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A Multi-Criteria GIS-Based Approach for Risk Assessment of Slope Instability Driven by Glacier Melting in the Alpine Area

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Abstract: Climate change is resulting in significant transformations in mountain areas all over the world, causing the melting of glacier ice, reduction in snow accumulation, and permafrost loss. Changes in the mountain cryosphere are not only modifying flora and fauna distributions but also affecting the stability of slopes in those regions. For all these reasons, and because of the risks these phenomena pose to the population, the dentification of dangerous areas is a crucial step in the development of risk reduction strategies. While several methods and examples exist that cover the assessment and computation of single sub-components, there is still a lack of application of risk assessment due to glacier melting over large areas in which the final result can be directly employed in the design of risk mitigation policies at regional and municipal levels. This research is focused on landslides and gravitational movements on slopes resulting from rapid glacier melting phenomena in the Valle d'Aosta region in Italy, with the aim of providing a tool that can support spatial planning in response to climate change in Alpine environments. Through the conceptualization and development of a GIS-based and multi-criteria approach, risk is then estimated by defining hazard indices that consider different aspects, combining the experience acquired from studies carried out in various disciplinary fields, to obtain a framework at the regional level. This first assessment is then deepened for the Lys River Valley, where the mapping of hazardous areas was implemented, obtaining a classification of buildings according to their hazard score to estimate the potential damage and total risk relating to possible slope instability events due to ice melt at the local scale.

Keywords: Alpine landscape; slope instability; glacier melting; risk assessment; GIS methodology; disaster risk management; urban planning

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1. Introduction

At present, a general agreement exists in the scientific community on the conclusions drawn by the Intergovernmental Panel on Climate Changes: Earth is undergoing significant and rapid warming, and this trend will continue throughout this century [1]. Even if climate change is well documented in a wide set of works at the global scale [2–4], its study at the regional and local scale is not yet systematic [5,6]. However, considering the current literature, it seems reasonable to conclude that climate change is not homogenously distributed, and specific areas seem to be affected more severely than others [7,8]. In addition, the effects of climate change on the environment do not seem to be linear, causing sudden changes in specific areas [9]. Among others, mountain environments seem to be one of the more fragile environments and the one in which climate change effects are more evident [10]. Indeed, mountains have been acknowledged by the ESA Climate Office as "sentinels of environmental change" because they have physical dynamics that are readily identifiable and respond more rapidly than other geographical entities to environmental modifications [11]. In fact, in mountain areas, a key element is represented by the cryosphere, which acts as a direct intermediary between the climate and the natural environment. The cryosphere is rapidly responding to climate warming through the melting of glacier ice, reduction in snow accumulation, and permafrost loss [12,13]. Changes in the mountain cryosphere are modifying not only flora and fauna distributions [14,15] but also the physical processes occurring in mountain regions. Indeed, permafrost and ice cover are currently acting as stabilizers for many mountain slopes. Their reduction will result in a significant change in the area, altering the forces acting on many slopes, causing their destabilization, increasing sediment transport into streams, and changing the entire ecosystem [16]. Processes such as landslides, debris flows, ice avalanches, glacier surges, the sudden formation and drainage of lakes induced by glacier melting, and large sediment transport into rivers due to deglacierization are expected to increase in the near future. Mountain areas are not only characterized by natural aspects: large cities, villages, and small settlements are present in mountain areas all over the world. Due to their reduced accessibility in the past, mountain valleys have been areas in which local communities have developed specific traditions that still exist, representing important tangible and intangible cultural values that need to be safeguarded [17,18]. In addition, activities associated with pasture, the production of food, and recreational activities like skiing and hiking represent important economic assets to be considered and secured, as well as having cultural value [19,20]. However, climate change in the mountain cryosphere may result in the loss of delicate ecosystems, the migration of plant and animal species to increasingly higher altitudes, and the decline of tourist attractions that sustain the small towns scattered throughout the valleys, causing, eventually, the depopulation of areas that are now too dangerous (or have too few resources) to be inhabited [14].

Few works in the literature have systematically analyzed the risk induced by cryosphere changes in the mountains [21–23], and even fewer public authorities are considering this in risk analysis and urban planning. However, the availability of a dedicated risk analysis would be useful for several specific purposes like urban planning [24], the definition of preventive actions to reduce the effects of dangerous events, catastrophe management [25], and first aid and rescue action organization [26], among others. This research fits into this framework, providing a multi-criteria methodology for the risk assessment of slope instability driven by glacier melting in the Alpine area. The geological–hydraulic risk, and, more precisely, the risk of landslides and slope instability, will therefore be covered here using a GIS-based approach. The presented approach was tested in the Valle d'Aosta region of the Italian Alps.

The Alps are a complex of mountain ranges that form an arc across western Europe between the latitudes of 44° N and 48° N. This mountainous region is about 1200 km long, up to 200 km wide, and has an area of 200,000 km^2. The Alps are the highest and most extensive mountain range system that lies entirely in Europe. Currently, more than 2000 km^2 (1%) of the Alps is covered by glaciers, although this glacierized area is rapidly decreasing. Most of the glaciers are located in Switzerland (35%), followed by Italy (27%), France (20%), and Austria (18%). Regarding the total glacier area, the majority of European ice is located in Switzerland (46%) and Italy (21%). About 50% of the glacier cover in the Alps has been lost in the past 150 years, and many glaciers at lower latitudes and elevations have disappeared. Valle d'Aosta, chosen as the case study for this work, is one of the main Alpine valley systems in the Po Valle with a surface area of 3262 km^2. It hosts the highest mountains in the Alps (more than 20 peaks over 4000 m), and only 20% of its surface area is below 1500 m; 59% of the territory lies between 1500 and 2700 m, while 21% is above this altitude. Today, more than 200 glaciers in Valle d'Aosta cover a total area of about 120 km^2, representing approximately 6% of the total area covered by glaciers in the Alps, while the surface of the valley represents only 1.6% of the Alpine area. In addition, the area is characterized by significant touristic attractions as well as small villages and medium-sized cities. For these reasons, it was considered a suitable area for testing the presented methodology.

More specifically, a two-stage analysis was carried out: the first one covering the entire Valle d'Aosta region and the second one focusing on a side valley (Lys Valley) with a more detailed evaluation of the risks. The first analysis was conducted over the entire region, and it was based on the combination of a slope stability hazard index (i.e., glacier-melting-induced landslide susceptibility map) with exposed values divided into social, physical, environmental, and economic aspects. As previously mentioned, the glacier-melting-induced landslide susceptibility map considers nine indicators divided into environmental conditions (slope inclination, slope aspect, paraglacial areas, glacial geomorphological features, vegetation and protection forests, existing lithology and geological setting) and triggering factors (permafrost degradation, gravitational processes, and distribution of precipitation). The result is a landslide risk map for the Valle d'Aosta region that identifies the most dangerous areas where action should be taken to protect the population living there. Finally, risk information at the level of municipalities and landscape types involved is also given. The developed methodology was then applied to the Lys River valley, a very high-risk area at the foot of the Monte Rosa Mountain range. The methodology applied at the regional scale was then further refined with vulnerability assessment and other considerations at the local scale due to the unique landscape of the place and its rich cultural heritage inherited from Walser culture [27]. In conclusion, what is proposed is a working method that aims to evaluate the landslide risk induced by glacier melting at a regional scale, moving in a different direction from some existing studies based on the point-specific analysis of single glaciers or landslides and/or a more sectorial perspective [28,29]. It is more related to the development of a methodology for predicting landslide hazards at a regional scale [30,31].

