Chapter

Val Ferret Pilot Action Region: Grandes Jorasses Glaciers - An Open-Air Laboratory for the Development of Close-Range Remote Sensing Monitoring Systems

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Abstract

The Val Ferret valley (Courmayeur, Aosta Valley, Italy) was included as a Pilot Action Region (PAR) of the GreenRisk4Alps project since it is both a famous tourist location and a high-risk area for all types of mass movement processes. Typical natural hazards that endanger this PAR are debris flows and avalanches, sometimes connected to ice collapses from the glaciers of the Mont Blanc massif. Thanks to the steep sides of the valley and widespread alluvial channels, these events can reach the valley floor, where public roads, villages and touristic attractions are located. This article presents the main challenges of natural hazard management in the Val Ferret PAR, as well as the role of forestry and protective forests in the Aosta Valley Autonomous Region. As an example of good practice, the monitoring systems of the Planpincieux and Grandes Jorasses glaciers are presented. Recently, these glaciers have become an open-air laboratory for glacial monitoring techniques. Many close-range surveys have been conducted here, and a permanent network of monitoring systems that measure the surface deformation of the glaciers is currently active.

Keywords: Val Ferret, protective forest, Mont Blanc, Aosta Valley, monitoring, glacial hazards, remote sensing

1. Introduction

Courmayeur (1,224 m asl) is a small mountain town located in the Aosta Valley Autonomous Region, in northwestern Italy. It is a famous tourist destination whose fame and history are largely related to the presence of the Mont Blanc massif, which is one of the most renowned attractions in the Alps. Two glacial valleys, the Val Veny to the west and the Val Ferret to the east, run parallel to the massif. Every year, these valleys become the holiday destination of thousands of tourists (more than 350,000 in 2019), and amongst them are many climbers and hikers who are drawn to this

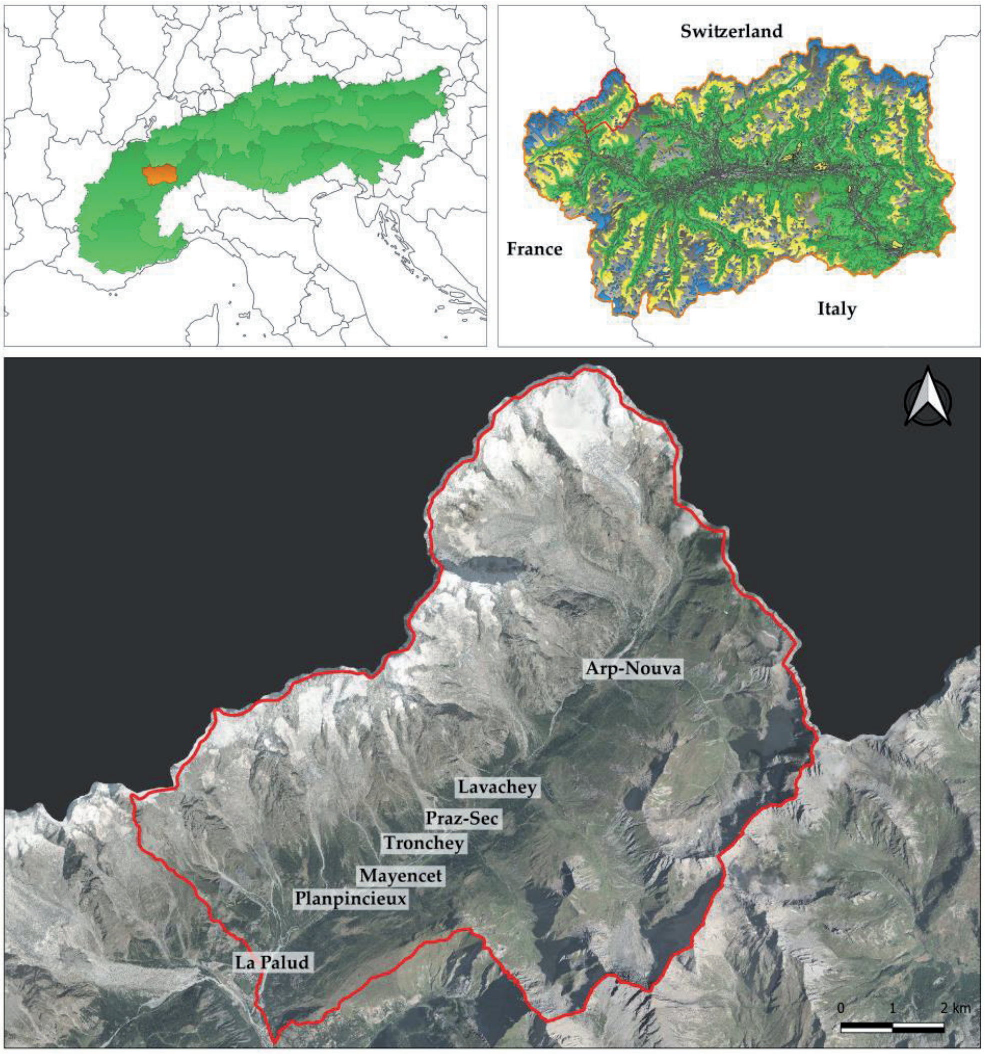

Figure 1.
The Aosta Valley Autonomous Region (northwestern Italy) and Val Ferret PAR in the municipality of Courmayeur.

area for its majestic landscapes. Courmayeur is a typical example of an Alpine location whose population can easily triple due to the presence of tourists. In addition, this area is home to the Mont Blanc Tunnel, which is part of a crucial roadway linking Italy and the rest of Europe, as well as to the new Skyway Monte Bianco cable car, which crosses the Mont Blanc massif and connects Courmayeur to Chamonix.

Over the last two decades, in many alpine areas, the effects of global warming have increased the frequency of numerous types of gravitational slope instabilities (i.e. rockfalls, ice avalanches and debris flows), especially at high elevations, mainly due to glacial and permafrost degradation or extreme rainfall events. The Val Ferret PAR (**Figure 1**) has been affected by all these hazards.

2. PAR description

2.1 General data

The Aosta Valley Autonomous Region is a wide mountain basin consisting of a long main valley (100 km), corresponding to the Dora Baltea hydrographic basin and thirty major tributary valleys.

This area has a temperate oceanic climate, which is transitional to hemi-continental and lacks a dry season. The mean annual temperature varies greatly in the different areas of the valley, mostly because of the considerable altitude differences. For example, the annual average temperature ranges between +10 and +12°C at 500 m, but it is around −7.5°C at 1,200 m [1].

The region has an alpine pluviometric regime, with two rainfall maxima in the middle seasons and two minima during summer and winter. In the central sector of the region, the maximum rainfall occurs in autumn, while the minimum rainfall occurs in summer. The central area of the Aosta Valley is one of the driest sites in the Alps (550 mm/y). The mean annual precipitation is about 950 mm and increases with altitude and towards the watersheds, with the highest contribution on the Great St Bernard Pass (2,476 m) on the northern watershed, which averages 2,000 mm/y (data set since 1817) [1].

The topographic elevation ranges from 400 m, where the valley mouth merges into the Po Plain, to the 4,810 m summit of Mont Blanc, the highest peak in the European Alps. From a geological point of view, the Aosta Valley region belongs to the axial zone of the Western Alps, an imbricated stack of continental and oceanic metamorphic complexes [2].

