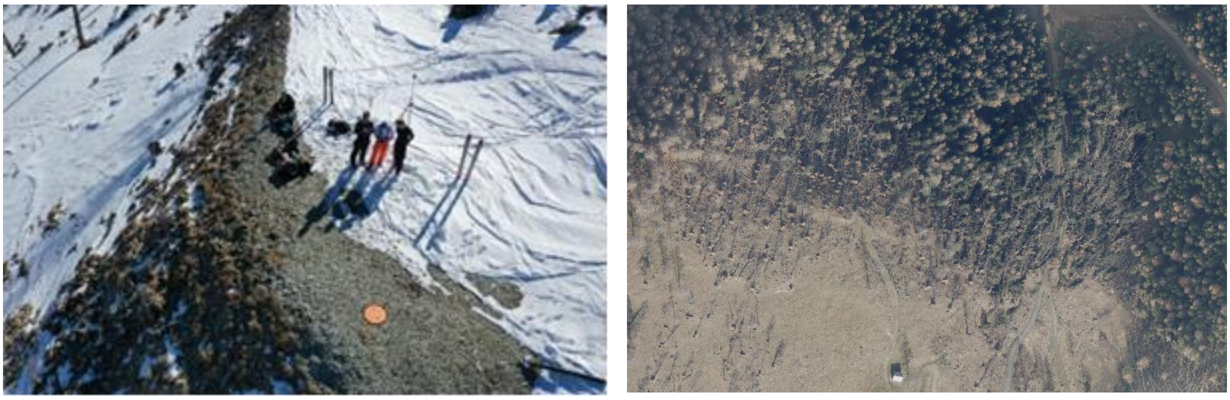

Figure 7: Aerial view of the fieldwork team positioned on a blown-off section of the forest road winding through the study site with the snow in the vicinity showing strong signs of wind influence (left); post-event orthophoto commissioned by the LFD documenting the extent of forest damage following the wind throw event at the study site in 2018 (right) (source: LFD, Land Tirol).

The potential cascading effect that was identified in Step 2 was the creation of new PRAs in the storm-damaged forest. The key variables that have changed due to forest damage that was identified as the loss of the forest canopy and an increase of the roughness of the terrain.

From the point cloud derived from aerial photogrammetry a DSM was compiled. An algorithm was developed to give a directional roughness index in the direction of the fall line to each point in the point cloud considering an area of approximately 10 m (Figure 8; different methods consider slightly different resolutions). The index was produced with custom-built software, which identifies the fall line of the terrain and then classifies the roughness with some existing roughness algorithms (Brožová et al. 2021, Baggio et al. 2022).

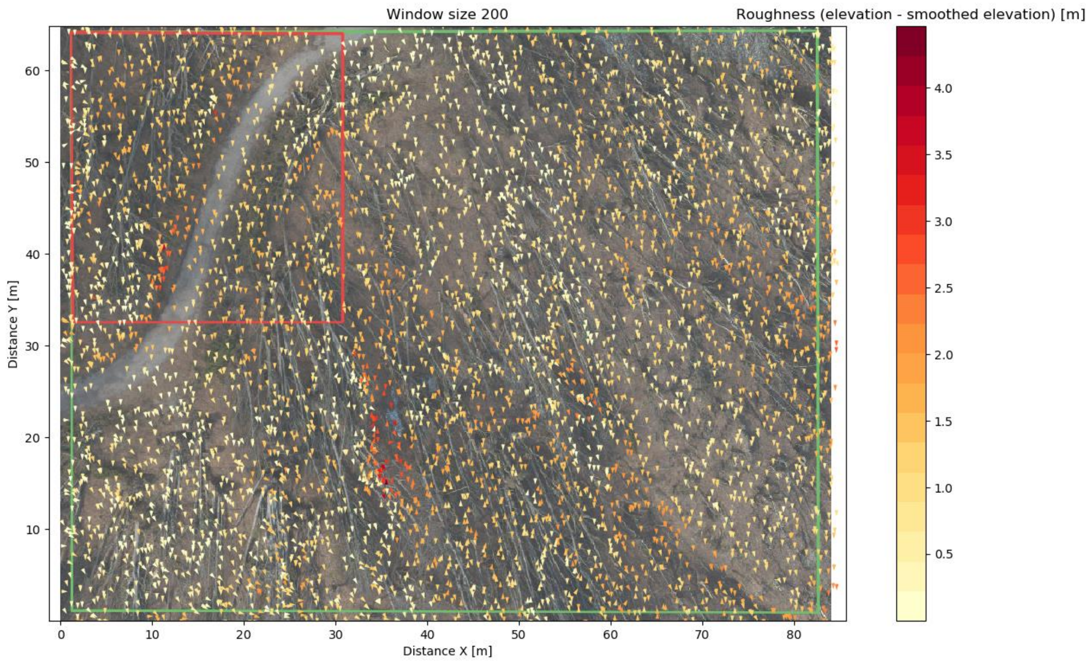

Figure 8: Directional roughness along the fall line of the terrain. The direction of the fall line and the roughness is calculated with a new point cloud algorithm. The background image: orthophoto of the terrain. Red rectangle: high roughness score where multiple tree stems have fallen; low roughness score along the forest road.

Current work is being done to determine the most suitable roughness algorithm for describing the directional surface roughness. The software needs to balance the robustness detail of the directional roughness index with the computer processing time for such a calculation, which is challenging because point cloud data can be computationally heavy. In addition, a plethora of measurements on the snowpack properties and layering was carried out in three measurement campaigns throughout the 2021 -2022 winter season. The overarching aim of this study is to quantify how the roughness affects the snowpack including the snowpack stratigraphy, which is linked to the possibility of avalanche release. If there is a quantifiable relationship between avalanche release probability and the surface roughness, the roughness index can be included in PRA models. A secondary focus of this study is to examine how forest management plans can be adapted in steep locations such that roughness is conserved in a way to mitigate avalanche risk in critical areas. One strategy would be to leave the stems in the steeper terrain creating surface roughness to oppose the forest cover change (Frey and Thee 2002, Kupferschmid Albisetti et al. 2003, Berger et al. 2013, Wohlgemuth et al. 2017, Teich et al. 2019).

To do a full risk assessment on the area in Kals am Grossglockner the Steps 4 and 5 must be carried out, and new PRAs opened up from the windstorm damage should be modeled (see Chapter 4). The results of the PRA model can then be used in avalanche runout models where the new transit and deposition areas is simulated. A suitable simulation tool would be Flow-Py (Neuhauser et al. 2021, D'Amboise et al. 2022; see Section 4.1.1). The risk assessment and new risk mitigation plans should consider new avalanche prone areas that have been highlighted by the simulations.

4 Post-windthrow avalanche risk: potential cascading effects exemplified for East Tyrol (Austria) and Cordevole Valley (Italy) after "Vaia"

4.1 Determination of new potential avalanche release areas and simulation of runout and deposition zones

4.1.1 East Tyrol (Austria)

The first step of a risk analysis is to determine the hazard potential. Therefore, it was necessary to identify PRAs in windthrow areas. In this example, existing avalanche paths or already known high alpine avalanche release areas, e.g., used for hazard zone mapping by the Austrian Torrent and Avalanche Control (WLV), where not considered. The focus was on potentially newly established avalanche release areas in windthrow areas resulted from the storm Vaia in October 2018. Theoretically, every one of the 1475 recorded windthrow areas can serve as a new avalanche release area if the main criterion of a minimum slope inclination is met. Therefore, only slope inclinations between 34° and 55° are considered here as PRAs. This value range is based on analysis of slope gradients of sites where avalanches were initiated in forest gaps (Perzl & Kleemayr 2020). Other criteria relevant for avalanche release like morphologically coherent terrain chambers or terrain curvature are not considered. Figure 9 shows yellow (background shape) and black areas (overlayed pixels). The yellow pixels represent recorded windthrow areas (see Section 3.3.1), while black pixels represent only pixels between 34° and 55° slope inclination within the yellow shapes. Therefore, only black pixels were considered in avalanche runout simulations. The total new PRAs for the whole of East Tyrol amount to 1077 hectares. These areas represent around 50% of the Vaia windthrow areas, which means that the other 50 % of the entire formerly forested windthrow areas are too flat or too steep for avalanche formation based on the analysis from Perzl & Kleemayr (2020).

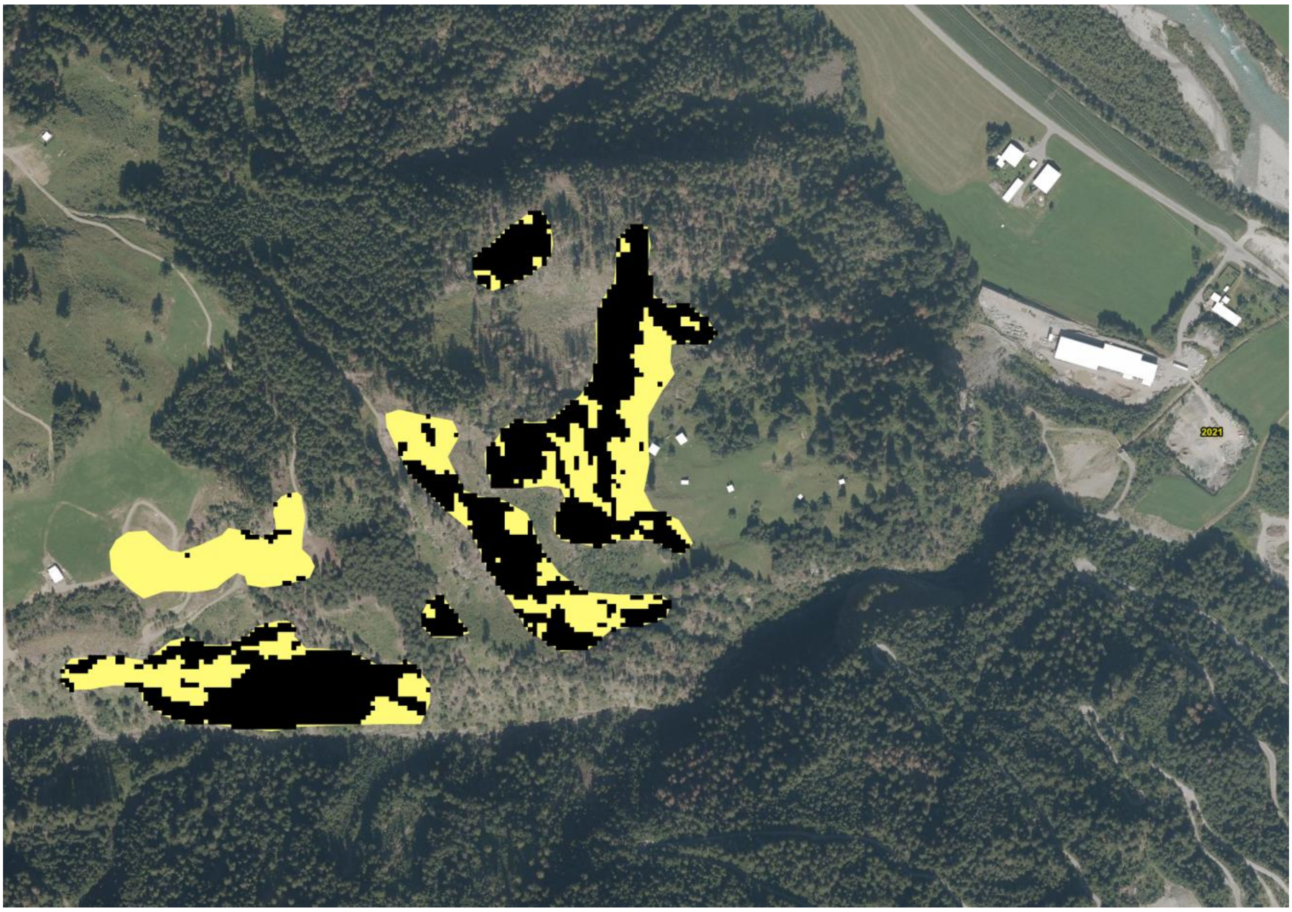

Figure 9: Example of cleared windthrow areas (yellow shapes) and terrain sections inside at inclinations between 34° and 55° (black pixels). The black pixels are PRAs and are included in the avalanche simulations with Flow-Py model.