The effective prediction of landslide hazards at a regional scale requires methodologies that integrate various data sources and analytical techniques. Several approaches have been developed to assess and predict landslide susceptibility, hazard, and risk. Statistical and heuristic models rely on historical landslide data and empirical relationships between landslide occurrences and contributing factors. Methods such as weights-of-evidence modeling and logistic regression have been widely used. Guzzetti et al. (2005) demonstrated the application of statistical models in mapping landslide susceptibility, highlighting the importance of comprehensive past landslide databases [32]. Deterministic models are based on the physical principles governing slope stability and often require detailed geotechnical and hydrological data. Examples include the infinite slope model and the limit equilibrium method. Montgomery and Dietrich (1994) developed a physically based model to predict shallow landsliding by integrating topographic, soil, and hydrological data [33]. GIS is a powerful tool for landslide hazard assessment, allowing the integration and analysis of spatial data. Van Westen et al. (2008) discussed the use of GIS for landslide susceptibility mapping, emphasizing its capability to handle large datasets and perform spatial analysis [34]. Remote sensing technologies, such as satellite imagery and LiDAR, provide valuable data for landslide detection and monitoring. The integration of remote sensing data with GIS has improved the accuracy of landslide hazard maps. Mondini et al. (2011) reviewed the application of remote sensing in landslide hazard assessment, noting its effectiveness in detecting terrain changes over time [35]. Recent advancements in machine learning have opened new possibilities for landslide hazard prediction. Algorithms such as random forests, support vector machines, and neural networks can analyze complex datasets to identify patterns and predict landslide occurrences. Reichenbach et al. (2018) demonstrated the application of machine learning techniques in regional landslide susceptibility mapping, showing improved prediction accuracy compared to traditional methods [36]. Probabilistic models assess landslide hazards by estimating the likelihood of occurrences based on statistical analyses of historical data and contributing factors. These models often incorporate uncertainty and variability in their input parameters. Gorum et al. (2014) discussed the utility of probabilistic models for landslide hazard assessment, emphasizing their ability to provide robust risk evaluation [37]. In this work, we are presenting a deterministic model based on a GIS approach with the following goals:

- Assess the impacts of climate change on mountain areas, particularly due to glacier melting, reduced snow accumulation, and permafrost loss;
- Investigate the effects of cryosphere changes on slope stability and risks associated with flora, fauna, and local populations;
- Develop a GIS-based, multi-criteria approach for assessing landslide and slope stability risks related to rapid glacier melting, specifically in the Valle d'Aosta region in Italy;
- Identify hazardous areas impacted by glacier melting as a foundation for developing effective risk reduction strategies;
- Provide spatial planning tools to assist local authorities in adapting to climate change in Alpine environments.

The remainder of this paper is organized as follows: Section 2 reviews related works in evaluating instability risks of glacier areas with a specific focus on the morphological elements and the triggering factors inducing slope instability. An overview of the Valle d'Aosta case study and of the proposed methodology is presented in Section 3, while an in-depth analysis of the developed method at the regional scale is discussed in Section 4, and the application of the risk assessment method for the Lys Valley is discussed in Section 5. The final section suggests various insights and possible future developments for implementing the study of landslide risk in changing environments such as high mountain glaciers.

2. Related Works

The factors that encourage, influence, and determine the instability processes of mountain slopes can be distinguished into structural or predisposing factors, which mainly act in a constant way over time, and into determining or triggering factors, which produce an external impulse, even in a short time, causing the alteration of natural balances [32]. However, triggering factors are not always easy to detect. They are often phenomena that are difficult to predict, or at least impossible to predict in the long term. Landslides are often caused by a combination of triggering and predisposing factors, which interact in complex ways. For instance, a strong meteoric event may trigger a mudslide in areas with particularly clayey soil, while the same event might not result in instability on rocky walls. Similarly, a moderate-sized landslide may be halted by the presence of a forest, thus protecting a settlement just below. A debris flow event, on the other hand, might be attenuated by the morphology of the slope, perhaps encountering a concave area where material can accumulate. Since the determining or triggering factors are challenging to assess, it is essential to work on the structural or predisposing factors, which often remain unchanged over time or are easier to be assessed [38].

Numerous studies in the literature address landslide risk assessment, though not specifically focused on slope instability caused by glacier melting, using GIS-based methodologies [34,39–47]. These methods evaluate different factors influencing landslide triggering, including environmental conditions, geology and soils, geomorphology, land use, and anthropogenic elements. Through assessing and potentially weighting these factors, they are combined into a single landslide susceptibility indicator for mapping risk areas.

The remainder of this section delves into a short review of the various predisposing factors that contribute, influence, and determine the instability processes of mountain slopes, providing an analysis of geological, hydrological, climatic, vegetative, and anthropogenic influences with a specific focus on slope instability driven by glacier melting.

Slope plays a significant role in the formation of, development of, and susceptibility to landslides and is defined as an input parameter in susceptibility studies by many researchers, such as in [48] and [49], which review more than 1500 publications on the subject to assess the effect of the slope angle and its classification of landslide occurrence. Some researchers suggest that landslides typically occur within slope ranges of 30° to 40°, while others argue they occur at angles greater than 25°. As a result, it emerges that there are differing viewpoints between the relationship of slope and landslides among researchers, and this situation may be influenced by regional factors. Cellek [49] proposed a synthesis of the slope values generally preferred in the literature, and these were adopted as the basis for the slope classification employed in this study, as detailed in Section 4.

Along with the steepness, slope exposure also plays a key role when it comes to glacier-related hazards: Yordanov and Brovelli [49] presented a study on the orientation of slopes, which is related to various factors such as temperature, microclimate, humidity, soil moisture content, and vegetation density. For instance, north faces can host higher quantities of snow and water in the soil for longer periods. Geomorphic evidence for a paraglacial (debuttressing and stress release) origin of rock slope failure is indicated by spatial coincidence between the location of failures and areas where glacial debuttressing was at its maximum [45]. The main mechanisms involved in the destabilization of paraglacial slopes are glacial erosion and oversteepening [46], as well as glacial debuttressing and permafrost degradation [47]. As most of the world's high mountain regions have lost about 20–50% of their total ice volume since the late 19th century, paraglacial landslides are becoming increasingly frequent phenomena [21].

Geological characteristics are fundamental to the stability of mountain slopes. The type of rock and its structural properties can significantly influence how slopes behave under stress. In particular, the lithological composition of slopes is crucial in determining their stability. Certain rock types, such as shale, clay, and other sedimentary rocks, are particularly prone to weathering and weakening, making them more susceptible to landslides [50]. The presence of joints, fractures, and faults within these rocks facilitates water infiltration, which can weaken rock mass and decrease slope stability [51]. For example, studies by Zêzere et al. (2002) have shown that slopes underlain by weak lithologies are more likely to experience landslides, especially under conditions of increased moisture [52]. Soil properties, including texture, mineralogy, and cohesion, are significant determinants of slope stability. Soils with high clay content, for example, can swell when wet and shrink when dry, leading to changes in volume that destabilize slopes [53]. Additionally, loose, unconsolidated soils typically have low shear strength, making them more prone to failure under load or when saturated. The structural arrangement and layering of geological materials significantly impact slope stability. Slopes composed of weak layers sandwiched between stronger ones are particularly vulnerable. The orientation of these layers relative to the slope surface can also influence stability; layers dipping parallel to the slope are more likely to slide [54].

Hydrological conditions are among the most immediate and powerful predisposing factors affecting slope stability. Groundwater dynamics critically influence slope stability by affecting pore water pressure. Elevated pore water pressure reduces the effective stress within the soil, decreasing its shear strength and increasing the likelihood of slope failure [55]. Long-term changes in groundwater levels, such as those caused by seasonal variations or anthropogenic activities, can thus predispose slopes to instability [56]. Surface water, including rivers, streams, and runoff, contributes to slope erosion, which can undermine slope stability. Erosion at the base of slopes can remove supporting material, leading to oversteepening and increased instability [33]. Persistent erosion gradually weakens slope materials, making them more susceptible to failure. Studies by Vanacker et al. (2007) have demonstrated that regions with high rates of fluvial erosion are more prone to landslides, especially during periods of heavy rainfall [57].