A very high regional mean altitude of around 2,100 m guarantees the presence of numerous glaciers (precisely, 175), which, according to the Aosta Valley Glacier Inventory (updated in 2019), have an overall extent of approximately 120 km^2, or 3.6% of the basin [3]. Amongst the morphodynamic agents in mountain environments, glaciers play the most important role, by modeling both erosional and depositional landforms as well as indirectly influencing slope dynamics.

Watercourses represent another crucial geomorphic agent, largely affecting the Aosta Valley's landscape through the progressive erosional deepening of valleys. Evident signs of the constant shaping and reshaping of this territory are the widespread alluvial and mixed fans, mainly created by debris-flow phenomena. Finally, yet importantly, gravitational phenomena also contribute to the evolution of the Aosta Valley's geomorphology.

2.2 Val Ferret

Located at the foot of the Mont Blanc massif, the longitudinal profile of the Val Ferret valley progresses in a succession of steps, a distinctive trait of a glacial valley (**Figure 2**), from the village of La Palud to the Col Ferret. Small settlements populate the valley floor, and even if they are not permanently inhabited, they are renowned summer and winter holiday destinations where tourists come to engage in cross-country and backcountry skiing during the winter season and alpinism, mountain biking and trekking in summer. Thus, many economic activities, such as hotels, restaurants and campsites, flourish in this valley.

From a naturalistic point of view, Val Ferret is a Special Protection Area (SPA) [4] that is home to numerous species of nesting birds. Along with Mont Blanc's glacial environments, the Talweg of the Val Ferret valley, an important reservoir for the conservation of hygrophilous plants, is also listed as a Site of Community Importance (SCI) [5].

Larch and pine forests cover both sides of Val Ferret up to an altitude of 1,750 m (on average). The right bank has steep rocky sides that descend from the peaks of the Mont Blanc range to the valley floor at 1,400 m. This incredible drop of approximately 2,600 m is the perfect terrain for avalanches and debris flows. In fact, these natural hazards usually originate well above the timberline and are often associated with rockfalls and extreme precipitation events or, sometimes, to the partial collapses of glacier fronts (i.e. Grandes Jorasses and Planpincieux glaciers). These events flow over existing stream incisions, and their frequency effectively precludes the presence of forests in these areas. The left bank, facing northwest, has more continuous forest cover, up to 2,000 m. On this side of the valley, the forest provides

Figure 2.
Mont Blanc, with Val Veny on the left and Val Ferret on the right (photo: FMS).

better protection from natural hazards, but despite the milder slopes, avalanche phenomena can still occur.

2.3 The main problems relating to natural hazards in the Val Ferret PAR

2.3.1 Winter management

During the winter season, the Val Ferret road is open up to the village of Planpincieux, which is located at the entrance of the valley. From this little town, cross-country ski trails extend to the village of Lavachey, halfway up the valley. The end of Val Ferret is accessible only with ski mountaineering equipment. During the cold season, the valley is a famous tourist destination, even though the high frequency of snow avalanches make access to the valley quite difficult (**Figure 3**).

In mountain areas, local avalanche risk management has always been of crucial importance. In addition to being a complicated task, it requires excellent knowledge of the terrain and avalanche sites, as well as a deep understanding of the seasonal snow cover and the alpine micro-meteorology. For these reasons, the Aosta Valley Autonomous Region has officially established the Local Avalanche Commission (CLV – Commissione Locale Valanghe) [6].

Born to support the decision-making process of avalanche risk management in municipal areas, CLVs have the task of carrying out forecasting activities and assessing the snow and the meteorological conditions and the stability state of the snow masses in the designated areas. It also acts as a body of vigilance, alert and intervention in situations of risk and emergency management, in order to ensure, at the local level, the control of dangerous situations in its area of competence. CLVs also provide a civil protection technical consultative opinion to the mayor.

Regarding the Val Ferret PAR, in the event of avalanche danger, the mayor issues an order for the permanent closure of the municipal road of the Val Ferret valley and, if there is high risk to inhabited areas, the mayor can order the evacuation of the whole valley. The closure is generally preceded by a controlled evacuation plan, according to an intervention regulation as part of the Municipal Civil Protection Plan.

Figure 3.
Aerial view of avalanches between Tête de Bernarde and Mont de La Saxe with the hamlet of Mayencet in the center (photo: FMS).

Avalanche sites	**80**
Total avalanche events	767
Avalanche events causing damage to forest cover	66
Avalanche events involving people	17
Avalanche events involving civil buildings	45
Avalanche events affecting the municipal road system	60
Avalanche events affecting the state road system	17

Table 1.
Avalanche sites and avalanche events in Val Ferret (data: 2020 update) [7].

Snow avalanche data for the Val Ferret PAR are obtained from the Snow Avalanche Inventory of the Aosta Valley Autonomous Region [7]. This database has been updated every winter since the early 1970s and since 2005, it has been fully available online. **Table 1** summarizes some data regarding Val Ferret.

2.3.2 Summer management

In summer Val Ferret is entirely accessible. The municipal road is open up to the hamlet of Arp-Nouva, and side paths are available for mountain bikers and trekkers. On the valley floor there are numerous tourist facilities, such as hotels, restaurants, campsites and a golf course. The valley is crossed by numerous hiking paths, the most famous of which is the Tour du Mont Blanc, a 170 km hiking trail that surrounds the Mont Blanc massif and passes through parts of Italy (Aosta Valley), France (Haute-Savoie and Savoie) and Switzerland (Valais). Every year, this trail becomes the stage of the Ultra-Trail du Mont Blanc, a world-renowned trail running race with up to 10,000 participants.

Given the large number of visitors throughout the whole summer season, risk management is more complex compared to the winter period. Regarding hydrogeological instability, the natural hazards that endanger the valley during summer are more rare and harder to forecast (i.e. debris flows) in comparison to the snow avalanches of the winter season. Alerting abilities are thus less developed, especially because the event precursors are not as evident as those in winter hazards. The Functional Center of the Aosta Valley Autonomous Region manages the meteorological alert system. In Italy, functional centers have been established in compliance with a decree of the President of the Council of Ministers [8] in 1999, following a tragic event in the year before, in an effort to better the civil protection system linked to weather-related hazards.

This legislative act established, for the first time in Italy, an integrated monitoring network, enabling the diffusion of hydro-pluviometric data throughout the whole country, while integrating them in a civil protection system designed to rapidly alert the population in case of a weather-related hazard.

In this context, the different functional centers create a tight net of forecasting, monitoring and surveillance bodies and provide technical support to the competent agencies dealing with risk management and civil protection.

The principal tool used by the functional centers to alert the different agencies and the municipalities is the Bulletin of Critical Issues. This concise report describes, with a progressive color scale, the increasing danger and the expected scenarios according to the forecasted weather and hydrological conditions.

In the Aosta Valley's Bulletin of Critical Issues, the regional territory is subdivided into four areas, for which a risk forecast is presented, in order to activate only the municipalities, authorities and emergency management bodies actually involved in the forecasted event. The municipalities included in the alert areas are required to activate the operational phases defined within the Municipal Civil Protection Plan. The data acquired regarding landslides, rockfalls, floods and debris flows affecting the regional territory are reported in a specific inventory called the "Catasto Dissesti" [9].

During the summer season, the most influential gravitational processes in the Val Ferret PAR are linked to water-related hazards, more precisely to floods and debris flows. These phenomena occasionally reach the valley floor, endangering crowded areas, such as houses, hiking trails and the main road (**Figure 4**).

Streams and river basins that can potentially be affected by these phenomena are very numerous; there are hundreds in the entire regional territory and at least twenty in Val Ferret alone.