The step following the determination of avalanche release areas was to model the runout paths and deposition areas of potential “post-windthrow avalanches.” For this simulation and the example East Tyrol, the Flow-Py model (D’Amboise et al. 2022), developed at the Austrian Research Centre for Forests (BFW), was used. Flow-Py is a data-driven empirically based runout model for gravitational mass movements on a regional scale, e.g., for preliminary studies in regional projects. As open-source software, the model code can be downloaded free of charge (Neuhauser et al. 2021). The input data and the output data generated by the model can be prepared or processed in common GIS programs since Flow-Py works with raster data such as ASCII or TIFF files with a variable resolution (pixel size). The primary required input data is a DEM ("DEM layer") and a raster defining the potential release cells ("release layer" -> black pixels in Figure 9). In addition, parameter specifications, which determine the process paths in the modeling are obligatory (Figure 10).

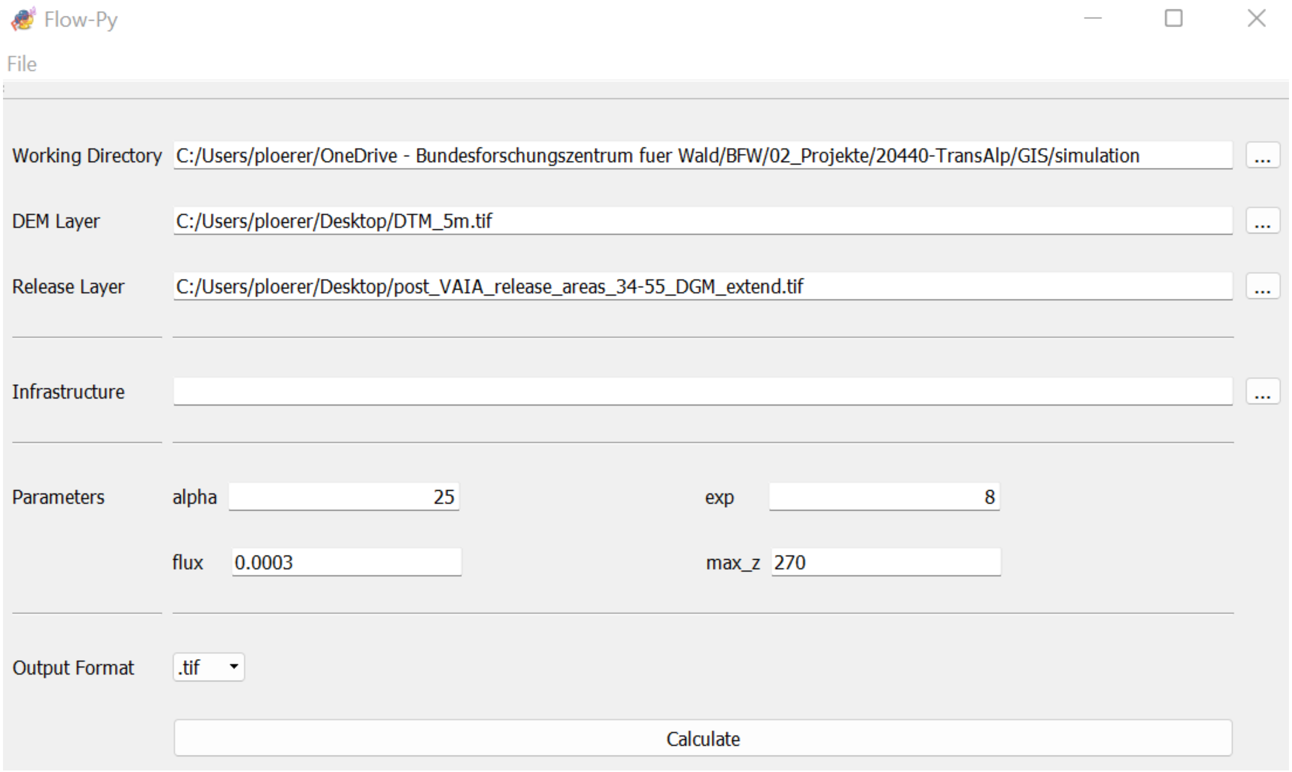

Figure 10: Flow-Py user interface for source layers and parameter settings.

The modeled process paths are based on a "stopping routine" (potential runout length; Figure 11) and a "routing routine" (which direction does the process take?). For these routines implemented in the model code, four parameters must be defined. "Alpha" limits the runout length (alpha angle), "exp" and "flux" determine or limit the lateral process propagation and "max_z" limits the natural hazard process to a maximum velocity or kinetic energy due to turbulent friction. These four parameters must be defined according to the hazard process modeled.

The concept of the runout angle is defined from a line formed from the top of the release to the farthest-reaching runout mass (Figure 11). This angle is often referred to as an alpha angle and used in statistical models to predict the runout of (large) avalanches. Statistical data on past events helps to identify the alpha angle and, in that way, determine the runout distance (Kobal et al. 2019). For this simulation, based on recommendations in a “GreenRisk4Alps” project report from Kobal et al. (2019), an alpha angle of 25° and an exponent of 8 were used to simulate destructive snow avalanches. These are typically used parameters for large avalanches with a minimum 100-year return period (Huber et al. 2017). The parameters “flux” (0.0003) and “max_z” (270) where used as the default values for avalanches.

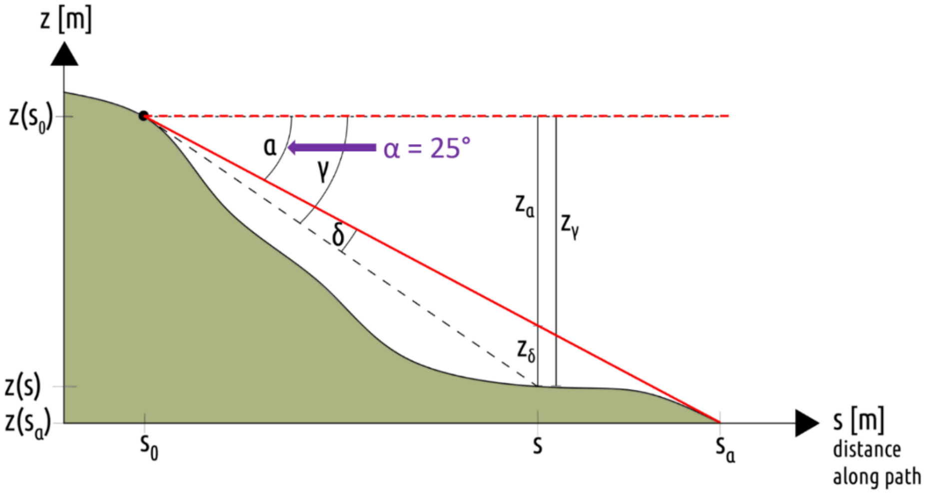

Figure 11: alpha angle concept for the modelling of avalanche runout distances in Flow-Py. Source: D'Amboise et al. (2022)

In the simulations, forests below release areas were not considered as resistance areas (stopping respectively energy reducing effect of forest growing in the avalanche path). The justification for that is, that these forests can also suddenly lose their protective effect by, e.g., bark beetle outbreaks that preferentially take place in windthrow areas with weakened or damaged trees. Furthermore, no snow entrainment was considered since this is not implemented in the model yet.

The overarching questions in this section were:

- How do new potential avalanche release areas that originate in cleared windthrow areas, affect the avalanche risk landscape? (Figure 12 and Figure 13)
- Are there new elements at risk (buildings and infrastructures)? (Figure 12, Figure 13, Figure 14)

Figure 12 shows a picture of the landscape around Kals am Großglockner in East Tyrol taken during a drone flight in the frame of field studies in Kals am Großglockner (see Section 3.4.1). The yellow areas show windthrown forest sites which are already cleared and now potentially function as avalanche release areas. The village of Kals (hamlet Großdorf colored in magenta) was suddenly exposed to a number of natural hazards after Vaia in 2018 including avalanches, rockfall and landslides. In case of Kals, it has to be mentioned that a multifaceted set of mitigation measures was installed in a short time, which can be seen in the middle of Figure 13 (avalanche release fences). Nevertheless, a lot of infrastructure is still newly exposed to natural hazards in East Tyrol, where mitigation measures have not been constructed until now.

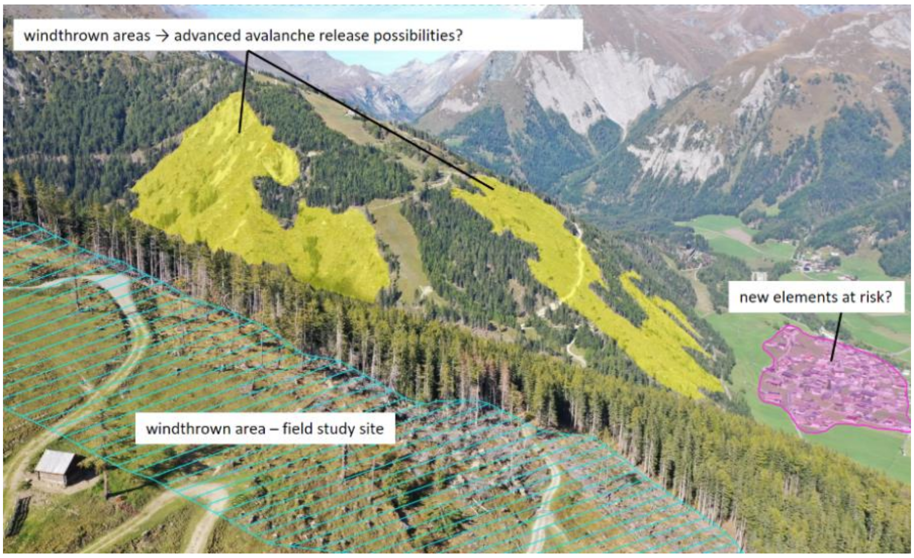

Figure 12: Windthrow in the area of the ski resort Kals am Großglockner, the hamlet of Großdorf at the bottom of the damaged forest and the BFW´s field study site in the front.

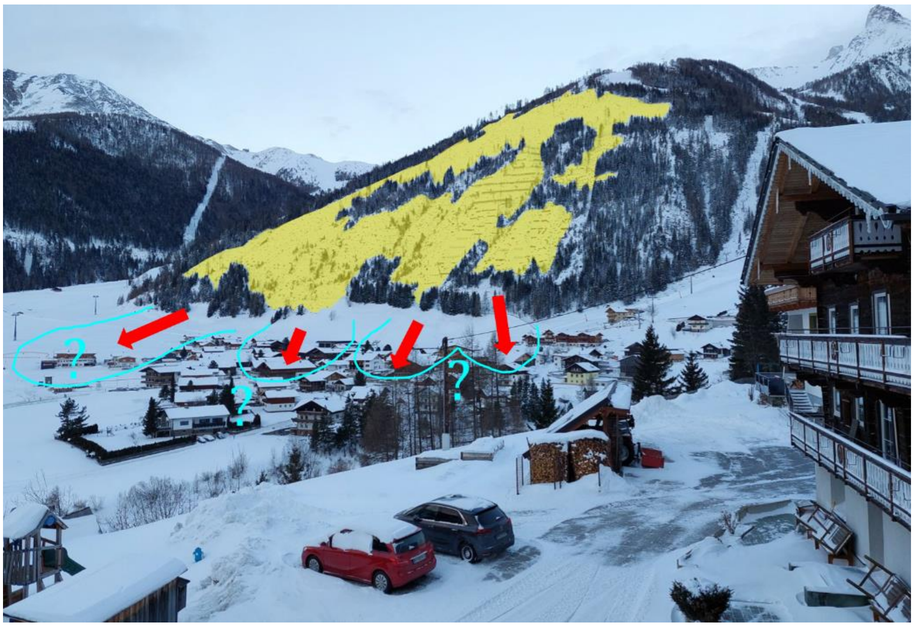

Figure 13: Is there a new avalanche risk scenario for settlements due to storm-related land cover change and cascading effects?