Climatic conditions play a significant role in the predisposing factors of slope instability. Climate influences the frequency and intensity of rainfall, temperature fluctuations, and freeze–thaw cycles, all of which affect slope stability. Regions with heavy, consistent rainfall or significant seasonal changes are more prone to slope instability. Freeze–thaw cycles, in particular, cause the mechanical weathering of rocks and soils, contributing to slope weakening over time [58]. For example, research by Gruber and Haeberli (2007) has shown that Alpine regions with significant freeze–thaw activity are particularly susceptible to rockfalls and landslides. Long-term climatic trends, such as global warming, can also impact slope stability [59]. Rising temperatures can lead to the thawing of permafrost in Alpine regions, destabilizing slopes that were previously stable [60]. Additionally, changes in precipitation patterns due to climate change can alter groundwater levels and increase the frequency of intense rainfall events, further predisposing slopes to failure [61].

Vegetation plays a crucial role in maintaining slope stability through root reinforcement and water regulation. Vegetation stabilizes slopes by binding soil particles together through root systems, which increases soil cohesion and shear strength [62]. Vegetation also intercepts rainfall, reducing the amount of water that infiltrates the soil and thus lowering pore water pressure. Deforestation and land use changes that reduce vegetation cover can therefore predispose slopes to instability [63]. The type and density of vegetation are important factors in determining the extent of root reinforcement and water interception. Dense forests with deep-rooted trees provide greater stability compared to areas with sparse or shallow-rooted vegetation [64]. Changes in vegetation type, such as the replacement of forests with agricultural land, can significantly affect slope stability.

Human activities often exacerbate natural instability processes, making slopes more susceptible to failure. Human activities, such as deforestation, agriculture, and urbanization, alter natural landscapes and affect slope stability. The removal of vegetation for agriculture or construction reduces root reinforcement and increases surface runoff, leading to higher erosion rates and decreased slope stability [54]. In particular, deforestation and agricultural expansion significantly increase the risk of landslides in many regions. Construction activities, including road building, mining, and urban development, can significantly impact slope stability. Excavation and loading associated with these activities can alter the natural balance of slopes, leading to oversteepening or undercutting and increasing the risk of landslides. Poor drainage management associated with construction can also exacerbate instability by increasing water infiltration and pore pressure [65].

In areas affected by glacier melting, the retreat of glaciers exposes slopes to a range of geological processes that can influence their stability. Glacial retreat often leaves behind a variety of unconsolidated sediments such as till, moraines, and outwash deposits. These materials generally have low cohesion and high permeability, making them susceptible to slope failures. Post-glacial sediments can also exhibit varying degrees of compaction and stability, influencing their susceptibility to landslides [66,67]. Glacial processes, including freeze–thaw cycles, plucking, and abrasion, can weaken rock masses. The removal of glacial ice reduces confining pressure on slopes, potentially leading to stress release and subsequent rock falls and slides. This stress release can create new fractures or expand existing ones, further predisposing slopes to instability [68]. Glacial erosion often results in oversteepened valley walls and slopes. These steep slopes are inherently unstable once the supporting ice is removed. Oversteepened slopes are particularly vulnerable to rock avalanches and other forms of mass wasting [69]. The removal of the glacier ice can destabilize these slopes, leading to increased rockfall activity [70]. In addition, glacial melting significantly alters groundwater flow patterns, increasing infiltration and groundwater recharge. Elevated pore water pressure from increased groundwater can reduce the effective stress in soils and rock masses, making them more prone to failure. The studies by Holm et al. (2004) highlight the importance of groundwater flow in assessing slope stability in deglaciated areas [71]. The re-establishment of surface water drainage systems following glacial retreat can lead to increased erosion at the bases of slopes. Rivers and streams generated from glacial meltwater can erode supportive materials, leading to oversteepening and slope failures [72]. Glacial meltwater is particularly erosive, often carving out new channels and destabilizing slopes further [73]. More generally, the overall hydrological changes post deglaciation, including altered precipitation patterns and increased runoff, can exacerbate slope instability. Increased precipitation and snowmelt contribute to higher infiltration rates and fluctuating groundwater levels, which are critical factors in slope stability [74].

Concerning vulnerabilities, most of the assets affected by landslides are buildings and transportation networks, followed by agricultural lands, service infrastructures, and public services [75]. Damages to public and private buildings and to transportation network result in indirect damages to the population, in the form of temporary homelessness, permanent or temporary unavailability of agriculture and farming structures, disruption of services, longer travel times, and so on [76]. In addition, the obstruction of a communication route, especially in mountain areas, can cause delays and difficulties for rescuers in reaching urban centres or remote areas that can only be reached by a single road or path.

3. Materials and Methods

3.1. Valle d'Aosta Case Study

As previously mentioned, the area used as a case study to apply the developed methodology was the Valle d'Aosta region; it is located in the Italian Western Alps on the border with France and Switzerland and is undoubtedly an interesting testing ground for glacial risk research since it is home to the highest mountains in the Alps: more than 20 peaks over 4000 m, including Mont Blanc, Monte Rosa, Matterhorn, and Gran Paradiso (Figure 1). In addition, Valle d'Aosta is a particularly exposed territory due to its conformation, the richness of glaciers located on often very steep slopes, with inhabited valley floors relatively close to the glaciers. The territory presents historical and current cases of different types of glacial hazards, such as the collapse of seracs from cold hanging glaciers, collapse of parts of temperate glaciers, and flash releases of water from glacial lakes present on the surface or contained inside the glaciers (endoglacial lakes). These glacial phenomena indirectly influence the dynamics of the current slopes due to the postponed effect of the pressure release of the glacial masses following their retreat. In particular, the types of gravitational movements in the Valle d'Aosta sector are varied, as are the dimensions of these events. They range from single collapses that accumulate at the base of rock faces to imposing phenomena of deep gravitational deformation that affect entire slopes. Other frequent manifestations are those of gravitational sliding, both planar and rotational, while extremely important manifestations from the diffusion and frequency point of view are the fluidification processes at the expense of the surface layer.

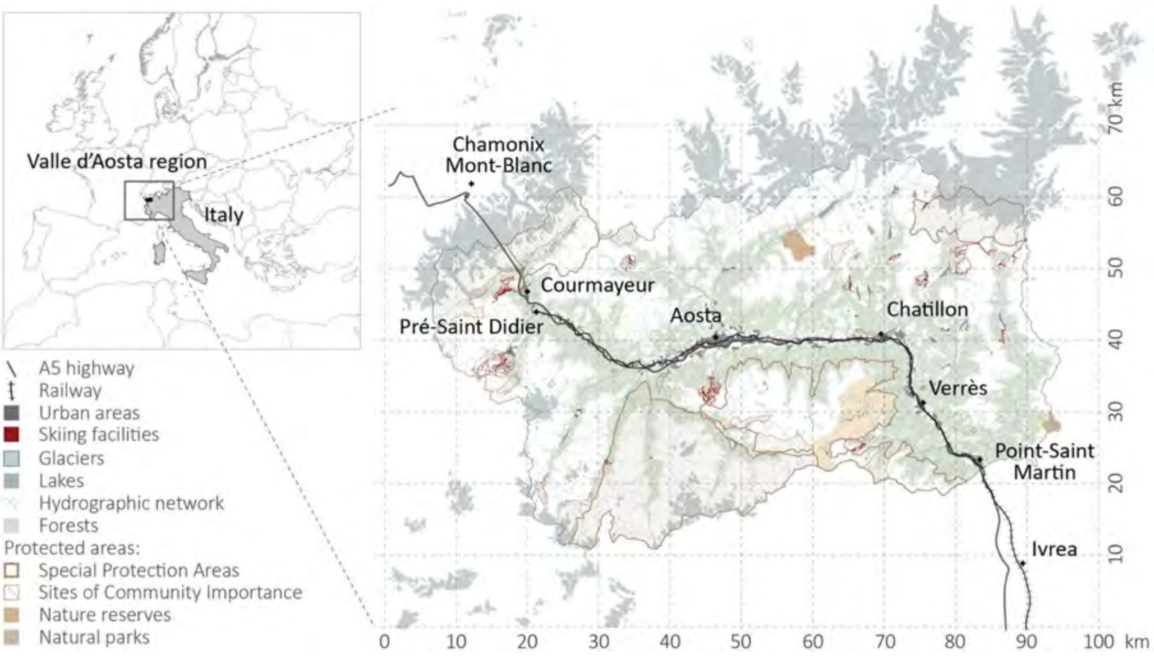

Figure 1. Map highlighting the location of the Valle d'Aosta region and its main characteristics: natural (glaciers, protected areas, and parks) and anthropic (roads, skiing facilities, and main cities). Data obtained from regional geoportals and databases of the Autonomous Region of Valle d'Aosta.