In addition, glacier-related hazards have to be considered as well in the risk assessment analysis of the Val Ferret PAR. In fact, the current risk management plan already considers ice avalanches originating from the Mont Blanc massif as a potential threat to the valley floor.

Figure 4.
Debris flow deposit in Val Ferret and clearing operations of timber and debris from the stream bed (photo: FMS).

This subject is addressed in depth in Chapter 3, which is dedicated to the best practices carried out in Val Ferret, such as the open-air laboratory of the Grandes Jorasses glaciers.

2.4 Forest and forestry

2.4.1 Forest management in the Aosta Valley Autonomous Region

About 30% of the total area of the Aosta Valley Autonomous Region is wooded, amounting to approximately 97,970 hectares [10], of which 38,207 hectares (39% of the total forest area) is public property and 59,763 hectares (61% of the total forest area) is private property.

The forestation index might seem low, especially when compared with the average of other Alpine regions. However, the surface morphology and characteristics of the Aosta Valley have to be taken into account. With an average altitude above 2,100 m, an entirely mountainous territory and the considerable presence of glacial and periglacial environments, the area available to forests is limited. In fact, excluding these barren areas would increase the potential surface area of forest to around 195,000 hectares, and would increase the forestation index from 30 to 45%. Therefore, the per capita area of forest in the Aosta Valley is 7,500 m^2, compared to the Italian average of 1,600 m^2. This clearly shows that the current wooded area is quantitatively a significant part of the regional territory. Potentially, this area can still see further expansion, however, and the forest has already regained areas where, in the last three decades, land-use has changed. The constant increase recorded for about a century (**Table 2**) is mainly the result of the decline of agriculture work in mountain areas, lower livestock pressure inside and on the edge of the forest, and reforestation carried out since the first post-war period.

Since the 1960s, the regional administration has implemented regional policies aimed at expanding knowledge about its forest heritage. An important planning instrument is the "Economic Plans of Forestry and Pastoral Assets", which provides a subdivision of property into separate economic classes. The different classes are based on the prevailing functions that wooded areas are required to satisfy: productive, protective, touristic-recreational, and naturalistic. The economic plans define a set of rules that establish the extent of the interventions needed for conservation purposes and the strengthening of the forest.

These regulatory plans for the region, municipalities and consortiums have been constantly updated for 50 years. However, in 2010, due to financial reasons, the review was temporarily interrupted. Today, opportunities to complete the economic plan review, as well as to develop the agricultural and forestry sectors, arise mainly through the EU Rural Development Plan. As a matter of fact, The

Year	Area (hectares)
1962	66,000
1974	75,000
1996	86,550
1999	89,539
2011	97,970

Table 2.
Variation in the forested areas of the Aosta Valley in the past years [11].

Rural Development Program 2014–2020 is currently operational in the Aosta Valley Autonomous Region, carrying out measures to guarantee forest conservation and to increase the potential of the forest-wood supply chain. The forestry plan for the Municipality of Courmayeur and the Val Ferret PAR is currently in place and valid until 2022.

The forest typology of the Aosta Valley Autonomous Region has been analyzed since 1998 in the context of various Interreg projects that have led to the creation of the publication "I tipi forestali della Valle d'Aosta" [12], which identifies 15 forest categories with 49 forest types. As part of the European Alcotra Renerfor Project, in 2011, a new forest map was created [10]. This inventory identified 21 forest categories (14 broad-leaved, 6 conifer and one mixed) and 95 forest types. High forests account for 68% of the wooded area as the prevailing silvicultural system, while coppices are limited to about 15% of the area. Conifers are certainly the most represented species, exceeding 90% in high forests. In particular, in order of occurrence, there are larch, spruce, Scots pine, stone pine and silver fir. Less common are broad-leaved trees, of which less than 10% are in high forest systems. The majority of broad-leaved trees are in coppice populations, generally old growth, and in spontaneous high forest successions. The most represented species are chestnut, downy oak, poplar, ash, cherry, rowan, sycamore maple and beech.

In regard to the Val Ferret PAR, **Table 3** shows the forest types according to the technical report of European Environmental Agency No 9/2006 "European forest types – Categories and types for sustainable forest management reporting and policy" [13].

The subdivision into prevalent functional destinations, with the exclusion of unmanaged forests, is linked to the different conditions of fertility, location and accessibility of each specific forested area. In the Aosta Valley, the main role of forests is protection from natural hazards, even if partially combined with timber production. In fact, it appears that about 80% of the forests of the Aosta Valley perform an irreplaceable protective function against rockfalls, avalanches, debris flows, floods and soil erosion.

2.4.2 Protective forests in the Aosta Valley Autonomous Region

With regard to forests protecting against natural hazards, a recent Italian legislative decree [14] defines "forest of direct protection" as wooded area that, thanks to its peculiar position, performs the function of the direct protection

CODE	Forest type	%
3.1	Subalpine larch-arolla pine and dwarf pine forest	71
3.2	Subalpine and montane spruce and montane mixed spruce-silver fir forest	10
8.4	Portuguese oak and Mirbeck's oak Iberian forest	3
11.2	Alder swamp forest	13
12.1	Riparian forest	< 1
12.2	Fluvial forest	1
13.4	Southern boreal birch forest	2

Table 3.
Val Ferret forest types according to European environmental agency No 9/2006 "European forest types – Categories and types for sustainable forest management reporting and policy" [13].

of people, goods and infrastructure from natural hazards such as avalanches, rockfall, landslides and debris flows, preventing the occurrence of such events or mitigating their effect.

In 2006, a publication containing guidelines for the management of protective forests [11] was published by the Aosta Valley Autonomous Region together with the Piedmont Region. This study, starting from the exchange of experiences between foresters in the Western Alps, provides the necessary silvicultural path needed to enable a specific forest to perform its protective role in a lasting and effective manner. These suggestions were defined considering the main natural hazards characterizing the area. However, the frequency and intensity of natural hazards seem to change, particularly under the effect of climate change. In fact, in response to shifts in temperature and precipitation, many climate models predict an increase in the frequency of extreme weather events (i.e. storms and fires), an impact on the population dynamics of insects, an alteration of ecological niches (species replacement), and an increase in sensitivity to pathogens.

The collaboration between the forest departments of the Piedmont and Aosta Valley regions, has been extended thanks to the Alcotra 2007–2013 Project [15]. This cross-border project between Italy (Aosta Valley and Piedmont regions) and Switzerland (Canton du Valais) resulted in, amongst other things, the publication of cognitive complements on the management of protective forests. The research and experience gained in these five years have been summarized in two publications [16, 17], which expand on the first one [11] through the deepening of the interactions between natural hazards and the stability of protective forest.

In the Aosta Valley, approximately 44,000 hectares of forest plays a "direct object protection" role, equivalent to 45% of the total forest coverage (**Figure 5**). This ratio is even greater in the Val Ferret PAR, despite only 10% of its territory being covered by forests.