Figure 14: Is there a new avalanche risk scenario for transportation routes due to storm-related land cover change and cascading effects?

The following Figure 15 shows an overview of the entire East Tyrol. The light blue to dark blue ranging pixels show the modelled avalanches and their paths starting in cleared Vaia windthrow areas respectively from the above described new avalanche release areas (Figure 9). As visible in the Figure, large areas of East Tyrol have potentially endangered infrastructures situated in main and side valleys of this district. Hotspot regions for new avalanche hazard scenarios are the center of East Tyrol including the Kalsertal, Hopfgarten in Defereggen and Huben in the middle of the Iseltal (see white box in Figure 15).

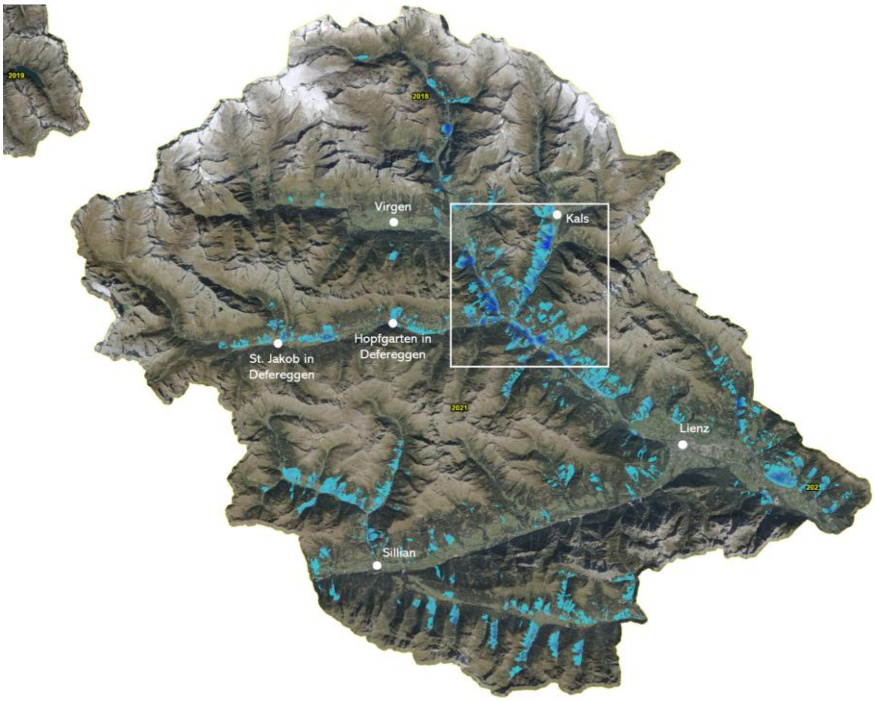

Figure 15: The entire area of East Tyrol (district Lienz) is covered with new potential avalanche paths, potentially released in cleared windthrow areas. Generated with the Flow-Py model. Most affected area highlighted in the white box.

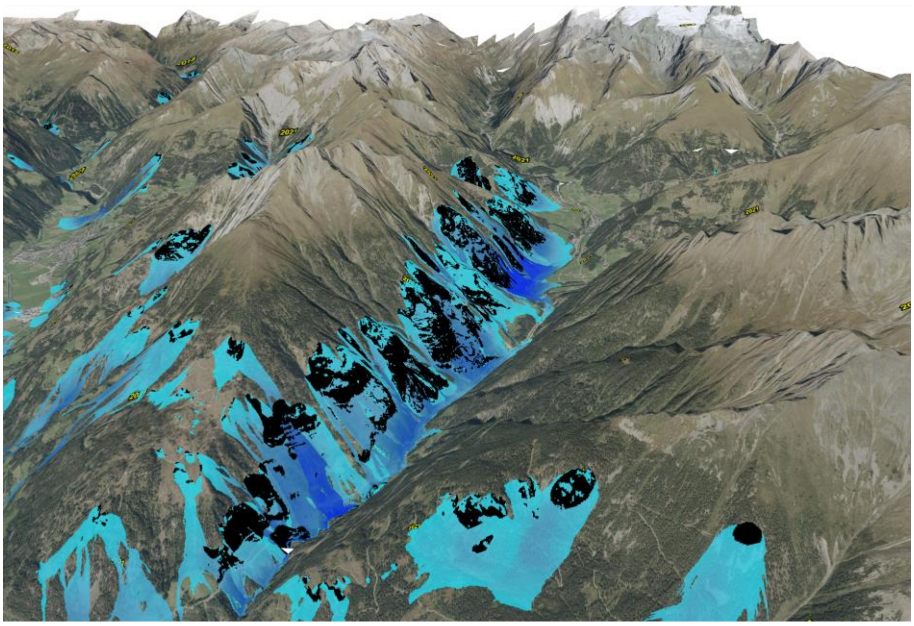

Figure 16: Hotspots like the Kalsertal show the intensified risk scenario due to new potential avalanche paths created by windthrow and cascading effects. Black pixels: new release areas on cleared windthrow sites. Blue shades: avalanche propagation from simulations.

Figure 16 shows the Kalsertal in the northeastern part of East Tyrol. This is one of the hardest affected regions. Newly created avalanche release areas and paths could, for example, endanger the road into the valley over a length of about 10 km. Basically, there are already long known and always active avalanche areas here, which create problems (road closures, evacuations), but the additional potential avalanches from the windthrow areas could intensify the risk scenario.

4.1.2 Cordevole Valley (Italy)

A correct avalanche risk analysis must consider several aspects: 1) the Potential Release Area (PRA) must be determined, 2) the avalanche runout must be assessed and 3) any vulnerable elements that may be affected by the avalanche path must be identified. The Arabba Avalanche Centre has developed, in the context of the TRANS-ALP project, a series of GIS tools capable of automatically identifying the parameters listed above. 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. Using GIS technologies in combination with DEMs, historic avalanche release area records have been analyzed with respect to topographic characteristics. Firstly, large-scale topographic parameters are derived from the DEM to automatically define PRAs. Secondly, every PRA is characterized by smaller scale geomorphologic parameters (Maggioni 2005). In general, avalanches can initiate on any slopes with an inclination between 30° and 60° except if dense forest is growing in the terrain to prevent avalanche initiation (Salm, 1982). As mentioned above, the windthrow of entire portions of forest leads to the creation of new areas of potential avalanche release Figure 17).

Figure 17: One of the many new avalanche sites created by the Vaia storm in the Cordevole Valley

In theory it is possible, that all these slopes will release at the same time, but usually avalanches occur on smaller portions that are distinguished from each other by topographic features such as ridges and show a certain topographic homogeneity within its area. Yet, a general definition of the criteria that separate neighboring release areas from each other is not available. Another criterion is the exclusion of main ridges from PRA and using them also as a separating feature for the PRA. The main ridges are automatically derived from the DEM using a procedure which is the combination of the two methods explained briefly in the following: The difference between lattices with different resolution (10 m and 60 m) is computed identifying regions with positive or negative values respectively for ridges or gullies; Areas with considerable aspect change and high positive values of curvature are selected with GRID commands to identify potential ridges. The intersection of these two regions delineates the main ridges. The resulting area must be divided into smaller areas that are comparable to the observed release perimeters, which has been done by computing the slope curvature in which the effects of gravitational processes are maximized or minimized. According to Maggioni (2005) for the definition of the PRA the plan curvature in used to separate concave areas from flat and convex ones, and the spatial resolution of the DEM must be reduced to 50 m so that only large-scale curvature changes are considered since smaller scale topographic curvature changes are not capable of separating neighboring release areas from each other. The model developed makes it possible, based on an updated land-use map following a storm event such as Vaia, to immediately compute new PRAs of a certain area (Figure 18).

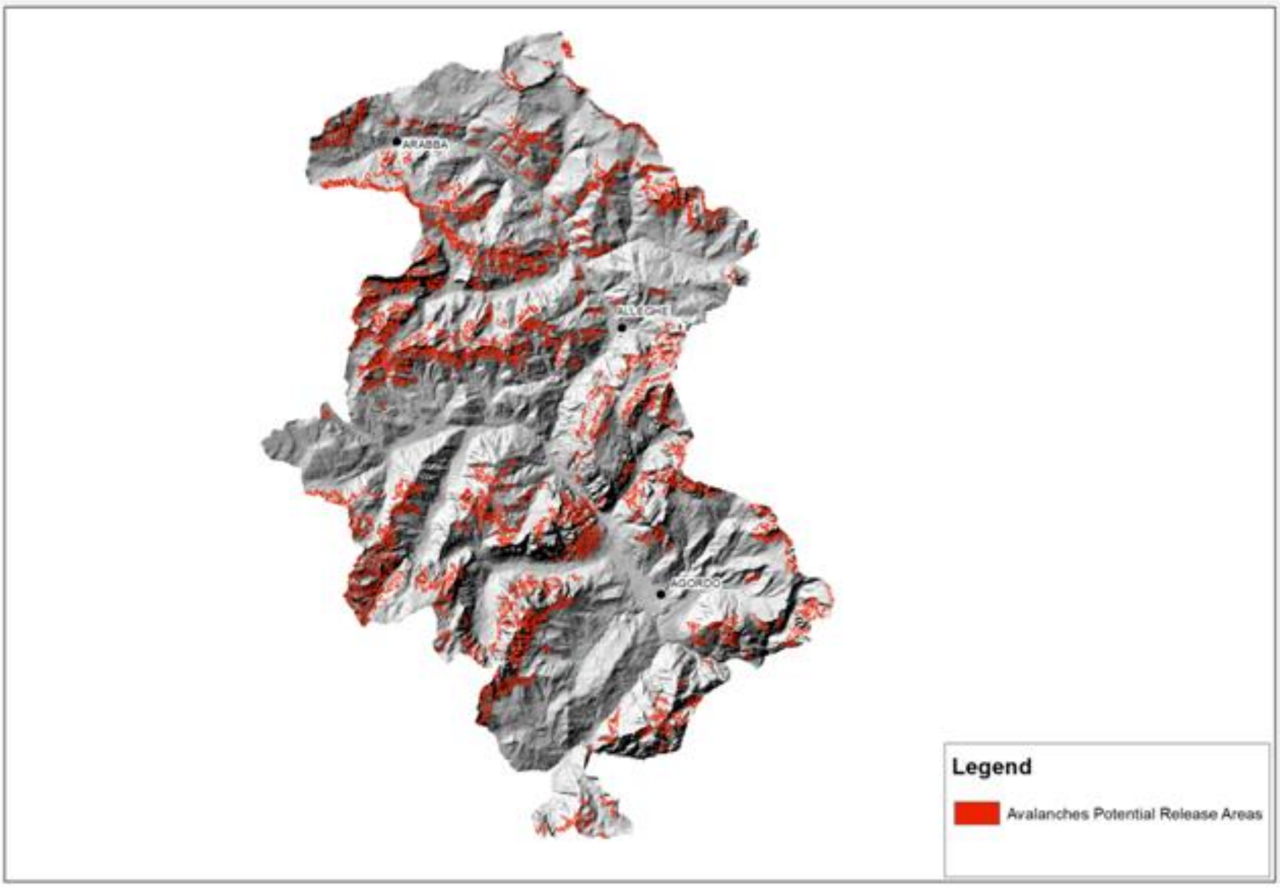

Figure 18: New Avalanche Potential Release Areas of the Cordevole Valley based on the forest changes due to the Vaia storm

It is interesting to see how the tool produced for the TRANS-ALP project accurately calculates the effects of land-use change. In Figure 19 below, it is possible to see how the PRAs that were calculated before and after the effects of the Vaia storm have changed. It is evident, therefore, that the destruction of forest vegetation leads to a significant increase in the number of potential avalanche sites.