From the data analysis included in the "Inventario dei Fenomeni Franosi in Italia—IFFI" Project (Inventory of Landslide Events in Italy), carried out by ISPRA and autonomous provinces [77], it results that an area comprising 16% of the whole territory is covered by and/or involved landslides. This statistic is already quite high; however, the inventory maps landslides in two ways: some are mapped over areas (about 30%), while most are just point elements in the dataset. This means that the area affected by landslides that have occurred in the past in Valle d'Aosta (covering 16% of the regional territory) is underestimated because point data cannot be counted in this calculation.

In addition, significant tourist flows, both in winter and summer, characterize the region: in 2015, Valle d'Aosta hosted 3,238,559 people of whom 1,283,293 were foreigners. Tourist districts, with both summer and winter facilities (skiing structures, hiking trails, etc.), and residences represent an important economic value for the area that may be threatened by landslides. Furthermore, with 27 areas declared Sites of Community Interest (SCIs) and 5 Special Protection Areas (SPAs), Valle d'Aosta is the European region with the highest concentration of protected areas. Thirteen percent of its surface area is occupied by parks, nature reserves, and oases. The largest protected area is the Gran Paradiso National Park (about 710 km^2), followed by the Mont Avic Regional Park (about 57 km^2), while nature reserves account for a further 0.023%. More than a quarter of the region territory is also covered by Special Protection Areas for wild birds. For this complex connection among glacier areas, touristic attraction, natural values, and economic values, the Valle d'Aosta region was specifically considered a significant test area for the proposed methodology.

3.2. Overview of the Proposed Methodology

As previously discussed, the main aim of this work was to develop an approach for the risk assessment of slope instability driven by glacier melting. The best-known and most suitable definition of "risk" for Disaster Risk Management is the one adopted in 1972 by UNESCO in the "Convention Concerning the Protection of the World Cultural and Natural Heritage" [78], defining "risk" (R) as a combination of hazard (H), vulnerability (V), and worth exposed (W) using the following formula:

$$\mathrm{R\ (E, I) = H\ (I) \times V\ (I, E) \times W\ (E)}$$

where E represents the type of element at risk, and I represents the intensity of the event.

In this work, we are adopting the same definition, and we are presenting two different levels of analysis: the first one at the regional level and the second one at the local level (Lys Valley). For the regional analysis, the specification of the different elements in the risk definition is summarized in Figure 2. The first step in the generation of the landslide risk map was the selection of hazard indicators (H) and their representation to find indices that could summarize the main factors, as highlighted in the literature review (see Section 2), that are involved in the occurrence of a landslide due to ice melting. The hazard component, in fact, only represents landslide susceptibility, as it does not include the time factor required for estimating probability. In this study, the hazard map reported was obtained by combining two intermediate maps corresponding to two main groups of indicators: environmental conditions and triggering factors [79]. Environmental conditions take into account acclivity, slope aspect, paraglacial areas, glacial geomorphological features, vegetation and protection forests, and existing lithology and geological setting, while triggering factors are identified as permafrost degradation, gravitational processes, and the distribution of precipitation (more in Section 4.1). The second element used to determine the landslide risk is the worth exposed (W) element, which identifies the assets potentially affected by landslides, such as built-up areas and population (social assets); transportation networks (physical assets); tourism and services (economic assets); and sites of community importance, important bird areas, nature reserves, and land cover (environmental assets); more details are in Section 4.2. The third element involved in risk assessment is vulnerability (V). Vulnerability assessment involves, in many cases, the evaluation of several different parameters and factors such as the building materials and techniques, state of conservation, presence of protection structures, presence of warning systems, and so on [80,81]. For the lack of information on expected intensities of landslides, the lack of accurate information on the state of conservation of buildings and presence of protection structures at the regional scale, the maximum value (equal to 1) was considered in this study. The proposed approach is certainly a preliminary phase that requires in-depth analysis at the local scale, as presented for the Lys Valley, but can give a general view that also allows comparisons at the regional scale to identify planning priorities and determine future evolutionary scenarios of these environments.

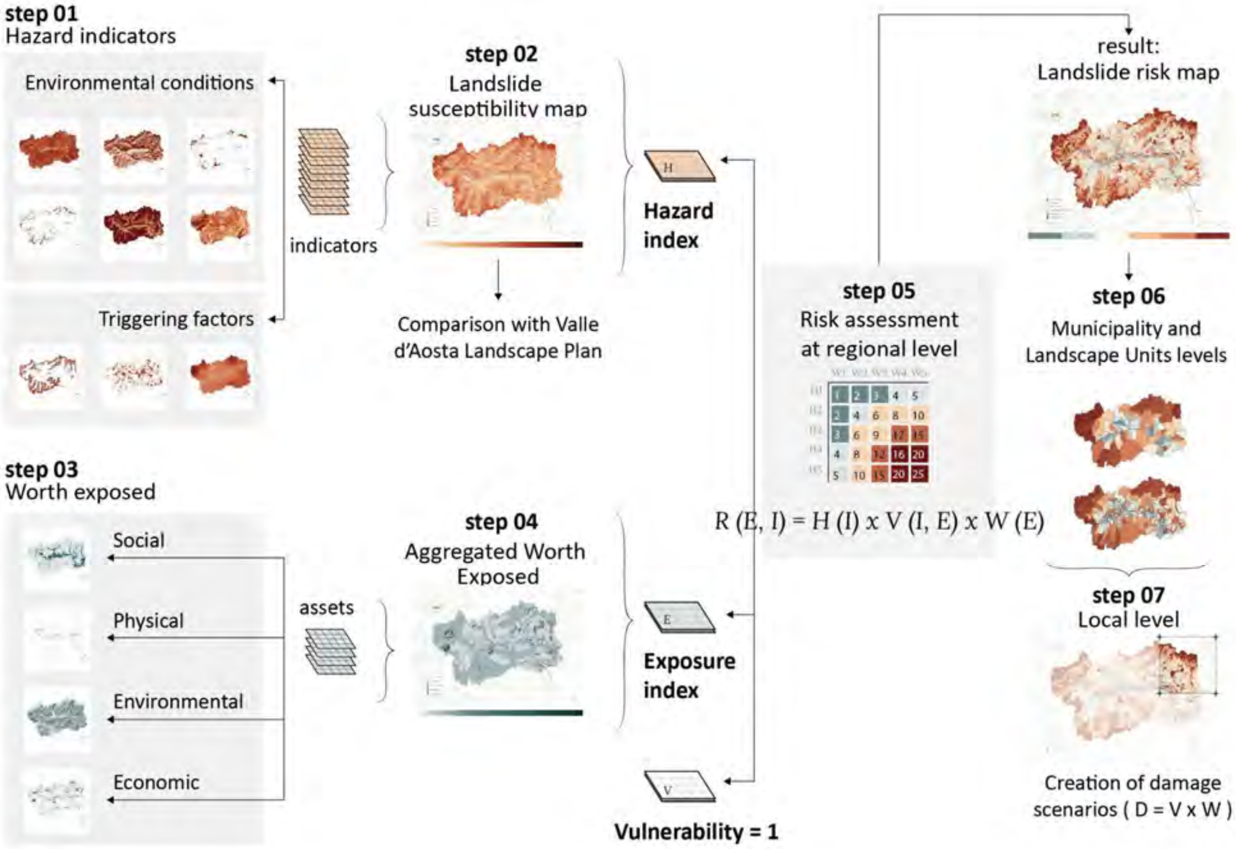

Figure 2. Methodology used for processing data to obtain the landslide risk map due to the ice melting of the Valle d'Aosta region.