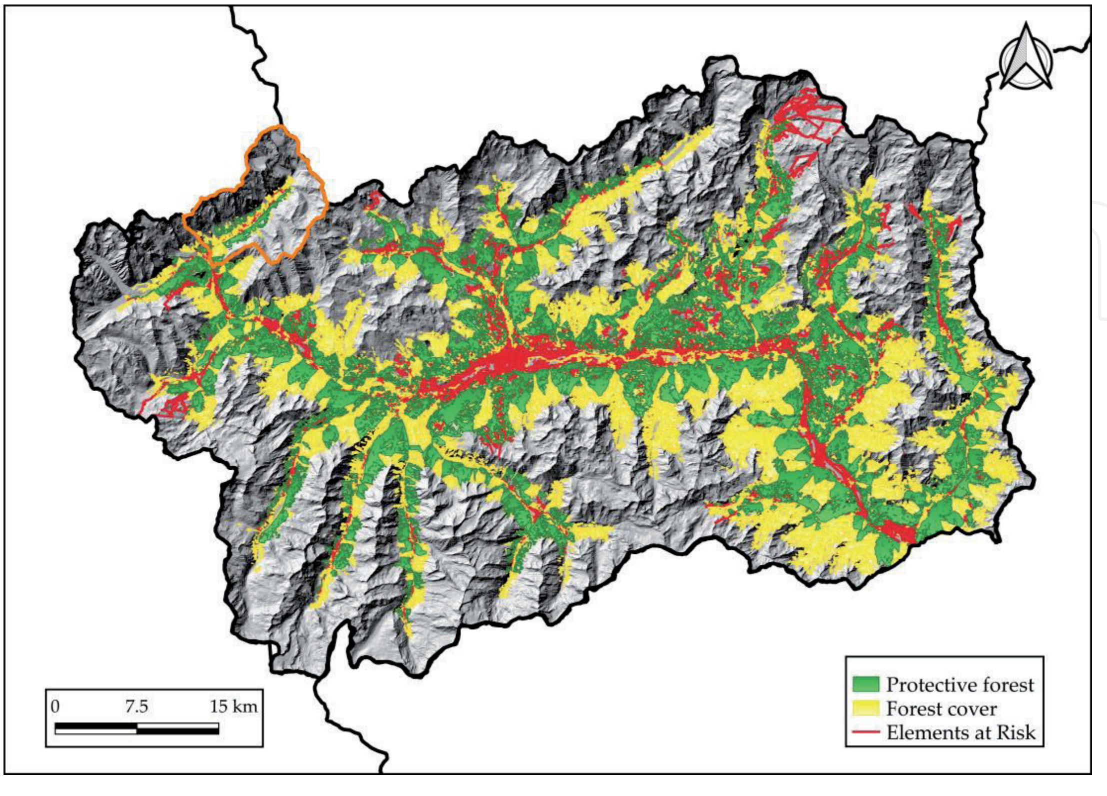

Figure 5.
Map of protective forests in the Aosta Valley Autonomous Region (data from [15]).

3. Grandes Jorasses Glaciers Open-Air Laboratory for the Development of Close-Range Remote Sensing Monitoring Systems: an example of good practice in the Val Ferret PAR

Research on Mont Blanc has always been an interdisciplinary effort, with numerous national and international projects built upon high mountain observation, mass balance measurement and glacial and periglacial environment monitoring. It is of crucial importance to study glaciers and their evolution, especially during this period of rapid change in which global warming is expected to drastically reduce glaciated areas and increase their instability. Moreover, in most mountainous regions of the world and especially in densely populated areas such as the European Alps, glacier-related hazards are a threat to lives and sustainable development. A thorough understanding of glacier dynamics is essential for glacier risk management, enabling the development of mitigation strategies against climate change cryosphere alteration. In order to attain this objective, scientific observation, data acquisition and analysis are fundamental, but the severe mountain environment where most glaciers are located, makes the survey activities very complex. Accessing these impervious areas implies high economic costs as well as potential risks for technicians and scientists. However, the recent development of remote sensing systems allows investigations to be carried out with minimal risks, enabling the measurement of many parameters without even accessing the glaciers, thus representing in many cases the most suitable monitoring solution.

Spaceborne earth observation techniques enable, for example, the extraction of information such as glacier topography, albedo, equilibrium line, mass balance or flow velocity. However, the spatial and temporal resolution of satellite data is not yet effective enough to the measure fast processes (e.g. sub-daily movements - cm/day), and often close-range remote sensing is the best monitoring solution for glacier stability evaluation and risk assessment. The effectiveness of these techniques has been successfully tested and used for several years in the Val Ferret PAR for the polythermal glacial complex of the Grandes Jorasses and Planpincieux glaciers (**Figure 6**). These glaciers, located on the Italian side of the Grandes Jorasses peak, have a southeastern orientation, and their elevation ranges from 2,600 m to 4,200 m. The research and survey activities that have been conducted here since 2009 are arguably amongst the most intensive in the European Alps. Today, this area is an open-air laboratory for close-range remote sensing monitoring systems focused on developing new monitoring solutions and advanced research activities.

3.1 Planpincieux Glacier

Several documented ice avalanches and glacial floods (1929, 1952, 1982, 2005, 2017), which, in some cases, have threatened the village of Planpincieux and damaged the municipal road, have been linked to the Planpincieux Glacier (**Figure 7**) [18].

The Planpincieux Glacier's accumulation area consists of two separate glacial cirques, the largest of which is located at the base of the Grandes Jorasses peak.

The two cirques converge into a singular basin area that feeds the two lower lobes, whose fronts are located at an altitude of about 2,600 m. The ice flow is channeled mainly into the right lobe, which, dynamically, is a very active area, with an average slope of 32° and has a strongly crevassed morphology.