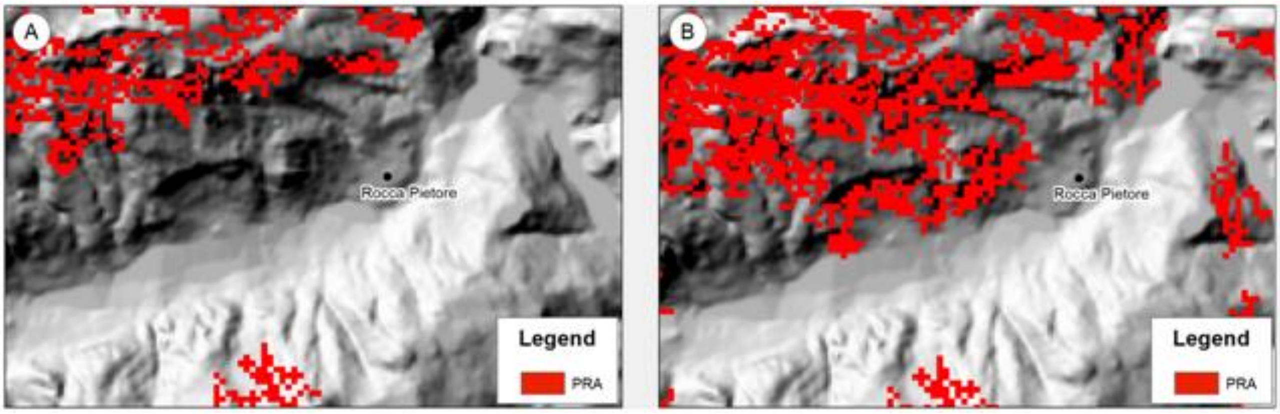

Figure 19: The Potential Release Areas evaluated by the tool developed by the Avalanche Centre of ARABBA (ARPAV). A) with the pre-storm Vaia forest condition; B) with the post-storm Vaia forest condition.

To estimate the potential avalanche runout, the hydrologic terrain analysis software tauDEM (Tarboton 1997) has been adapted to derive avalanche paths identified from the DEM. The tool is capable to detect all locations downslope of a given starting cell(s) until a pre-defined alpha angle from the starting cell is reached (Figure 20).These runout alpha angles were based on studies of return periods of avalanche runouts in the study area. Such studies have shown that angles between 20° and 23° are sufficient to stop most avalanches.

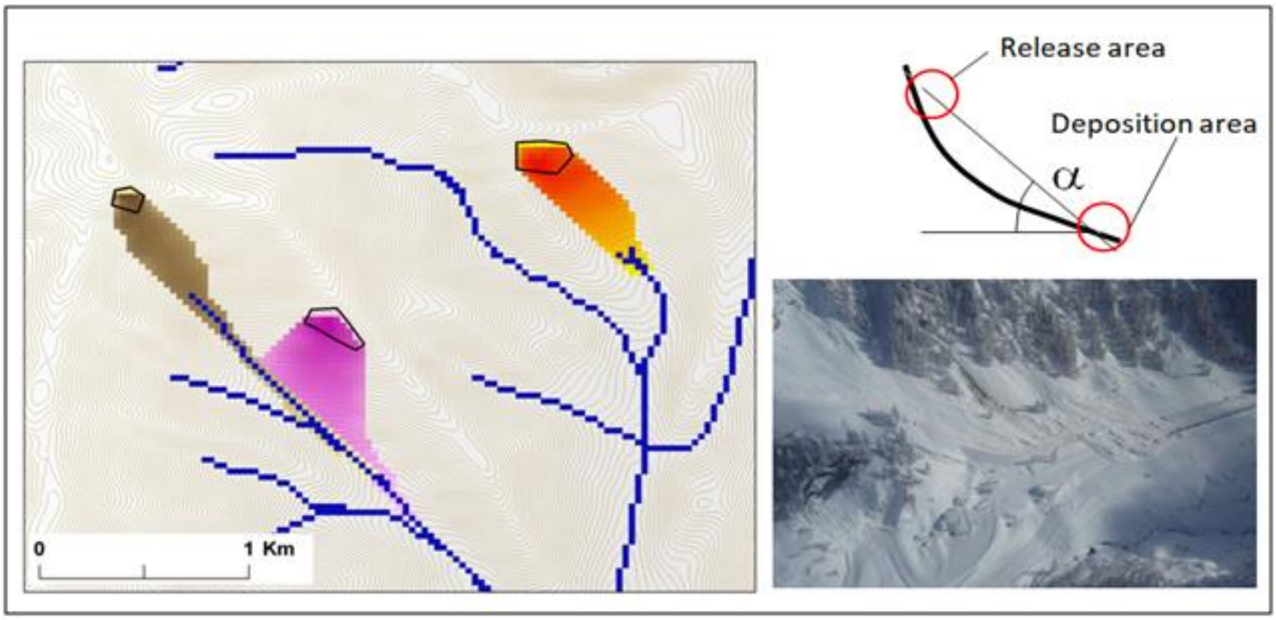

Figure 20: Example of model operation based on morphological stopping conditions. The runout of the avalanche is simulated on the propagation of the D-infinity model developed by Tarboton 1997 until the flow reach the stopping angle conditions

The advantage of a morphological-based approach to identify the runout of potential avalanches is that it allows simultaneous analysis over large areas to identify potential hazard areas in a short time (Figure 21).

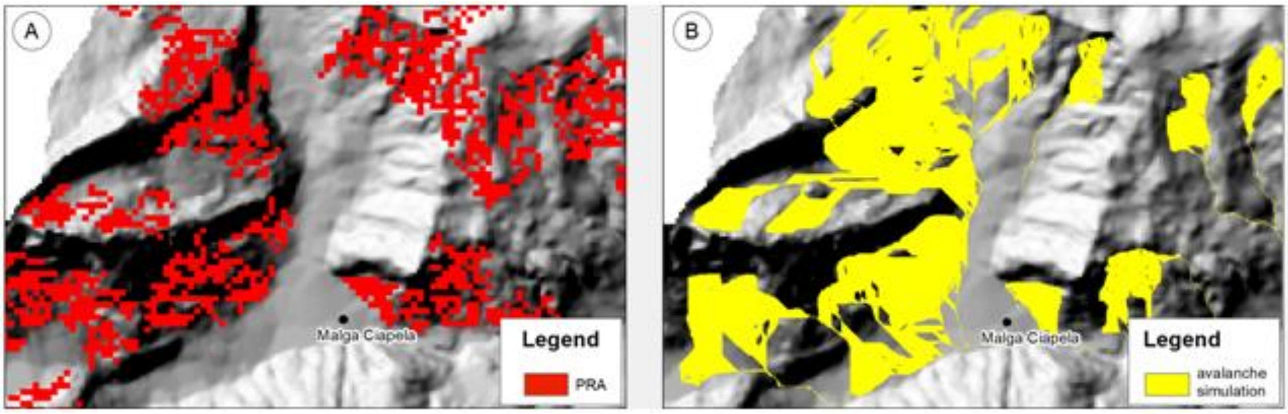

Figure 21: Example of how the tool developed by the Arabba Avalanche Centre (ARPAV) works: Once the PRA have been identified (A); from these, the runout of all potential avalanches in the study area are simulated simultaneously (B)

The tool developed by the Arabba Avalanche Centre is, moreover, capable of reporting the avalanche susceptibility for the entire study area, which refers to the proneness of an area to avalanche occurrence. The main difference with the PRA map is that the latter is a binary map that identifies the avalanche release areas and differentiates them from the rest of the area. Instead, the susceptibility map, based on morphological characteristics, exposure and land use, proposes a scaling of the probability of avalanche release. In contrast to the tool that identifies PRAs, the susceptibility map samples the entire study area by splitting it according to different degrees of proneness to the release of the avalanche phenomenon. Years of field research have revealed that occurrence of avalanches is mainly affected by terrain, weather, vegetation cover and snowfall. In the tool developed, the terrain factors mainly included elevation, slope, aspect, plan curvature, profile curvature, terrain ruggedness index (TRI), topographic position index (TPI), Distance to Stream (DTS), topographic wetness index (TWI), Distance to Road and solar radiation, which were derived from analysis of the DEM. For the land-use map, the official map of the Veneto Region was used, from which the portion of vegetation destroyed by the Vaia storm was removed, considering the downed trees as bare ground. Each individual map was subdivided by its various parameters and, thanks to a statistical cross-reference with the avalanches recorded in the study area, each individual parameter was indexed by importance. The final result is a map that identifies areas which are subject to avalanches and measured from very low to very high susceptibility (Figure 22), and this aspect is fundamental for proper future land-use planning.

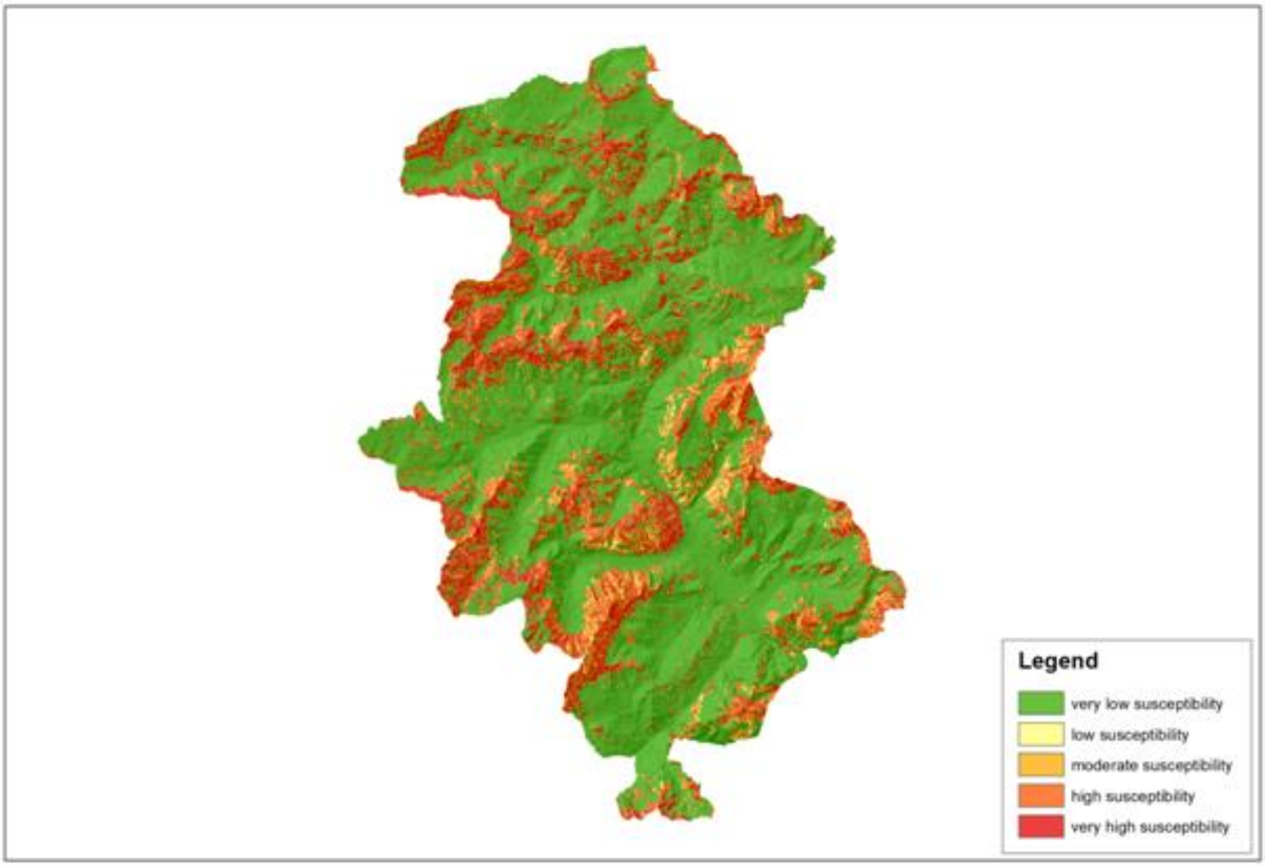

Figure 22: Avalanche susceptibility map of the Cordevole Valley

Here too an attempt was made to analyze the difference in model processing before and after the effects of the Vaia storm. Figure 23 clearly illustrates how the effects of the storm on vegetation affects all degrees of avalanche proneness.