In conclusion, the methodological steps, as illustrated in Figure 2, are as follows:

- Step 01. Development of hazard indicators based on environmental conditions and triggering factors, as illustrated in Section 4.1;
- Step 02. Aggregation of the nine indicators in a glacier melting landslide susceptibility map;
- Step 03. Development of worth exposed layers, divided into social, physical, environmental, and economic aspects (explained in Section 4.2);
- Step 04. Aggregation of the worth exposed value in the Valle d'Aosta region;
- Step 05. Development of a methodology for risk assessment at the regional level (discussed in Section 4.3);
- Step 06. Comparison of risk scores from Valle d'Aosta municipalities and landscape typologies involved;
- Step 07. Local scale analysis (discussed in Section 5).

The local scale analysis in the Lys Valley makes use of the same framework introduced for the regional analysis with some in-depth analysis and the definitions of hazard, vulnerability, and worth exposed values. In particular, the main changes moving from the regional to local scale analysis are the following:

- Improved hazard calculation: higher-resolution data were used for the computation of the susceptibility map;
- Site survey and vulnerability assessment: the vulnerability of the buildings was refined through data collected during on-field survey consisting of five parameters (age and state of conservation, road access and reachability, exposed slope facade and protections, number of floors and building size and use, and the functions and presence of people);
- Worth exposed analysis: this takes into account the "temporal spatial probability", i.e., the probability that people at risk are in the area affected by the hazard at the time of its occurrence; this is specifically relevant for the Lys Valley due to the strong seasonal nature of tourist fluxes.

An in-depth discussion of the local scale analysis is presented in Section 5.

4. Regional Scale Analysis

4.1. Hazard Indicators

The actions that perturb the natural equilibrium on slopes can cause geological–hydraulic instability phenomena; they originate from many interrelated factors, whose different combinations have an extremely variable impact on the balance of the natural environment. The indices proposed in this section try to summarize the main factors that may contribute to the occurrence of a landslide event. It must be specified, however, that this is an assessment made at a large scale. The objective of this first phase of the work was to provide a useful tool for large-scale planning that can later coordinate more specific actions on areas particularly at risk. Each indicator quantifies, on a scale of values from 1 to 5, the most favourable situation for a landslide event to occur (5) and the least favourable (1). However, it must be specified that at this stage of the work, knowledge of the mechanisms and contexts of landslide activation is not detailed enough to identify a dominant factor; therefore, the influence of each factor is equal. To give weights to the indices, it would also be necessary to choose a type of event for which to make an assessment, a choice that would exclude, or give less weight to, events that would occur with the same probability. The factors analyzed were the following:

1. Acclivity;
2. Slope aspect;
3. Paraglacial areas;
4. Glacial geomorphological features;
5. Permafrost degradation;
6. Vegetation and protection forests;
7. Existing gravitational processes;
8. Distribution of precipitation;
9. Lithology and geological setting.

A summary of the indices is given in Table 1 and Figure 3, which specifies the subdivision of the index into the five scores from 1 to 5, the sources taken as reference for its determination, and the database used for the calculation applied to the case study of the Valle d'Aosta region. Finally, an ideal update frequency of the data is also suggested: the data can be subdivided into those points that are more or less static and those that are dynamic and need to be updated regularly. Examples of static datasets are related to geology, soil types, geomorphology, and morphography. The time frame for the updating of dynamic data may range from hours and days, for example, for meteorological data and their effect on slope movements, to months and years for land use and population data (used in the next sections for exposure and vulnerability assessment).

Table 1. Indices used for the evaluation of the hazard indicator and defined scores for the subdivision into different hazard classes.

z	Index	Scores	Description	Database	Bibliographic Reference
1	Acclivity	Very small slope, 0–3° = H1 Small slope, 3–10° = H2 Moderate slope, 10–20° = H3 Steep slope, 20–30° = H4 Very steep slope, >30° = H5	Slope is the measurement of surface steepness, is measured as a degree, and ranges between 0 and 90°.	Regional DTM [82]	Yordanov and Brovelli, 2021 [48] Çellek, 2020 [49]
2	Slope aspect	Good exposition (N, NE, NW: $0° < x \leq 67.5° + 292.5° < x \leq 360°$) = H1 Moderate exposition (Z, E, W: $67.5° < x \leq 112.5° + 247.5° < x \leq 292.5°$) = H3 Low exposition (S, SE, SW: $112.5° < x \leq 247.5°$) = H5	Aspect depicts the direction of the slope with respect to the cardinal points.	Regional DTM [82]	Yordanov and Brovelli, 2021 [48] Çellek, 2020 [49]
3	Paraglacial areas	Deglaciated areas between 1850 and 1975 = H1 Deglaciated areas between 1975 and 1999 = H2 Deglaciated areas between 1999 and 2005 = H3 Deglaciated areas between 2005 and 2019 = H4 Potential deglaciated areas in the future (glaciers in 2019) = H5	Slope stability in Alpine and high-latitude regions is significantly influenced by glacier retreat, leading to paraglacial slope adaptation.	GlaRiskAlp database "Inventory of Current and Past Glacier Extents" [83]	GlaRiskAlp project [83] McColl, 2012 [69]
4	Glacial geomorphological features	Bedrock = H1 Glacial lakes = H3 Epiglacial lakes = H4 Deposits and tills = H5	Geomorphological mapping is useful for reconstructing different glacier extensions since the end of 19th century.	Catasto ghiacciai della Regione autonoma Valle d'Aosta [82]	GlaRiskAlp project [83]
5	Permafrost degradation	Permafrost in almost all conditions (values $0 < x \leq 51$) = H1 Permafrost mostly in very cold conditions (values $51 < x \leq 102$) = H2 Permafrost mostly in cold conditions (values $102 < x \leq 153$) = H3 Permafrost only in favourable conditions (values $153 < x \leq 204$) = H4 Permafrost only in very favourable conditions (values $204 < x \leq 255$) = H5	The term "permafrost" is defined as "soil or rock having temperatures below 0 °C over at least two or more years".	PermaNET project [84] and PERMOS [85]	PermaNET project [84]

Table 1. *Cont.*

z	Index	Scores	Description	Database	Bibliographic Reference
6	Vegetation and protection forests	Protection forest 42° = H1 Protection forest 28° = H2 Generic wood from Corine Land Cover 2000 = H3 Areas which are not covered by forest = H5	Soil cover is important in the assessment of risk since vegetation plays an important role in slope stabilization.	Rockfall database in Alpine Space: past events, rockfall areas and rockfall protection forest [82]	ROCKtheALPS project [86]
7	Existing gravitational processes	Buffer of 50 m from existing gravitational events = H2 Deep-seated gravitational slope deformations = H4 Landslides ("dissesti_frane" + "dissesti_alluvione_frane_2000" + "dissesti_alluvione_esondazioni_2000") = H5	Past events are important because they can reactivate over time after long periods of dormancy.	Catasto Dissesti della Regione Autonoma Valle d'Aosta [82]	Roccati et al., 2021 [39]
8	Distribution of precipitation	0–1.4 mm = H1 1.4–2.1 mm = H2 2.1–2.3 mm = H3 2.3–2.7 mm = H4 2.7–4.1 mm = H5	The effect of the water condition is reflected in reducing the shear strength of sliding surface and increasing the weight of sliding mass.	Centro funzionale Regione Autonoma Valle d'Aosta [86]	Zhang, 2020 [43]
9	Lithology and geological setting	Sedimentary rocks = H5 Landslides bodies, alluvial deposits, glacial deposits, and slope debris = H4 Igneous and metamorphic rocks = H2	Landslides are greatly conditioned by the lithological properties of the surface.	Carta Geologica della Valle d'Aosta [82]	D'Agostino and Marchi, 2003 [87]