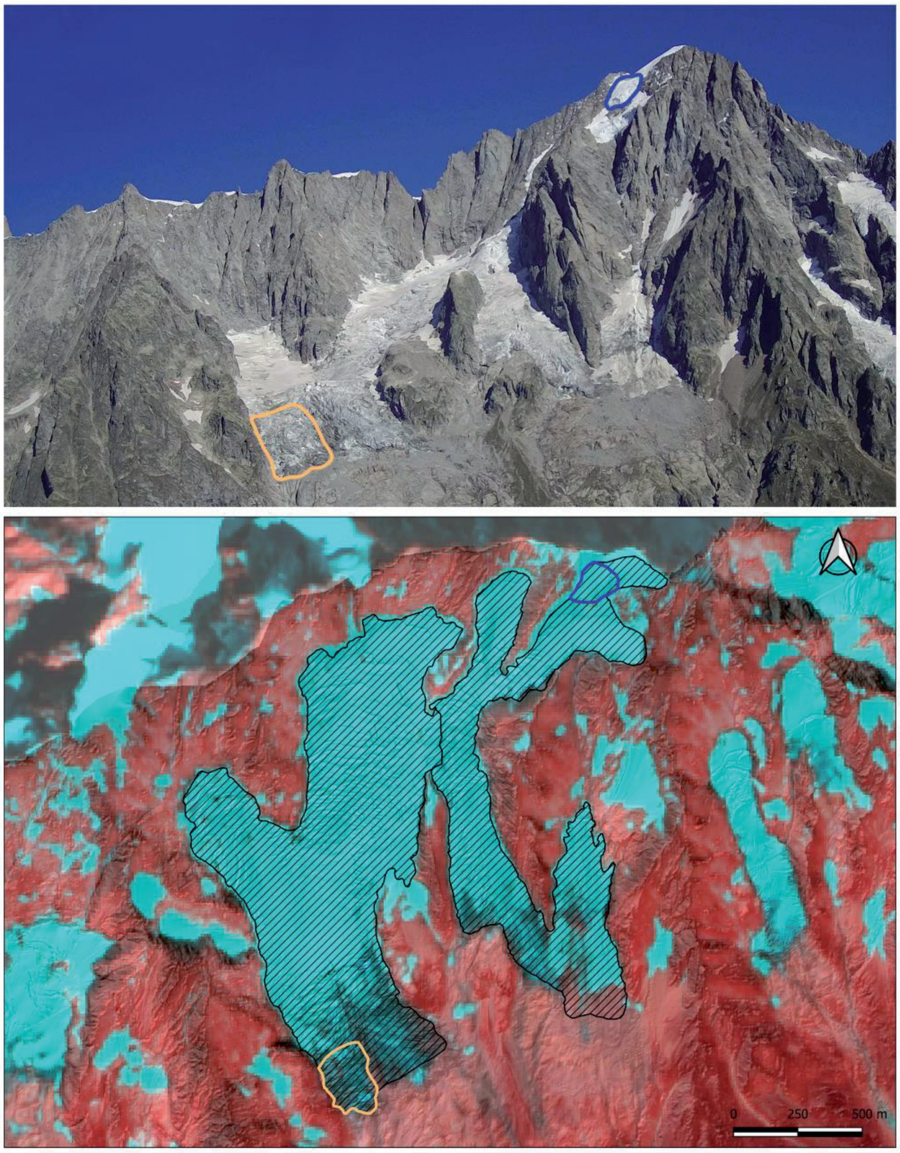

Figure 6.
Overview of the Planpincieux and Grandes Jorasses glaciers. Orange and blue areas indicate the Montitaz lobe and the Whymper Serac, respectively.

Figure 7.
Aerial view of the Planpincieux Glacier and Montitaz stream (photo: FMS).

The right lobe, characterized by a vertical front wall that reaches heights of up to 30 meters, leads into the steep Montitaz stream (**Figure 7**), where numerous ice collapses occur, mainly during the summer season.

Since 2011, when a large crevasse opened in the lower part of the right lobe, the glacier has been closely monitored using different technologies and methodologies. During this 10-year study period, speed increases of the entire right side of the glacier tongue have been recorded (up to 2 m/day at the glacier front), especially during the summer seasons. This fast-flowing motion is mainly induced by the flow of water present between the bedrock and the ice.

In the summer of 2019, a volume of about 300,000 m^3 showed multiple signs of possible collapse. Phases of marked accelerations and decelerations of the ice flow, a subglacial drainage network distributed under most of the tongue, and a state of pervasive fracturation of the ice were all conditions that were present at the Planpincieux front. These unstable conditions could lead to the sudden detachment of the entire portion of the glacier, which, because it is hanging over a steep slope, could generate a large ice avalanche that could potentially reach the valley floor. These same conditions have been recorded in all known cases of temperate glaciers destabilizations: Le Tour – 1949 [19], Allalin – 1965, Fee Glacier – 2009, and Allalin – 2000 [20].

3.1.1 Time-lapse camera applications

The Planpincieux Glacier is monitored by two time-lapse cameras with different focal lengths placed on the opposite side of the Val Ferret valley, 3,800 m from the glacier [21]. The monitoring station is equipped with two solar panels, and an electric cell for power supply and is remotely controlled by a single-board computer connected to a server. A robotic webcam was installed in 2018 to survey the functionality of the station. This monitoring system has been active since 2013 and acquires images at hourly frequency, enabling the accurate identification of the different phenomena affecting the glacier over time. Between 2013 and 2020, this camera system collected more than 40,000 images, contributing to one of the longest continuous series of hourly images in the European Alps.

The surface kinematics of the right lobe of the Planpincieux Glacier has been deeply investigated with image analysis of eight years of time-lapse monitoring [18 21]. The images are processed with a digital image correlation technique to estimate surface ice flow velocities (**Figure 8**).

The ice flow pattern is often composed of distinct kinematic domains, especially during summer. Observation of this phenomenon may indicate the action of high strain rates localized in areas where large crevasses appear.

The behavior of the glacier snout is noteworthy because it reveals the occurrence of a few speed-up periods per year, which can end in significant ice collapses.

3.1.2 Terrestrial radar interferometry applications

The Planpincieux Glacier is likely one of the few glaciers for which terrestrial radar interferometry investigations have been carried out using four different radar models [18], namely: GPRI™ (Gamma Remote Sensing), IBIS-L™ (IDS GeoRadar), FastGBSAR-S™ (MetaSensing) and LiSALab™ GbInSAR (Ellegi).

The surface kinematics of the glaciers was surveyed in five campaigns, in 2013, 2014, 2015, 2016 and 2019. The first two campaigns were conducted using the GPRI™ real-aperture radar (RAR), which surveyed the glacier from both the valley floor and the valley ridge opposite to the glacier. Both campaigns lasted for two days and were able to detect the surface displacement of the glacier tongue. For the following surveys, synthetic aperture radars (GB-SAR) were used.

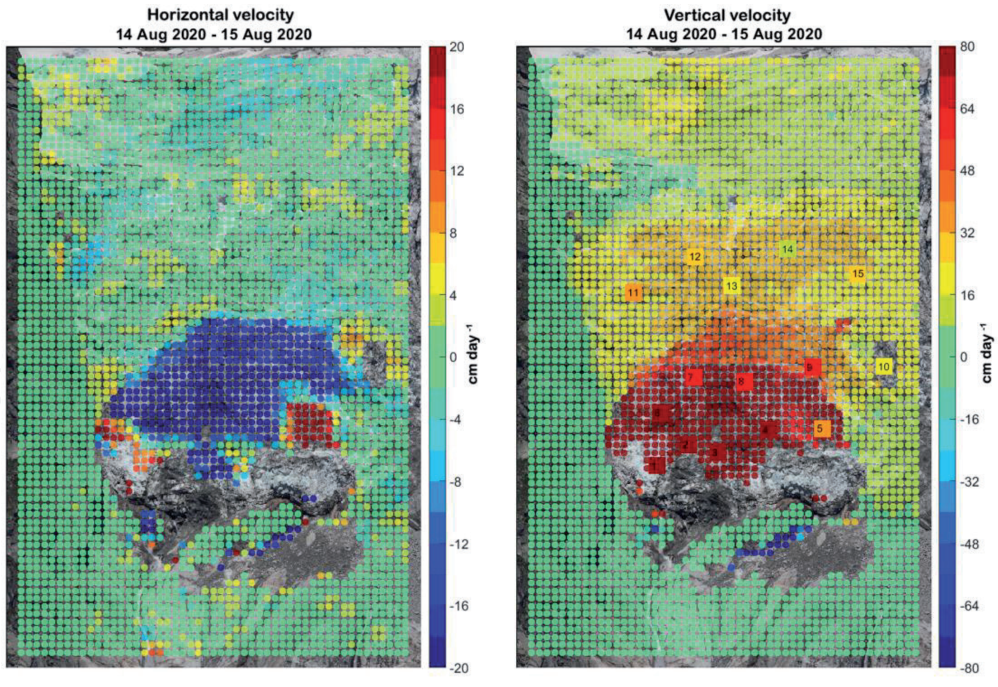

Figure 8.
Digital image correlation of the right anterior lobe of the Planpincieux Glacier. The displacement difference in the frontal area of the glacier, below the large crevasse, is clearly visible.

Thanks to the 2015 campaign, which lasted for a longer period compared to the previous ones, it was possible to distinguish the different kinematic domains of the Montitaz Lobe, although the meteorological conditions were severe, and the radar acquisitions were affected by a strong atmospheric phase screen.