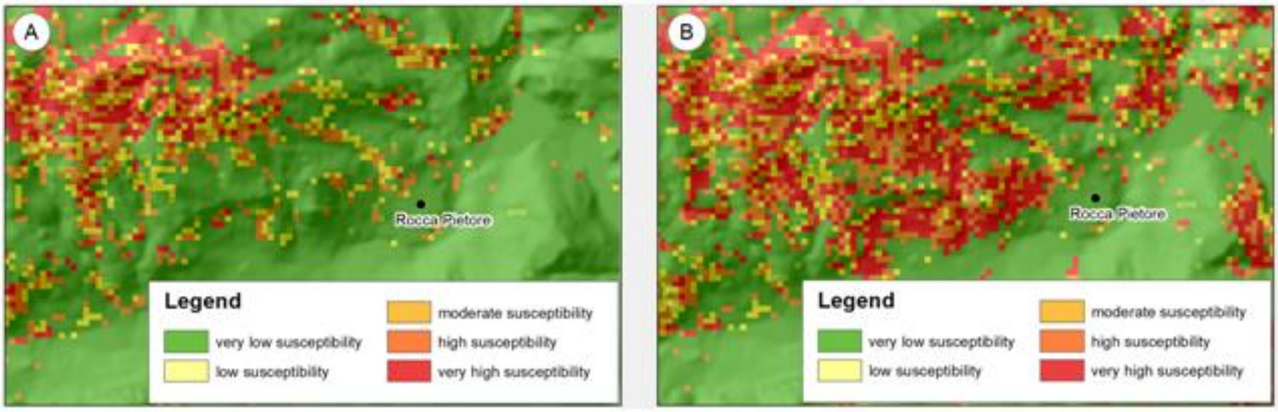

Figure 23: Susceptibility map evaluated by the tool developed by the Avalanche Centre of ARABBA (ARPAV). A) with the pre-storm Vaia forest condition; B) with the post- storm Vaia forest condition.

4.2 Assessment of the newly exposed assets due to post-windstorm avalanche hazard

4.2.1 East Tyrol (Austria)

In the following, some examples on how newly established post-windstorm avalanche release areas and the corresponding runout can negatively affect the avalanche risk to buildings and infrastructure are summarized:

1. Exacerbation of the hazard situation due to increased avalanche runout lengths beyond the red and yellow hazard zones defined by regional experts and authorities (Figure 24):

The example (Figure 24) shows small hamlets in East Tyrol connected by a primary road (red line) and the current hazard zone plan (yellow) elaborated from the Austrian Avalanche and Torrent Control. From this current hazard zone plan, the yellow zone (furthest reaching relevant avalanche pressures) is visualized. The yellow arrows indicate the general avalanche flow direction. Considering this hazard zone plan, the major road (red line) is affected by avalanches only on a short section highlighted in the white rectangle. Under consideration of newly established release areas after the Vaia windstorm (black pixels), the potential avalanche runout distance partly increases up to about 150 meters. The consequence is a longer section of the road network potentially affected by the modelled avalanche (black rectangle) and therefore an intensified risk scenario.

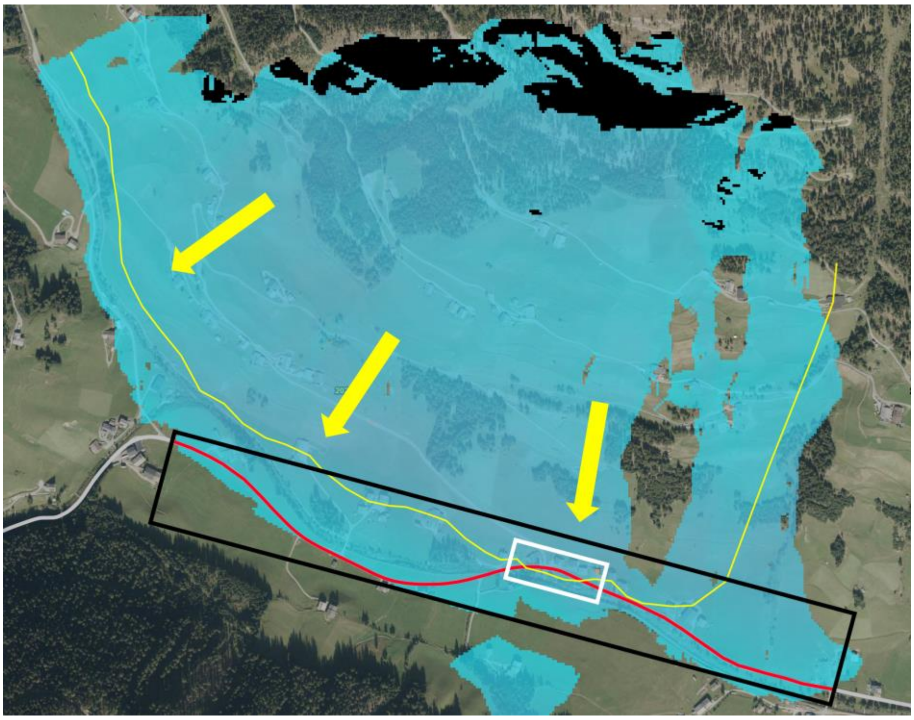

Figure 24: A small hamlet in East Tyrol. The yellow line indicates the yellow hazard zone approved by the authorities. The blue pixels show the potential avalanche runout after simulations with new release areas situated in cleared windthrow areas. The main road (red line) could now be more effected than before the Vaia windstorm. Source hazard zone plan: Land Tirol / Tiris

2. New avalanche runout paths and deposition zones within the settlement area, which could not yet be considered by the official hazard zone planning (Figure 25):

As in several valleys of East Tyrol, well known major avalanches endanger settlements. In most of the areas of risk relevant avalanches, mitigation measures such as steel snow bridges were implemented in avalanche release areas. Due to these achievements, many areas are well protected against avalanches up to a certain avalanche size without evacuation activities. On the one hand, this made it possible to adapt hazard zone plans. On the other hand, hazard zones remained in their original shape without considering engineered protection measures to include potential structural failure or overload cases. However, by considering new established avalanche release areas in cleared post-windthrow areas potential avalanche paths and deposition zones can be highlighted. The example in Figure 25 shows a large yellow hazard zone. The yellow arrows indicate the avalanche flow direction. Shown on the bottom of Figure 25 is a “new” potential avalanche released from a windthrow area. Due to no relevant release areas in this forest site before Vaia, the authority did not consider protecting the zone highlighted in red.

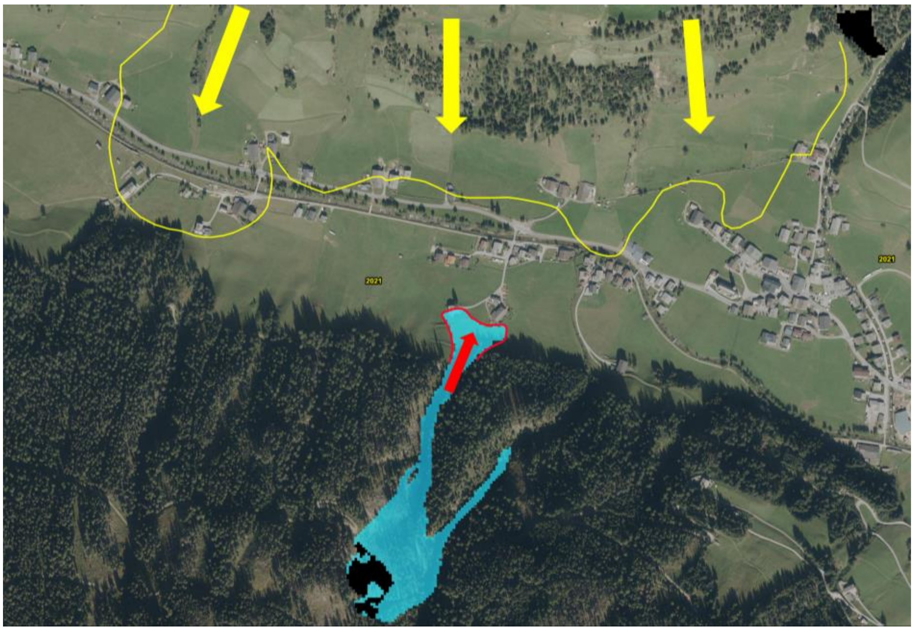

Figure 25: All official avalanche danger zones are located in the north of the village. Due to the lack of probability of avalanche releases within the forest and the lack of known avalanche paths, zoning in the south has not yet been carried out. The current simulations show a new potential of damaging avalanches for the settlement area. Source hazard zone plan: Land Tirol / Tiris

Another example is delivered in Figure 26. Although this shows a so-called spatially relevant settlement area, i.e., an area that needs to be protected (black dashed line), no yellow and red hazard zones for avalanches have been designated in the center of the hamlet because there was no corresponding exposure until now. Storm Vaia has resulted in such a large gap in the protective forest that, with appropriate simulations, a new risk scenario can now be assumed and the adaptation of the hazard zone plan could be initiated.

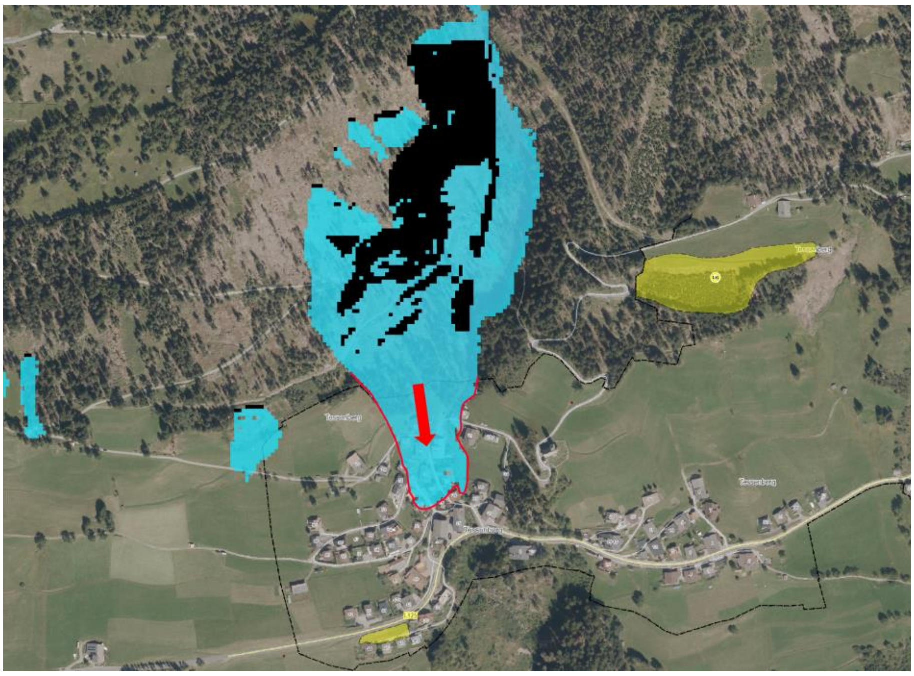

Figure 26: Current hazard zone plan from the WLV (yellow shapes). The blue area highlights new potential avalanche paths generated from the cleared windthrow areas above the hamlet. Source hazard zone plan: Land Tirol / Tiris

3. Sudden exposure of sensible infrastructure to avalanches and associated potential for cascading effects (Figure 27):

The following image (Figure 27) shows a newly built power plant (white rectangle). Due to the protective forest orographically to the left and right of the plant, no official hazard zone has been designated so far and no protective measures against avalanches were necessary. After storm Vaia, significant gaps opened in the protective forest orographically left above the power plant. As the avalanche runout of the simulations with Flow-Py shows, the power plant itself is not affected. However, newly created avalanche paths can reach the river flowing through the valley and subsequently dam it. A backwater into the nearby area of the power plant would be possible as a cascading effect. This example shows that, in addition to the technical protection measures against avalanches per se, multi-hazards and cascading effects must also be considered.