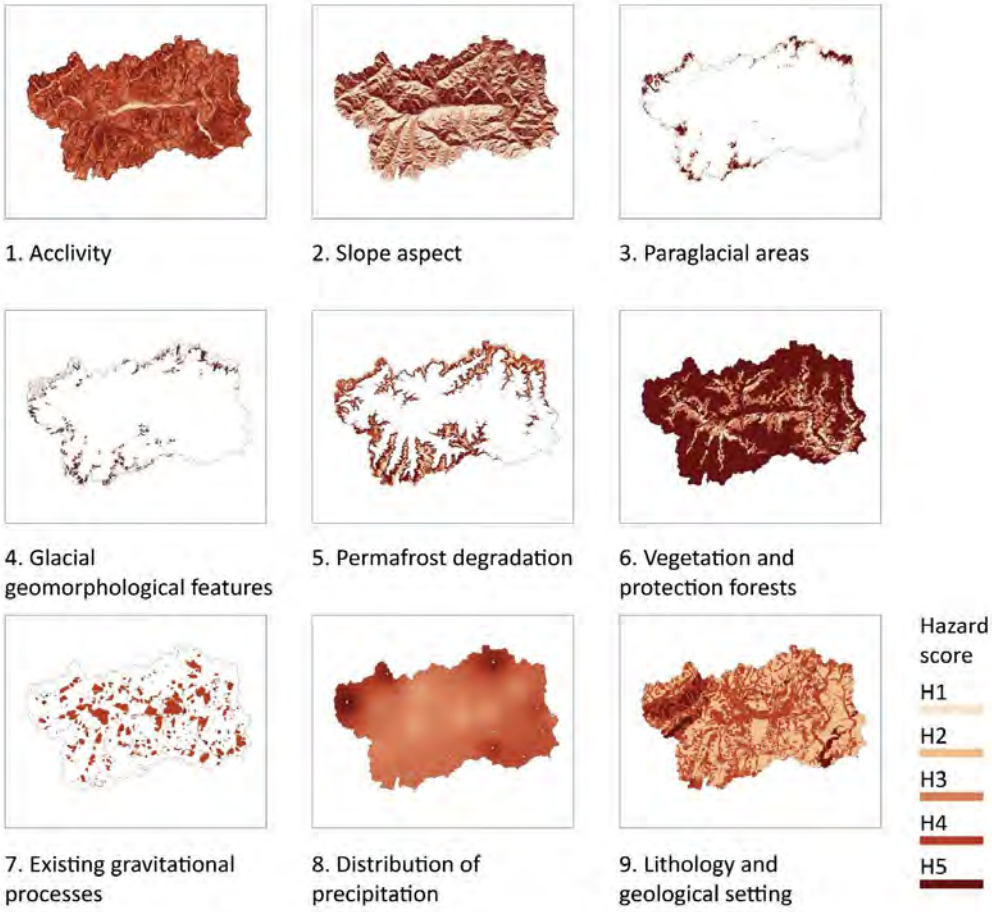

Figure 3. Individual hazard layers obtained through GIS software processing. Data sources are listed in Table 1.

The hazard assessment methodology and the data employed are explained in more detail as follows:

1. The slope was calculated from a Digital Terrain Model (DTM), and the risk classes were derived from the findings of research conducted by Cellek [49]. This research proposed a synthesis of the slope values that were generally preferred in the literature review. The classes used in this work were selected based on these findings.
2. Aspect depicts the direction of the slope with respect to the cardinal points of all the slopes of the territory. The references that have been examined in this work divide the aspect value into nine classes (north, northeast, east, southeast, south, southwest, west, northwest, zenith), which have been reclassified in 3 classes to evaluate the potential hazard: good, moderate and low exposure.
3. Slope stability in Alpine and high-latitude regions is significantly influenced by glacier retreat, leading to paraglacial slope adaptation. There are a lot of studies about paraglacial areas; among all, "paraglacial rock slope stability" [69] has been used as theorical reference to calculate the index. In the framework of the GlaRiskAlp project, an "Inventory of Current and Past Glacier Extents" has been produced to quantify the general glacier retreat in the Western Alps since the end of the Little Ice Age. For this work, the temporal thresholds of glacier extent have been used: 1850, 1975, 1999, and 2005. Since the latest data are not so recent, the GlaRiskAlp database has been completed with the last available data of 2019 from Catasto ghiacciai della Regione autonoma Valle d'Aosta.
4. For the glacial geomorphological feature layer, a qualitative analysis was conducted based on the typology of material derived from glacier retreat. Index values have been

reclassified into four classes: since bedrock can be considered “stable”, it is classified with a low potential hazard, differently from deposits and till, which are classified with the highest scores. Glacial land epiglacial lakes are classified with middle values.

5. For the permafrost degradation index, the PermaNET project was used as a reference in this research, which uses one of the statistical permafrost distribution models developed. The explanatory variables are the mean annual air temperature, potential solar radiation, and mean annual precipitation. These were calculated for the entire Alps and were used to derive estimates of the probability of rock glaciers being intact or of the rock face temperature being below 0 °C. The values of the final raster file ranged from 0 to 255 and were divided into five equal classes.
6. The capacity of forests and vegetation to protect from landslides events was classified into four classes. The protection forests identified from the ROCKtheALPS project have the lowest hazard index, while the other woods from the Corine Land Cover database were classified as a medium hazard. Finally, the areas that are not covered by wood have the highest hazard value.
7. For the existing gravitational processes, the classification is based on [88]. This classification could be further developed depending on the availability of data (for example, different hazard values could be assigned to events depending on whether they are (i) active/reactivated/suspended landslides, (ii) dormant landslides, (iii) inactive/stabilized landslides, or (iv) areas affected by widespread shallow landslides). The available database for the Valle d’Aosta did not have this level of detail, and therefore, the raster was classified in a qualitative way.
8. Precipitation data are based on rainfall data of the region. The map of the spatial distribution of precipitation was obtained from the data measured by the rain gauges of some stations, and an extension to the whole territory was made using an interpolation algorithm (Interpolating Point Data) that creates a continuous surface from discrete points when it is impossible to take measurements throughout all the territory taken into consideration. The raster derived from the interpolation was classified into five classes through a quantile classification.
9. The hazard index related to the lithology and geological setting was differentiated for the three types of landslide phenomena: for each map, different values for the three macrocategories were used (a—landslides bodies, alluvial deposits, glacial deposits, and slope debris; b—sedimentary rocks; c—igneous and metamorphic rocks). The final index is obtained by summing the three results.

What is important to underline is the fact that areas with hazard values of 4 and 5 (high and very high) are quite widespread and distributed among all indices. The indicator that includes more territory in the “very high hazard” category (H5) is the sixth one, “vegetation and protection forests”. This is due to the fact that the Valle d’Aosta region has forests in the lowest part of the mountain ranges. Vegetation thins out, leaving space for exposed rock, which is assigned the highest score, occupying an area of 2523 km^2, equal to 77% of the regional territory. Another index that classifies most of the territory in class 5 is the second one, “slope aspect”, with 1282 km^2 in H5, equal to 39%. The explanation for this lies in the morphology of the Valle d’Aosta, formed by an almost horizontal valley and consequently by many slopes facing south. Other indicators assessing a large part of the territory subject to high hazard are the first, “acclivity” and the last one, “lithology and geological setting”, with, respectively, 1663 km^2 (51%) and 1428 km (44%) in class H4. This is because a large part of the region has steep slopes, between 20° and 30° in most of the territory. As far as lithology is concerned, a high hazard is evident since the variety of phenomena occurring (falls and topples, earth and mud flows, rotational and translational slides) take into account many lithological types that have been therefore included in the classification.