In order to minimize the atmospheric disturbance, FastGBSAR-S™ measurements with an acquisition frequency of 10 seconds, were carried out in 2016. The last

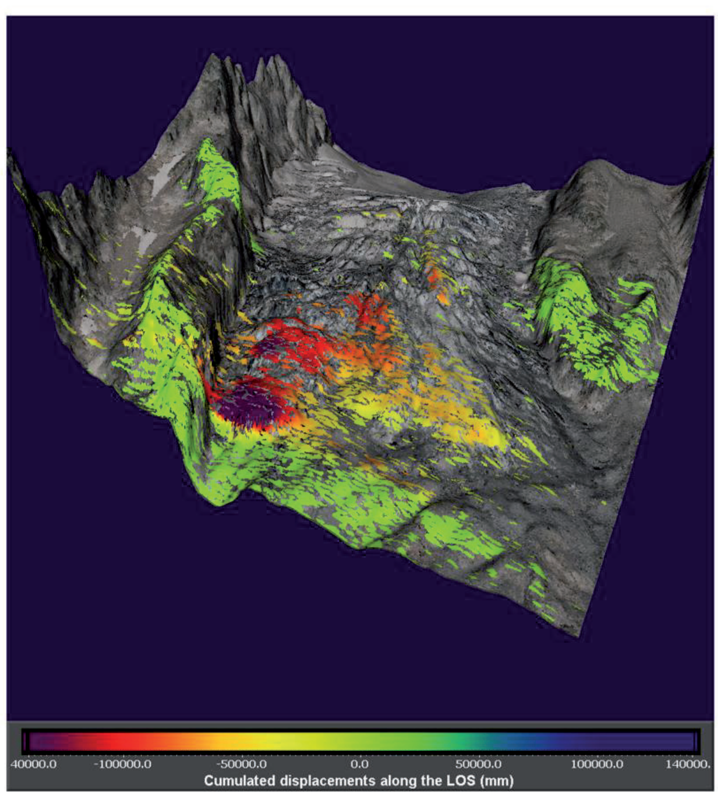

Figure 9.
Cumulated displacement measured by the LiSALab™ GBInSAR from December 2019 to march 2021.

investigation (LiSALab™ GBInSAR) began at the end of September 2019 for civil protection purposes (**Figure 9**). This campaign, which was still active during the writing of this article, is by far the longest, allowing for a dataset of almost two years.

During the Planpincieux Glacier 's most active phases, velocity displacements up to 200 cm/day were recorded on the right lobe, while movements on the left lobe never exceeded 20 cm per day. This separation and difference in surface velocities occurs during the summer season in particular.

3.1.3 Doppler radar applications

In 2020, an AVYX™ Doppler radar (Geopraevent) was installed for real-time detection of ice avalanches from the Planpincieux Glacier (**Figure 10**). After the calibration phase and numerous simulations, the alert system went into operation at the beginning of July 2020. This system includes automatic road closures upon avalanche detection in the defined "closure zone". The road is automatically re-opened if the avalanche does not reach the "danger zone", which is a specific area at the bottom of the slope visible from the radar location.

The avalanche radar system placed in Planpincieux detected 103 avalanche events between July and December 2020. Of these, 75 were detected within, or at the border of, the closure zone, which led to the closure of the road. The radar further detected 28 events outside the closure zone which did not lead to a road closure.

3.1.4 Hydrometer applications

In the summer of 2020, a water measurement system was installed in the Montitaz stream, at the end of the right lobe of the Planpincieux Glacier. This data could be useful for eventually identifying water pockets retained by the glacial body.

This system has been tested throughout the whole summer season but snow and ice deposition into the Montitaz channel, from glacier ice collapses, have made these data somewhat unreliable.

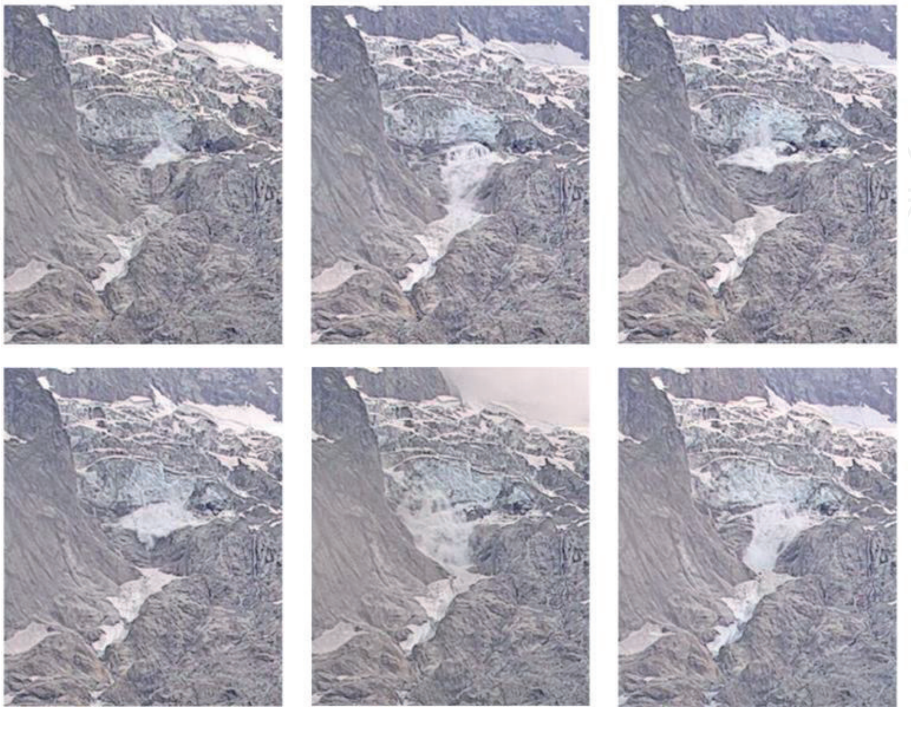

Figure 10.
Consecutive Doppler radar ice collapse detections from the Planpincieux Glacier (photo: Geopraevent AG).

3.2 Whymper Serac of the Grandes Jorasses Glacier

The south face of the Grandes Jorasses peak contains two steep glacial cirques, which form the accumulation zone of the Grandes Jorasses Glacier. The Whymper Serac, whose front is located at 3,800 m, forms the left cirque (**Figure 11**) and is defined as an unbalanced cold hanging glacier.

When hanging glaciers are entirely located above equilibrium-line altitude, ice avalanching becomes the dominant form of glacial ablation. Morphological evidence and historical data indicate, in fact, that the Whymper Serac is progressively increasing in volume, reaching unstable geometries that are subject to recurrent breakoffs. The time between these collapse events ranges from a few years to more than a decade.

Therefore, a collapse can also occur during the cold season, when it might easily trigger a large snow avalanche that could seriously threaten the buildings and the road located on the valley floor. Four collapse events have been well documented so far: August 1993, June 1998 [22] (**Figure 12**), September 2014 [23] and November 2020.

Despite the absence of fresh snow and the limited dimension of the avalanche triggered by the 1993 event, eight mountaineers that were climbing in the area lost their lives.

3.2.1 Time-lapse camera applications

Since 2010, the Whymper Serac has been continuously monitored by a time-lapse camera placed on the Skyway Monte Bianco cable car station platform at Pointe Helbronner. Since 2019, digital image correlation has been applied to the images of the Whymper Serac in order to measure the surface displacement. However, due to the high brightness, low color contrast and smooth texture of the scene, measuring the ice flow is more difficult than for the Planpincieux Glacier. This requires a robust outlier correction method to remove the artifacts present in the displacement maps.