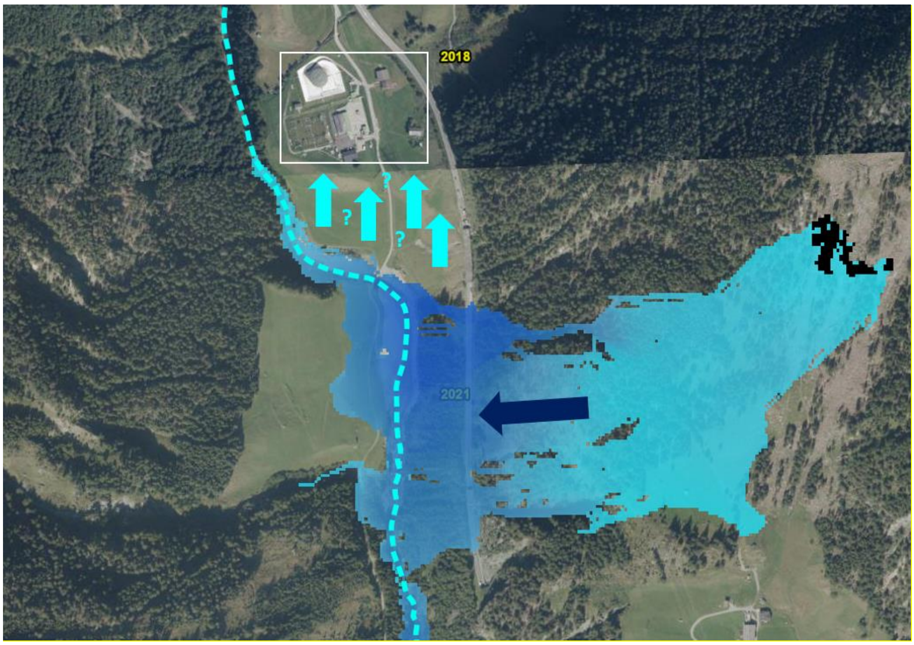

Figure 27: Possible cascading effects' scenario due to a potential post-windthrow avalanche, damming and flooding the river. Dark blue arrow: avalanche flow direction. Light blue dashed line: river stream. Light blue arrows: possible damming direction. White rectangle: power plant.

4.2.2 Cordevole Valley (Italy)

For a correct assessment of avalanche risk, it is essential to distinguish the factors that constitute it: hazard, exposure, and vulnerability. In Section 4.2.2, we described how the PRA map, the susceptibility map and finally the avalanche runout map were derived thanks to the GIS tools developed by the Arabba Avalanche Centre. A supplementary extension of the GIS tool developed for the TRANS-ALP project makes it possible to identify, which elements at risk may be affected by avalanches. Elements at risk is a generic term that signifies everything that might be exposed to hazards, ranging from buildings to the economy and from individual persons to communities. Elements at risk is about exposure to the hazard: What is there that can be damaged or destroyed, injured, or killed, hampered, or interrupted. The degree to which this happens depends on the intensity of the avalanche and the vulnerability of each element at risk to suffer loss due that particular hazard with that particular intensity. In the literature, numerous methods can be found to classify elements at risk, depending on the country, the setting (urban, rural, etc.), the objectives of the risk assessment, the spatial scale, available resources etc. To assess the risk of a given avalanche, therefore, a hazard map must be used to consider not only the avalanche runout, but also its magnitude. A dynamic avalanche model running on a catchment scale, capable of returning the impact pressures and velocity of each individual avalanche of the thousands present on a certain area, is not available on the market to date, except by contract to specific third-party organizations. On the other hand, more and more avalanche dynamics software is available to simulate avalanches on specific avalanche sites. The tool developed by the Arabba Avalanche Centre therefore allows, based on the avalanche runout map, to automatically extrapolate the elements at risk concerned. Based on which elements at risk may be affected by avalanches, it is then possible to make a priority list on which to base the dynamic avalanche calculation and civil protection interventions. To do this, it was therefore essential to prepare a map, as input data, with the elements at risk ranked by importance. To understand the priority of the intervention in the Cordevole Valley two different scales of analysis, ranging from national scale to a detailed scale were used.

In Table 2 below, an overview is given of these two scale levels versus the detail of the elements at risk that could be used.

Table 2: The table shows the classification adopted for the priority of the interventions in the Cordevole Valley. The classification in the first column was made to understand where to make specific insights with dynamic avalanche modelling, while the second was used to calibrate civil protection plans.

Elements at risk	Scale of analysis	
	Regional <1: 50.000	Large (Local) 1: 10.000
Buildings	Homogeneous units: • Predominant type (e.g., residential, commercial, industrial, touristic) • Nr. of buildings	Building footprints • Occupancy type • Construction type • Number of floors • Generalized replacement value
Transportation networks	Road networks: • with general classification of road types, • Road cuts, • General traffic density information	Detailed road networks: • with detailed type classification, and information per unit length (e.g., 1 km) of: • Road cuts and embankment fills, • Bridges, • Road conditions, • Drains, • Traffic data
Lifelines	Only main networks • Water supply (pipelines) • Electricity (power lines)	Detailed networks and related facilities: • Water supply with sources, tanks, pipelines, and main distribution network • Wastewater treatment plants • Electricity, with plants, stations, powerlines, and pylons • Communication, with cell towers • Gas supply stations
Essential facilities	As points • Fire brigade stations • Police stations • Medical centers • Schools • Shelters	Individual building footprints • Fire brigade stations • Police stations • Medical centers • Schools • Shelters
Population data	By enumeration districts • Population density	By mapping unit • Population density

		• permanently inhabited houses/holiday houses • Daytime/nighttime • Age
Land cover	By pixel: • Land cover type • Crop types • Yield information	By cadastral parcel • Crop types • Crop rotation • Yield information • Agricultural buildings
Ecological data	Natural protected area with national relevance	General flora and fauna data per cadastral parcel

The final result is a raster map in which each element at risk has been indexed (Figure 28). Such indexing allows the identification of a priority for action in risk mitigation.

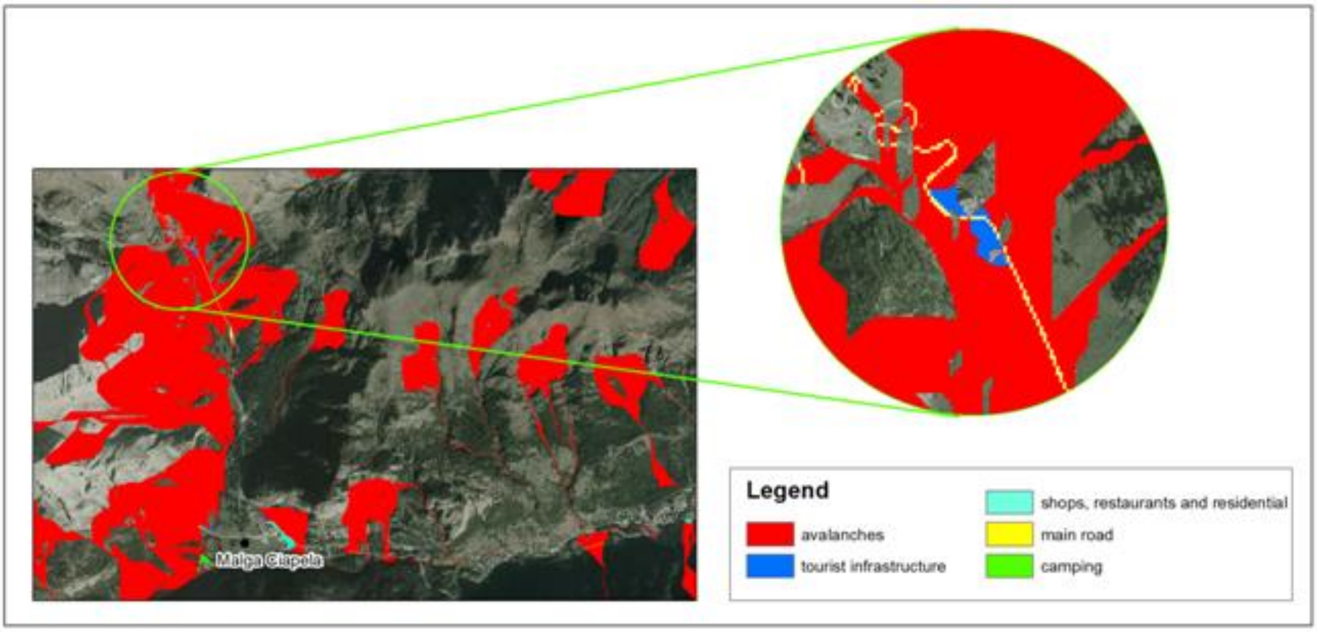

Figure 28: The map of the elements at risk as calculated by the application developed by the Arabba Avalanche Centre overlaid on the avalanche map

Once the areas characterized by a higher degree of vulnerability have been identified, a series of dynamic modelling was conducted to indicate along the avalanche path the maximum flow heights, impact pressures and the perimeter of the avalanche itself (Figure 29). It also considered the parameters relating to the characteristics of the snowpack and the friction that can develop at the specific site for different return periods. For the simulation we used the software RAMMS developed by the WSL Institute for Snow and Avalanche Research SLF (Christen et al., 2010).