The final hazard map is obtained by combining in an arithmetic average of the different indicators (Figure 4).

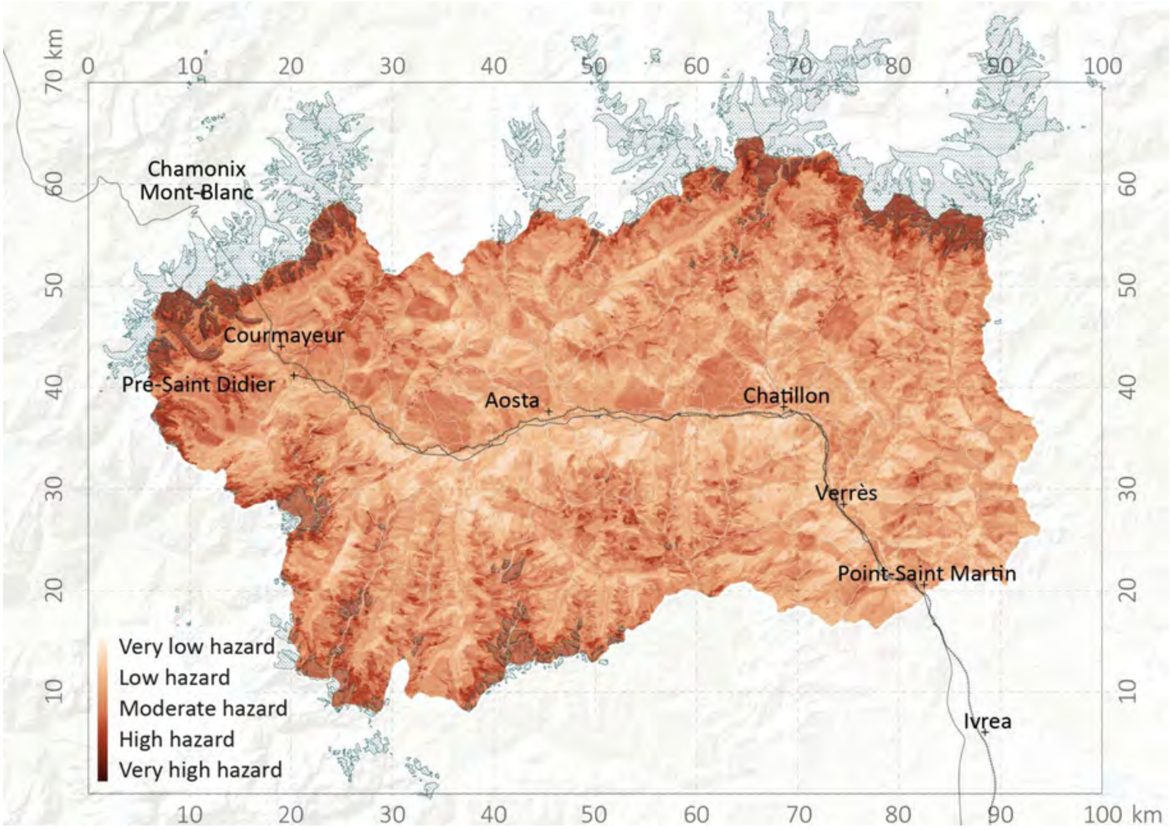

Figure 4. Aggregated hazard value: glacier melting landslide susceptibility map. The map was created through QGIS (v. 3.26.0) software, employing the data outlined in Table 1.

As shown in the maps of the individual indices previously mentioned, the areas with the highest hazard values are located as follows:

- In the northwest along the border with France, in Val Veny, Val Ferret, and Valle di La Thuile (Courmayeur area, Mont-Blanc, Col d’Arguerey, Aiguille-des-Glaciers, Aiguille-de-Bionnassay, Dent-du-Géant);
- In the northeast along the border with Switzerland, near the Matterhorn and Monte Rosa groups;
- In the area of the mountain ranges to the south, along the steep slopes of Valgrisenche, Val di Rhemes, Valsavarenche, and Val di Cogne.

However, other high hazard areas are located along the central part of Valle d’Aosta, with hazard scores of up to 26 out of 41 (maximum value), due to a combination of lithological types susceptible to instability, landslides that have already occurred in the past and are likely to recur, the absence of vegetation, and the slope facing south. The obtained result is very useful to make a comparison with the existing documentation included in the Piano Territoriale Paesistico—PTP (Territorial Landscape Plan), approved on 10 April 1998 through regional law n. 13. Valle d’Aosta has produced, for the entire regional territory, a map of geological and hydraulic hazards on a scale of 1: 100,000, as reported in Figure 5.

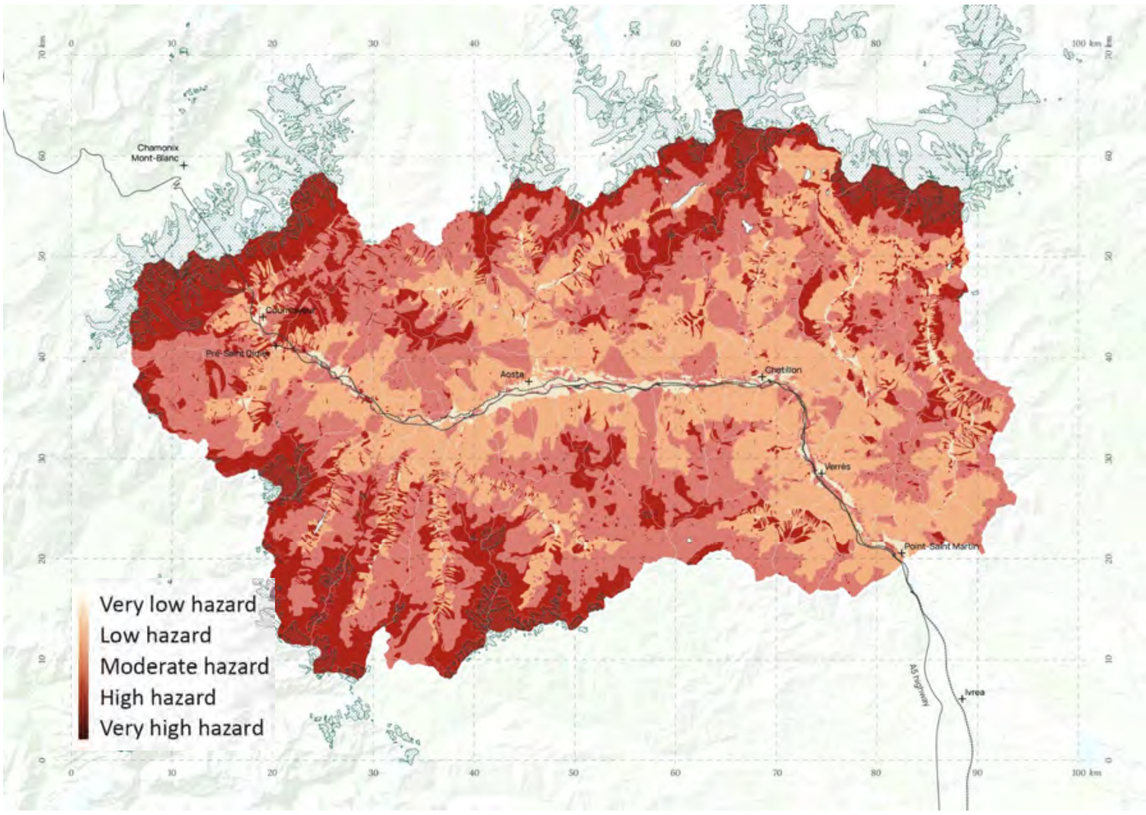

Figure 5. Geological and hydraulic hazard map included in Piano Territoriale Paesistico. Data from the Geoportale of Valle d'Aosta region.