Figure 11.
Aerial view of the Whymper Serac of the Grandes Jorasses Glacier (photo: FMS).

Figure 12.
Aerial view of the deposit of the 1998 collapse. The ice and snow mass stopped a few hundred meters from the municipal road and houses of Val Ferret (photo: Lorenzo Cosson).

3.2.2 Robotic total station applications

Surface velocity measurements of the Whymper Serac from a robotic total station installed in front of the village of Planpincieux 4,800 m from the glacier have been continuously taken since 2010 [22, 23]. The survey is conducted with a Leica TM30 that operates automatically on target recognition mode. The reflector network is composed of several prisms installed on poles inserted into the serac's unstable portions (**Figure 13**), while a few prisms placed in the surrounding bedrock serve as reference points. A complete acquisition of the entire network is conducted every two hours, tracing the position of the prisms and enabling the analysis of surface displacements.

Figure 13.
One of the prisms positioned on the Whymper Serac, pointing towards the robotic total station located in the hamlet of Planpincieux (photo: FMS).

Even if the sensor-to-target distance is beyond the operating limits declared by the producer, the instrument works correctly. However, extreme atmospheric conditions due to the high-mountain elevation, such as heavy snowfall and strong wind, occur frequently, causing the loss of some reflectors, which must be replaced with the help of mountain guides. It is thus clear that measuring the surface velocity of the Whymper Serac with a robotic total station is a difficult task, and a robust data processing method has been developed especially for it. Nonetheless, this data allowed the break-off of the serac in October 2014 to be forecasted ten days in advance [23].

3.2.3 Terrestrial radar interferometry applications

In 2020, an IBIS-FM™ GbInSAR (IDS GeoRadar) was installed to test the capability of radar to monitor the Whymper Serac displacements beyond the instrument's operating limits (approximately 5 km) and in unfavorable environmental conditions. In addition to the correlation between radar data and the existing monitoring system, this new tool was of fundamental importance in identifying the kinematic domains that underwent a progressive acceleration before the ice collapses of 18 October and 11 November 2020.

Starting from the end of October 2020 and during the month of November, a further test was carried out with a LiSALab™ GbInSAR (Ellegi) under the same conditions. This experimentation allowed the acquisition of important data allowing the comparison between the two radar systems, especially regarding the sensitivity to the glacial velocity increase before the collapse of the 11 November 2020 (**Figure 14**).

3.2.4 Other studies: thermal regime investigations

Due to climate change, the high altitude glaciers in the Mont Blanc massif are known to be warming. If the base of these glaciers nears the melting point, they could slide on their beds and become unstable, causing massive ice avalanches.

Observations of internal temperatures of the Whymper Serac were made for the first time in 1997, with thermistors installed in boreholes (**Figure 15**). At that time, the recorded ice temperatures where all below 0°C. These measurements were repeated in October 2020 (**Figure 16**).

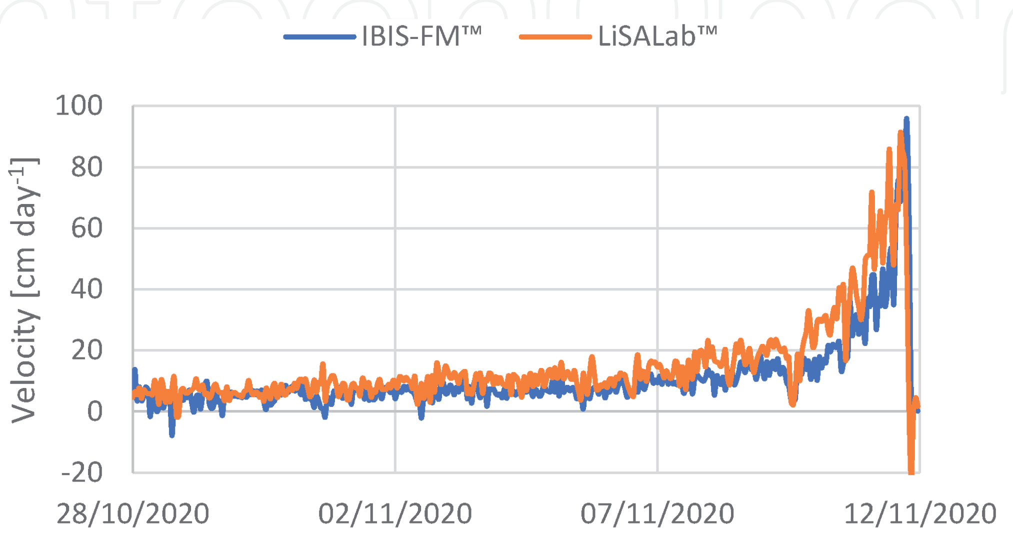

Figure 14.
Comparison of the measurements (surface velocity) made by two different GbInSAR before the failure of 11 November 2020.

Figure 15.
Preparation of boreholes on the Whymper Serac in 1997 (photo: FMS archive).

Figure 16.
Preparation of the working site in 2020 (photo: FMS).

According to the new observations, the upper part of the glacier, near the rimaye, seems temperate (0°C), while the downstream part, near the front, remains at a negative temperature.

In comparison with the observations of 1997, it seems that the ice has warmed significantly, but it has to be considered that the glacier does not have the same geometric configuration (especially after the substantial collapse of 1998) and that the topography of the current glacier is, undoubtedly, very different from that of 1997. It should also be noted that the glacier, which is located on a very steep slope, is strongly fractured and that some of the temperature profiles (in 1997 and in 2020) have been disturbed by the presence of crevasses. Nevertheless, the warming of this glacier ice over the past 23 years is clearly evident. In order to collect more data, a new measurement campaign has been planned for 2021.

3.3 Grandes Jorasses and Planpincieux glacial complex

3.3.1 Ground-penetrating radar applications

A helicopter-borne ground-penetrating radar (GPR) survey was conducted on the Planpincieux - Grandes Jorasses glacial complex in 2013, and 16 GPR traces homogeneously distributed on the glacial surface were acquired.

Due to the difficulties caused by the rough glacier surface and numerous crevasses, which often caused the scattering of electromagnetic waves and obscured the reflections, there was considerable noise in the radar data. However, in the areas of high-profile densities, it was possible to estimate the ice thickness quite reliably.

In the framework of the stability assessment of the lowest part of the Planpincieux Glacier, GPR measurements were repeated in 2020 with a novel dual polarization system. In total, 12 km of profile data were acquired. The data quality allowed the identification of the bedrock for 7 km of profile data. The ice thickness of the Planpincieux - Grandes Jorasses glacial complex ranges between 10 and 100 m, while in the unstable lower part of the Planpincieux Glacier, the thickness varies between 20 and 60 m. By comparing the two measurement campaigns (2013–2020), it can be stated that the two data sets do not provide any evidence of a significant change in the ice thickness during this period. In addition to the glacial thickness data, important information regarding altitude and rough morphology of the bedrock was obtained.

3.3.2 Digital elevation model analysis

Digital Elevation Models (DEMs) obtained during LiDAR and regional terrestrial laser scanning surveys and from specific photogrammetric surveys by drone and helicopter (**Figure 17**) enable the monitoring of the morphological evolution of the glacier surface. Furthermore, consecutive surveys can be analyzed through DEM of Difference (DoD) calculation, allowing the estimation of the surface elevation change between different periods. This can allow, for example, the measurement of the current instable ice volume or the ice mass lost or gained by the glacier.