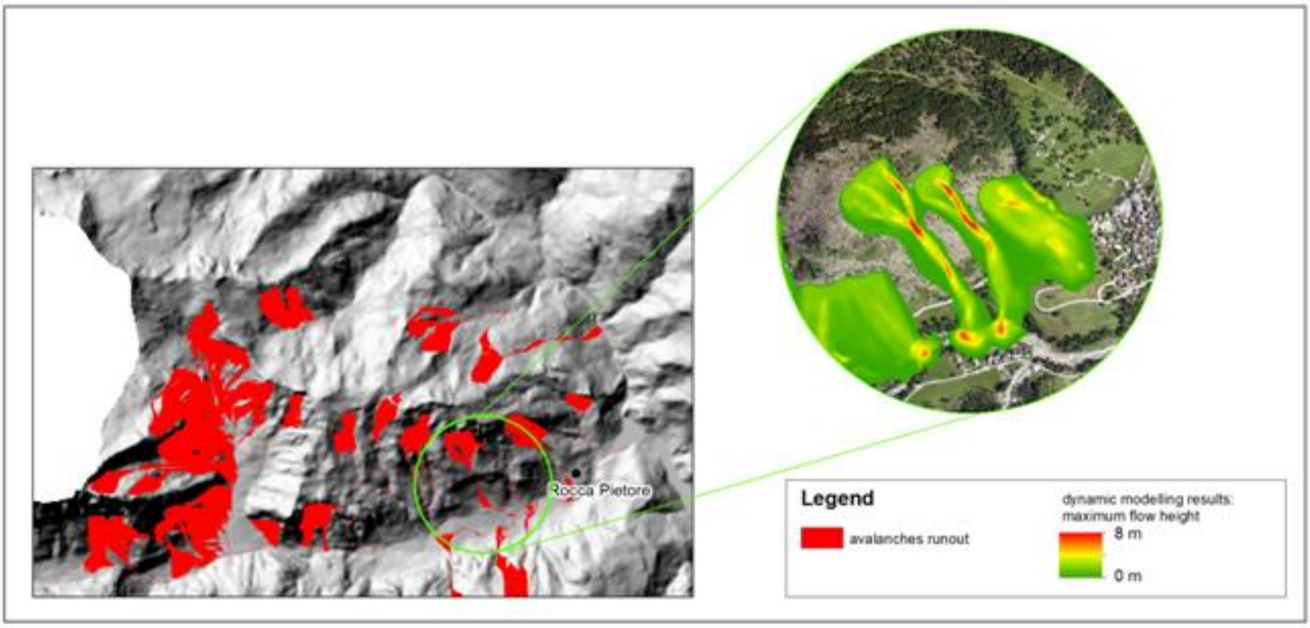

Figure 29: The box shows the dynamic modelling of avalanches that may affect the vulnerable elements identified using the tool developed by the Arabba Avalanche Centre. The example shows the maximum flow height.

The results of this final modelling were used for the implementation of special civil protection plans and will be applied in the future, when the countermeasures work will be completed, for the reclassification of avalanche hazards in accordance with the current national legislation.

5 Synthesis and recommendations for harmonized trans-boundary management of cascading effects and related risks

5.1 Adapting existing civil protection tools and passive mitigation measures

The examples described in Chapter 4 highlight that new potential avalanche release areas as well as other natural hazards can occur as cascading effects after windthrow events in protective forests, especially if the downed trees are being removed (see Chapter 2 and Section 3.4.1). This leads to newly exposed elements at risk requiring specific technical protection measures depending on the hazard. It is well known that such measures are expensive both in terms of financial resources as well as in terms of the time it takes to implement them. To mitigate the risk when implementing technical protection measures, specific civil protection plans can be used.

Regarding the avalanche risk in the Cordevole valley, extraordinary civil protection plans were made to ensure adequate safety conditions to infrastructures and public and residential buildings, as preventive avalanche control measures such as the artificial avalanche release cannot be considered due to the presence of buildings potentially subject to damage. 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, already described in Section 4.2.2, 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 following simulations were conducted in relation to the level of potential risk:

1. Snow height increase values in 72 h (HN3gg) for a return period (T) of 100 years - Low-risk area delimitation;
2. For areas characterized by medium or high risk, several simulations appropriate to the size of the study area and the number of houses were conducted to define different threshold values of HN3gg. The resulting alert thresholds were set with a minimum interval of 30 cm of new snow, corresponding to several hours of precipitation.

The avalanche release height was calculated using the formula proposed by Salm et al. (1990) and Burkard and Salm (1992):

$$Hd_{(T;z)} = \left[DH3gg_{(T;z)} \cdot \cos 28° + Hsd_{(T)}\right] f(\theta)$$

T = return period;

Z = average release altitude

DH3gg = snowpack thickness accumulated on three consecutive days (measured vertically on a horizontal surface)

Hsd = overload of wind-deposited snow

f(Θ) = decreasing factor of the average slope of the release area

Snow height measurements are conducted at the snow observation sites indicated by the Avalanche Centre of Arabba, representative of the avalanche release area under consideration. The alert thresholds defined in the civil protection plan correspond to snow thicknesses measured vertically at the snowfield. The defined value already considers the potential higher altitude of the area of potential release and the slope inclination.

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 (

Table 3), as well as indicating on special maps which buildings or roads could be affected by avalanches if the above thresholds were reached. Examples are shown in Figure 30 and Figure 31 for the hamlets of Sief and Corte, near Livinallongo del Col di Lana (municipality head).

Figure 30: The village of Sief and the new potential avalanche site above.

Table 3: Potentially affected property by risk threshold in Lasta Sief site

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

The final result is a detailed plan for more than 60 sites in the Cordevole Valley, that includes daily monitoring of HN3gg in special snow observation sites performed by civil protection volunteers, and when the above thresholds are reached, it is clearly indicated on the map which houses have to be evacuated and which roads have to be closed to traffic (Figure 31).

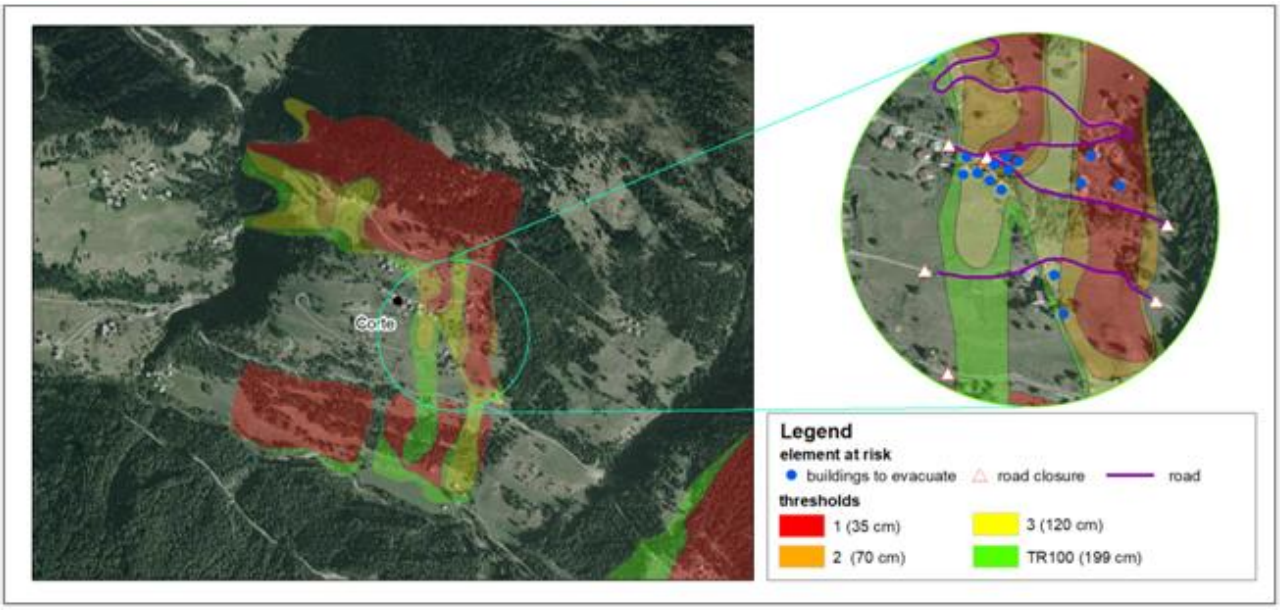

Figure 31: The risk classification in Lasta Sief site as a function of ground snow thresholds recorded. In the box is outlined which houses must be evacuated depending on the DH3gg threshold reached and where the road should be closed to traffic.

In Austria, for example, in Kals am Großglockner in East Tyrol, potential new avalanche release areas that were cleared after windthrow by Vaia, had technical protection measures installed by the Austrian Torrent and Avalanche Control. However, due to the extensive forest damage, areas with a considerable potential avalanche risk can still be identified where no technical protection measures have been implemented until now and the hazard zone plan has also not been adapted yet. According to the regional modelling (see Sections 4.1.1 and 4.2.1), new avalanche risk hotspots should be considered individually and in detail, as well as evaluated for plausibility. For the simulation performed by BFW within the framework of the TRANS-ALP project, it is likely that the new hazard scenario has been overestimated for certain cases. For example, some PRAs with relatively small areas (a few 5x5 m pixels) resulted in considerable avalanche runout lengths; however, if these small release areas can actually produce such large avalanches must be validated with, e.g., physical models such as the open avalanche framework Avaframe (https://avaframe.org/).

The described and already implemented method by the Avalanche Centre of Arabba could be a blueprint for other storm-affected regions to manage and mitigate the risk of the cascading effect of potential avalanche release from windthrow areas.

Adapting trans-boundary civil protection plans temporally until planted trees or the natural regeneration have reached a sufficient height to protect against snow avalanche is an effective and cost-efficient measure and a valuable alternative to technical protection measures that are costly to implement.

5.2 HARMONIZING POST-EVENT MULTI-HAZARD SURVEYING

The experience from and difficulties that were encountered during the surveys conducted after the Vaia storm (Section 3.3.2) led to the creation of a series of post-event multi-hazard survey sheets (see Chapter 7 Annex).

These sheets have been structured through a general sheet in which the data relating to the place of the survey, the type of event and impact (landslide, avalanche, forest destroyed and beetle spread), the surveyors and the other people present at the inspection, the survey of the damages and the specification of the interference with a watercourse are noted. Four sub-sheets are connected to the general sheet, one for the different impacts / events mentioned above. Each of the sub-sheets has been structured in two main parts, one relating to the survey of the event (now) and one relating to the impact assessment (future scenario); moreover, it is always possible to attach maps, photos and other useful documentation to the post event multi-hazard survey sheets to detail the survey carried out in the field. The general sheet and the 4 sub-sheets are attached to this report (see Chapter 7 Annex).

Harmonizing post-windthrow multi-hazard surveying in a structured way with easy to apply survey sheets as proposed above that are built on already existing survey sheets for single hazard assessments could be one way to structure and organize the often-hectic post-event phase. In that way, the respective authorities are already familiar with the general survey process and important data will be recorded in one step and not later when some information might not be available anymore.

Applying such survey sheets in trans-boundary regions could amplify the exchange between authorities and the collection of all relevant data that can be used in follow-up trans-boundary event analysis to strengthen the preparedness, response and recovery from such events in the future.

5.3 DEVELOPING AND HARMONIZING METHODS TO MAP AND ASSESS POST-WINDTHROW CASCADING EFFECTS RELATED TO NATURAL HAZARDS

Identifying and mapping windthrow areas, especially in steep terrain combined with site visits to further quantify remaining protective effects against natural hazards or areas where other measures must immediately take place is a major task after large-scale severe forest disturbances.

Considering the cascading effects related windthrow can be fulfilled by different methods and tools:

1. Identify areas where the forest has been damaged → *combination of satellite images and manned and unmanned aerial photography (see Section 3.2)*,
2. Identify potential cascading effects and the key variables controlling it → *site visits and field surveys (see Section 3.3)*,
3. Measure the key variables that may have changed due to forest damage → *remote sensing techniques such as UAS photogrammetry or lidar data acquisition in combination with in-situ measurements (see Section 3.4)*,
4. Assess the new scenario with a simulation tool or model → *GIS and simulation tools to model PRAs and simulate resulting runout and disposition areas (see Section 4.1)*,
5. Develop new mitigation plans based on the new state of the system → *e.g., adapting hazard zoning and civil protection plans (see Section 4.2)*.
6. Implement a monitoring plan and evaluate mitigation plans following future disturbance events → *e.g., apply suitable monitoring methods (see Sections 3.2, 3.2 and 3.4) and regularly update hazard simulations and risk assessments (see Sections 4.1 and 4.2) as well as civil protection plans (see Sections 5.1 and 5.2).*

Based on the examples and experiences from East Tyrol (Austria) and Cordevole Valley (Italy) that are compiled in this report, we emphasize that harmonizing methods and the continuous exchange between authorities but also between research institutions, which often support the development of new methods that can be applied in practice (see e.g., Section 3.4.1), will support and strengthen a trans-boundary management of storm risks and related cascading effects. For example, the institutions BFW and ARPAV that collaborated on this report chose different parameter values for assessing the risk. For example, the slope inclination to determine PRAs was chosen by BFW between 34° and 55° while ARPAV chose 30°-60°. The alpha runout angle was set by ARPAV to 20°-23°, while BFW used an alpha angle of 25°. Such parameters settings as well as input data for risk analysis should be harmonized in the future to assure trans-boundary comparisons and risk mitigation strategies being homogenized.