Since 2019, numerous surveys of the topography have been carried out in order to identify and quantitatively determine the morphological changes of the two glaciers.

3.3.3 Other studies: numerical simulation of ice avalanches

In 2009, a numerical simulation of ice avalanches from the Whymper Serac was carried out using the RAMMS::Avalanche [24] and RAMMS::RKE Rock-Ice models developed by the Institute for Snow and Avalanche Research (SLF).

In 2012 and 2020, these activities were repeated for the Planpincieux Glacier, using new software versions and updated terrain models.

In parallel, Fondazione Montagna sicura, in collaboration with the University of Vienna and University of Graz, carried out the same simulations using the r.randomwalk [25] and r.avaflow [26] models.

The results obtained from the two different methodologies are comparable and confirm the robustness of the analyses (**Figure 18**), which, for the calibration of the parameters, were based on the back calculation of ice avalanches from the Planpincieux Glacier that were mapped between 2017 and 2020.

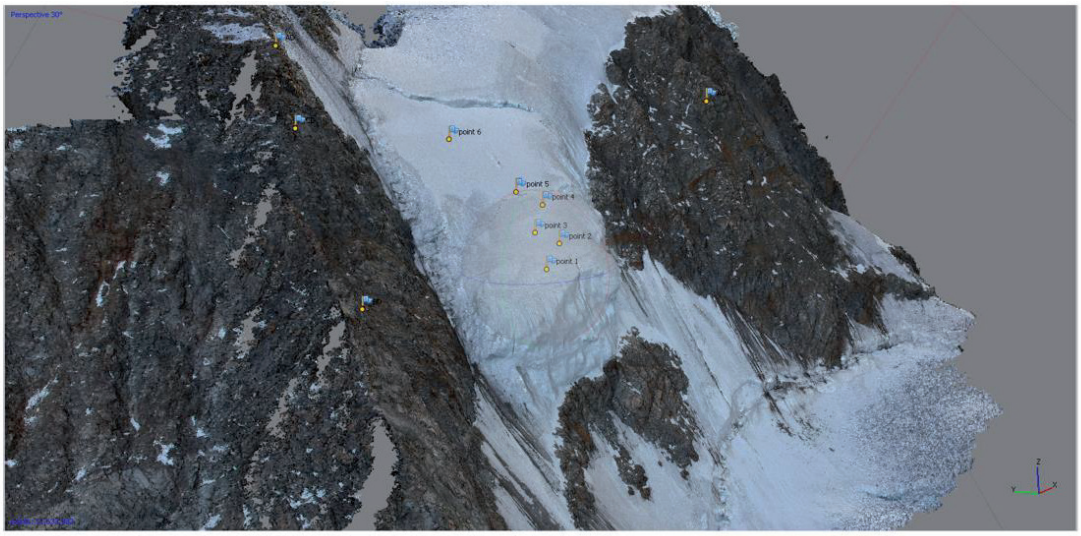

Figure 17.
Point cloud rendering of the Whymper Serac obtained from a drone survey.

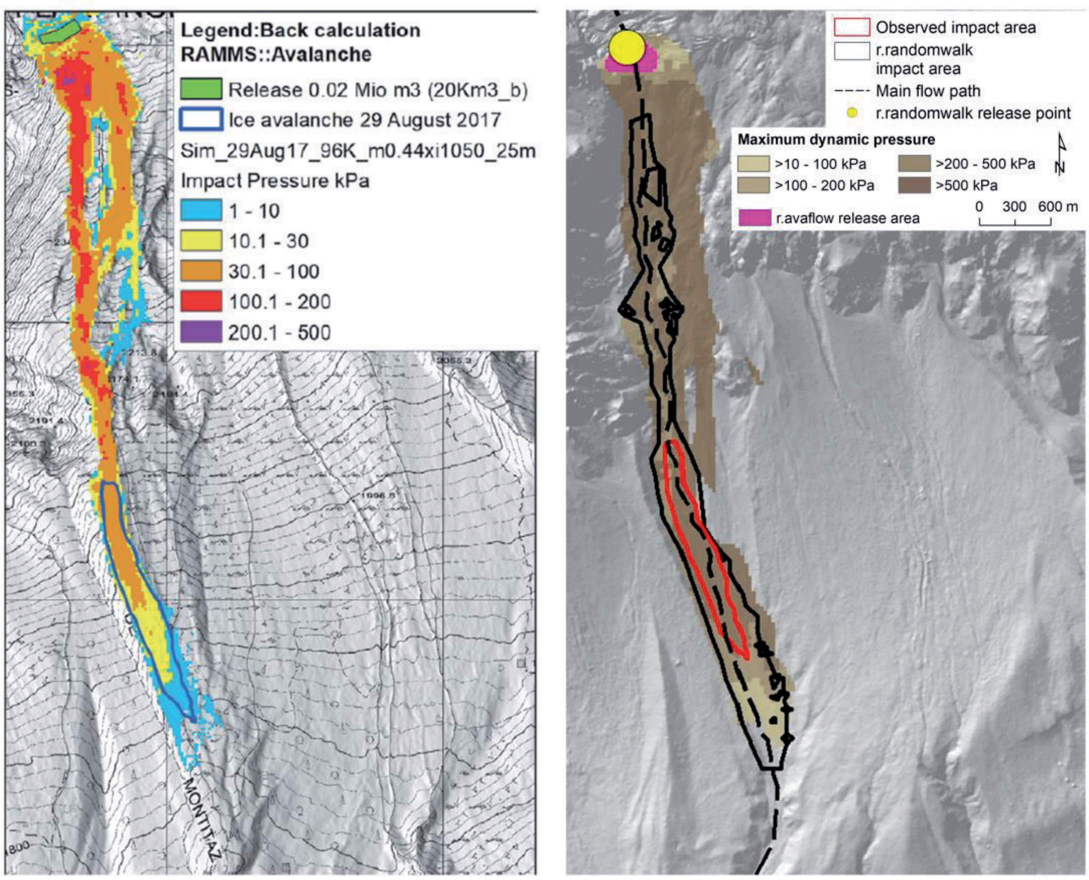

Figure 18.
Back calculation from the RAMMS model (left) and r.avaflow model (right) of an ice collapse mapped in 2017.

The results of the simulations were then translated into risk scenarios and safety concepts based on the unstable volumes of the glacier.

4. Conclusion

The Val Ferret valley was included as a PAR of the GreenRisk4Alps project since it is both a famous tourist location at the foot of Mont Blanc and a high-risk area for all types of mass movement processes. Risk management in this area includes, in addition to the construction of structural measures, both site-specific knowledge and forecasting capabilities of the Aosta Valley's CLVs and Functional Center. More than 45% of the PAR's total wood coverage plays a "direct object protection" role, proving to be effective not only in reducing soil erosion but also in preventing avalanche release and mitigating rockfall impact in runout zones. Nonetheless, glacier-related hazards develop well above timberline in high mountain environments and in areas that are difficult to access, making both technical and ecosystem-based measures partially or completely ineffective. Monitoring and early warning systems are therefore essential, and remote sensing methods that are able to measure many parameters without accessing the glaciers often represent the most suitable solution. For these reasons, the Grandes Jorasses and Planpincieux glacial complex is a reference area for natural risk assessment and management, where different close-range remote sensing techniques can be used and tested in an open-air laboratory that improves our knowledge of new technologies while increasing our understanding of the recent evolution of alpine glacial environments.

Acknowledgements

A special thanks to everyone who contributed to the production of the materials used for the drafting of this text.

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