The TRANS-ALP project helped significantly to push this needed exchange and to establish and strengthen trans-boundary collaboration.

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7 ANNEX

Funded by European Union	**TRANS-ALP Project** ***Transboundary Storm Risk and Impact Assessment in Alpine Regions***	arpav Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto

POST EVENT MULTIHAZARD SURVEY SHEET – GENERAL PART

Form number:	1/2018

FIELD SURVEY DATA

Date	Province	Municipality	Location and coordinates
10.11.2018	Belluno	Canale d'Agordo	Pisoliva

Requested by	Date	Lat.	46°21'56''
Municipality of Canale d'Agordo	05.11.2018	Long.	11°53'58''

Event date	Event time	Type of	Landslide	Avalanche	Blowdown	Insect outbreak
29-30.10.2018	N.A.	Event	NO	NO	YES	NO
		Impact	YES	YES	YES	YES

Surveyors	External parties attending
Matteo Cesca – Arpa Veneto	Mario Rossi – Municipality of Canale d'A.
Roberta Dainese – Arpa Veneto	Mario Rossi – Veneto Region
Fabrizio Tagliavini – Arpa Veneto	Mario Rossi – Province of Belluno

DAMAGE DETECTED

Persons	Displaced	1	Dead	0	Wounded	0	Description / notes

Buildings	Level	No evaluable	Description / notes
Productive activities	Level	low	Description / notes
Communication routes	Level	medium	Description / notes
Agriculture	Level	high	Description / notes
Underground services	Level	high	Description / notes
Defense structures	Level	high	Description / notes
Other	Level	high	Description / notes

PRESENCE OF A WATERCOURSE

YES	X	NO	
Name	Torrente Tegosa		
Regional basin	Fiume Piave		
Barrage?	YES	Description / notes	
Total deviation?	NO	Description / notes	
Partial deviation?	NO	Description / notes	
Lateral erosion?	NO	Description / notes	
Other	NO	Description / notes	

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POST EVENT MULTIHAZARD SURVEY SHEET – LANDSLIDE

Form number:	1/2018

FIELD SURVEY DATA

Date	Province	Municipality	Location and coordinates
10.11.2018	Belluno	Canale d'Agordo	Pisoliva Lat. 46°21'56'' – Long. 11°53'58''

SURVEYORS	**ANNOTATIONS**
Matteo Cesca – Arpa Veneto Roberta Dainese – Arpa Veneto Fabrizio Tagliavini – Arpa Veneto	

EVENT DETECTION (now)

<table>
<tr><td colspan="3" rowspan="3">Type of movement</td><td colspan="3">Type of material</td></tr>
<tr><td rowspan="2">Bedrock</td><td colspan="2">Engineering soils</td></tr>
<tr><td>Predominantly fine</td><td>Predominantly coarse</td></tr>
<tr><td colspan="3">Falls</td><td>Rockfall</td><td>Earth fall</td><td>Debris fall</td></tr>
<tr><td colspan="3">Topples</td><td>Rock topple</td><td>Earth topple</td><td>Debris topple</td></tr>
<tr><td rowspan="3">Slides</td><td>Rotational</td><td></td><td>Rock slump</td><td>Earth slump</td><td>Debris slump</td></tr>
<tr><td rowspan="2">translational</td><td>Few units</td><td>Rock block slide</td><td>Earth block slide</td><td>Debris block slide</td></tr>
<tr><td>Many units</td><td>Rock slide</td><td>Earth slide X</td><td>Debris slide</td></tr>
<tr><td colspan="3">Lateral spreads</td><td>Rock spread</td><td>Earth spread</td><td>Debris spread</td></tr>
<tr><td colspan="3" rowspan="3">Flows</td><td>Rock flow</td><td>Earth flow</td><td>Debris flow</td></tr>
<tr><td>Rock avalanche</td><td></td><td>Debris avalanche</td></tr>
<tr><td>(Deep creep)</td><td colspan="2">(Soil creep)</td></tr>
<tr><td colspan="3">Complex and compound</td><td colspan="3">Combination in time and/or space of two or more principal types of movement</td></tr>
<tr><td colspan="3">Assessed volume</td><td colspan="3">10.000 m^3</td></tr>
<tr><td colspan="3">Assessed area</td><td colspan="3">1000 m^2</td></tr>
<tr><td colspan="3">Mean slope</td><td colspan="3">30%</td></tr>
<tr><td colspan="3">Range of altitude</td><td colspan="3">1000 – 1250 m a.s.l.</td></tr>
<tr><td colspan="3">Aspect</td><td colspan="3">N</td></tr>
</table>

<table>
<tr><td colspan="2">Velocity</td><td colspan="3">Landslide position</td><td colspan="2">Depth</td><td colspan="2">Close to a watercourse</td></tr>
<tr><td>Slow</td><td>Rapid</td><td>Single</td><td>Internal</td><td>Extended</td><td>Superficial</td><td>Deep</td><td>Yes</td><td>No</td></tr>
<tr><td>X</td><td></td><td></td><td>X</td><td></td><td>X</td><td></td><td>X</td><td></td></tr>
</table>

Age		Defense structures		Monitoring and alert systems		Intervention priority		
Old	New	Yes	No	Yes	No	Low	Medium	High
X		X		X			X	

Short description

IMPACT ASSESSMENT (future scenario)

Type of movement			Type of material		
			Bedrock	Engineering soils	
				Predominantly fine	Predominantly coarse
Falls			Rockfall	Earth fall	Debris fall
Topples			Rock topple	Earth topple	Debris topple
Slides	Rotational		Rock slump	Earth slump	Debris slump
	translational	Few units	Rock block slide	Earth block slide	Debris block slide
		Many units	Rock slide	Earth slide X	Debris slide
Lateral spreads			Rock spread	Earth spread	Debris spread
Flows			Rock flow	Earth flow	Debris flow
			Rock avalanche		Debris avalanche
			(Deep creep)	(Soil creep)	
Complex and compound			Combination in time and/or space of two or more principal types of movement		

Velocity		Landslide position			Depth		Impact on watercourse	
Slow	Rapid	Single	Internal	Extended	Superficial	Deep	Yes	No
X			X		X		X	
Age		Defense works		Monitoring and alert systems		Intervention priority		

Old	New	Yes	No	Yes	No	Low	Medium	High
X		X		X				
Short description								

ANNEXES	
X	Cartography (regional technical map, orthophoto, ...)
X	Photographic documentation
	Other ___________________
	Other ___________________
	Other ___________________

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POST EVENT MULTIHAZARD SURVEY SHEET – AVALANCHE

Form number:	1/2018

FIELD SURVEY DATA

Date	Province	Municipality	Location and coordinates
10.11.2018	Belluno	Canale d’Agordo	Pisoliva Lat. 46°21’56’’ – Long. 11°53’58’’

SURVEYORS	ANNOTATIONS
Matteo Cesca – Arpa Veneto Roberta Dainese – Arpa Veneto Fabrizio Tagliavini – Arpa Veneto	

EVENT DETECTION (now)

Site morphology	Open Slope	X	Channel		Mixed	
Forest species impacted	List					
Damaged forest	100%	X	> 50%		< 50%	
	Few trees on the ground		Few standing trees			
Mean slope	30%					
Range of altitude	1000 – 1250 m a.s.l.					
Aspect	N					
Damaged infrastructures in the site	None		Inhabited centers	X	Few houses	
	Touristic buildings		Communication routes		Other services	
Existing defense structures / management plan	Active structures	X	Passive structures	X	Management plan	
	None		Other			

Short description

IMPACT ASSESSMENT (future scenario)						
Potential forest species impacted by the potential avalanche	List					
Potential damaged infrastructures by the avalanche (downstream the site)	None		Inhabited centers	X	Few houses	
	Touristic buildings		Communication routes		Other services	
New defense structures / management plan	Active structures	X	Passive structures	X	Management plan	
	None		Other			

Short description

ANNEXES	
X	Cartography (regional technical map, orthophoto, ...)
X	Photographic documentation
	Other ___________________
	Other ___________________
	Other ___________________

TRANS-ALP Project		
Funded by European Union	**TRANS-ALP Project** ***Transboundary Storm Risk and Impact Assessment in Alpine Regions***	arpav Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto

POST EVENT MULTIHAZARD SURVEY SHEET – WINDTHROW FOREST

Form number:	1/2018		
FIELD SURVEY DATA			
Date	Province	Municipality	Location and coordinates
10.11.2018	Belluno	Canale d'Agordo	Pisoliva Lat. 46°21'56'' – Long. 11°53'58''

SURVEYORS	ANNOTATIONS
Matteo Cesca – Arpa Veneto Roberta Dainese – Arpa Veneto Fabrizio Tagliavini – Arpa Veneto	

EVENT DETECTION (now)						
Forest management	Coppice	X	High forest			
Within Natural Park area	YES	X	NO			
Forest management plan	YES	X	NO			
Assessed volume of blowdown timber	10.000 m^3					
Assessed area	1000 m^2					
Mean slope	30%					
Range of altitude	1000 – 1250 m a.s.l.					
Aspect	N					
Type of soil	short description					
Impacted forest species	short description					
Blowdown severity	100%	X	> 50%		< 50%	
	Few trees on the ground		Few standing trees			
Silvicultural interventions	short description					

Priority	Low – Medium – High
OTHER ANNOTATIONS	
Short description	
IMPACT ASSESSMENT (future scenario)	
Future silvicultural interventions	short description
Unstable trees management	short description
OTHER ANNOTATIONS	
Short description	

ANNEXES	
X	Cartography (regional technical map, orthophoto, ...)
X	Photographic documentation
	Other ___________________
	Other ___________________
	Other ___________________

TRANS-ALP Project		
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POST EVENT MULTIHAZARD SURVEY SHEET – INSECT OUTBREAK

Form number:	1/2018

FIELD SURVEY DATA

Date	Province	Municipality	Location and coordinates
10.11.2018	Belluno	Canale d'Agordo	Pisoliva Lat. 46°21'56'' – Long. 11°53'58''

SURVEYORS	ANNOTATIONS
Matteo Cesca – Arpa Veneto Roberta Dainese – Arpa Veneto Fabrizio Tagliavini – Arpa Veneto	

EVENT DETECTION (now)

Forest management	Coppice	X	High forest	
In Natural Park area	YES	X	NO	
Ownership	Public	X	Private	
Forest management plan	YES	X	NO	
Assessed volume of forest affected	10.000 m^3			
Assessed area	1000 m^2			
Mean slope	30%			
Range of altitude	1000 – 1250 m a.s.l.			
Aspect	N			
Type of soil	short description			
Impacted forest species	short description			
Type of damage	short description			
Silvicultural interventions	short description			

Priority	Low – Medium – High
OTHER ANNOTATIONS	
Short description	
IMPACT ASSESSMENT (future scenario)	
Assessed timber volume to be impacted	10.000 m^3
Assessed area to be impacted	1000 m^2
Need for monitoring	short description
Forest species exposed to insect attack	short description
Silvicultural intervention in the damaged area	short description
Silvicultural intervention close to damaged area	short description

OTHER ANNOTATIONS	
Short description	

ANNEXES	
X	Cartography (regional technical map, orthophoto, ...)
X	Photographic documentation
	Other ___________________
	Other ___________________
	Other ___________________