With regard to the protection against hydrogeological risks and instabilities, the PTP adopts regional law n. 32 of 1996, which identifies four classes of areas, with different degrees of hydrogeological hazards:

(1) Extensively disrupted areas susceptible to further evolution to a very high hazard level, including large landslides, avalanche areas, active debris layers, active alluvial conoids, and floodplains; unstable areas with very high propensity to disruption; minor flooding areas, with very high probability of hydrogeological events; and the probability of hydrogeological events;
(2) Unstable areas, with a locally high level of hazard: areas that are floodable during exceptional events and sectors of slopes that are more vulnerable during hydrological emergencies due to the potential for landslides, especially of surface soils;
(3) Areas with moderate instability and a low hazard level: floodable areas with secular frequency and areas characterized by local instability phenomena for potential landslides during hydrological events;
(4) Areas that do not present particular problems from the point of view of hydrogeological hazard: flat valley bottom territories and morphological terraces free from instability phenomena.

A comparison of the two mappings reveals a similarity of results, even though the present methodology introduces additional parameters beyond those of the Piano Territoriale Paesistico. The proposed methodology aims to specify hazard levels on 10 × 10 metre "pixels", derived from the resolution of the starting datasets for the individual indicators presented in the previous section. In addition, the work carried out analyses on a specific type of risk, which is the risk of slope instability, while the existing documentation of Figure 5 refers to hydrogeological risk in general.

4.2. Exposure Indicators

The second step for the risk assessment is the evaluation of the worth exposed, which is defined as the number of units (or "value") of each of the elements at risk in a given area: it can be expressed as the number of human presences or by the value of the economic and natural resources that are exposed to a certain hazard, which may be lost in the case of a destructive event occurring. For the qualitative assessment of the relative importance, the assets were divided into four different types: physical, social, economic, and environmental [89]. The elements considered are built-up areas and population (social assets); transportation networks (physical assets); tourism and services (economic assets); and sites of community importance, important bird areas, nature reserves, and land cover (environmental assets). The different indicators and the score values associated with them are summarized in Table 2.

Table 2. Indices used for the evaluation of the exposure indicator and defined scores for the subdivision into different exposure classes.

z	Index	Scores	Description	Database	Bibliographic Reference
1	Social asset	Less than 5 residents = W3 5–30 residents = W4 More than 30 residents = W5	Number of residents potentially involved	ISTAT [90]	Totschnig et al., 2011 [91]
2	Physical asset	Trail, distance < 5 m = W3 Main road, distance < 5 m = W4 Motorway and railway, distance < 10 m = W5	Potentially affected infrastructures and communication routes	Geoportale SCT [82]	Roccati et al., 2021 [39]
3	Environmental asset	Natural areas = W2 Woods and grazing lands = W3 Protected areas (conservation areas, parks, and nature reserves) = W4	Threatened landscape and natural elements	Geoportale SCT [82]	Papathoma-Köhle et al., 2011 [92]
4	Economic asset	All elements were rated with the maximum value W5	Touristic facilities exposed to slope instabilities	Geoportale SCT [82]	Fuchs et al., 2007 [93]

Then, the single results were combined in order to obtain the final map (Figure 6) on the spatial distribution of the worth exposed values. Generally, the higher level of exposure (the "very high" exposure class) is located at the foot of mountain slopes, around the main urban areas located in the centre of the valley. The importance of social, physical, and economical assets is greater here, due to the high presence of people, cultural elements, transportation networks, and touristic facilities. Other areas with very high scores are touristic spots located in high altitudes, such as skiing facilities, in protected sites or in natural areas with a high value. The following class ("high" exposure) covers areas with existing landslides and with important environmental assets, such as natural reserves, national parks, important bird areas or sites of community importance. Less exposed areas are located in small lateral valleys, characterized by very few inhabited villages.

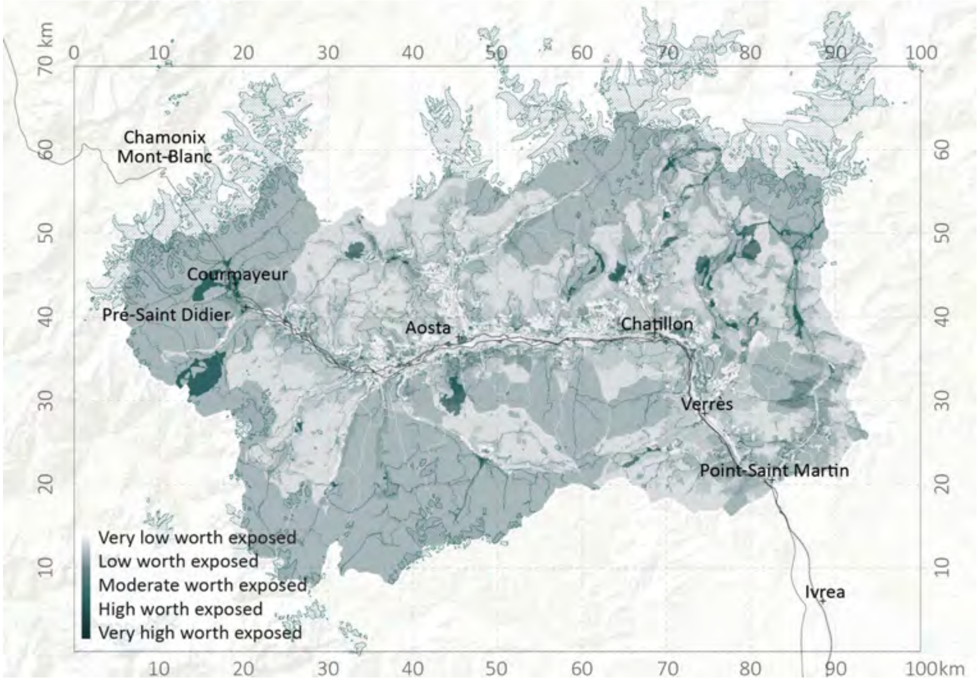

Figure 6. Aggregated worth exposed value in the Valle d'Aosta region. The map was created through GIS software, employing the data outlined in Table 2.

4.3. Results

The information on the worth exposed was then combined with the landslide hazard map in order to obtain the risk assessment of slope instability at regional level reported in Figure 7, through the process summarized in Section 3.2.

Analysis of the results shown in Figure 7 demonstrates that about 42% of the territory is located in areas ranging from very low to moderate risk (1.6% very low, 12.3% low, 28.5% moderate). This means that most of the territory ranges include moderate–high risk (23.6%), high risk (16.7%), and finally very high risk (17.3%). In order to better describe the distribution of the risk associated with landslides due to glacier melting, two analyses were carried out: (i) the distribution of the risk at the municipality level and (ii) the distribution of the risk in different landscape units. The main aim of this phase was to provide a landslide risk map as support to local governments for identifying the priorities for the design of appropriate mitigation plans.

At the municipality level, the computed risk index has been put in relation to Valle d'Aosta municipalities by averaging the values of the pixels that fall within the different town boundaries. In Figure 8, the risk distribution in the municipality in Valle d'Aosta was organized into box-plots. Comparing the results, we observe that the interquartile range box (called the IQR, which represents the middle 50% of the data) ranges between 75 (lowest value for Q1) in the low-risk class and 203 (highest value for Q3) in the high-risk class. The interquartile box for the whole region is between 105 and 162: this means that half of the territory was classified in this range, including risk values ranging from "moderate" to "high". Some municipalities that present the highest risk scores are, in order, Bionaz (570), Gressoney-La-Trinité (528), Courmayeur (494), Pré-Saint- Didier (493), Valtournenche (486), and Cogne (465).

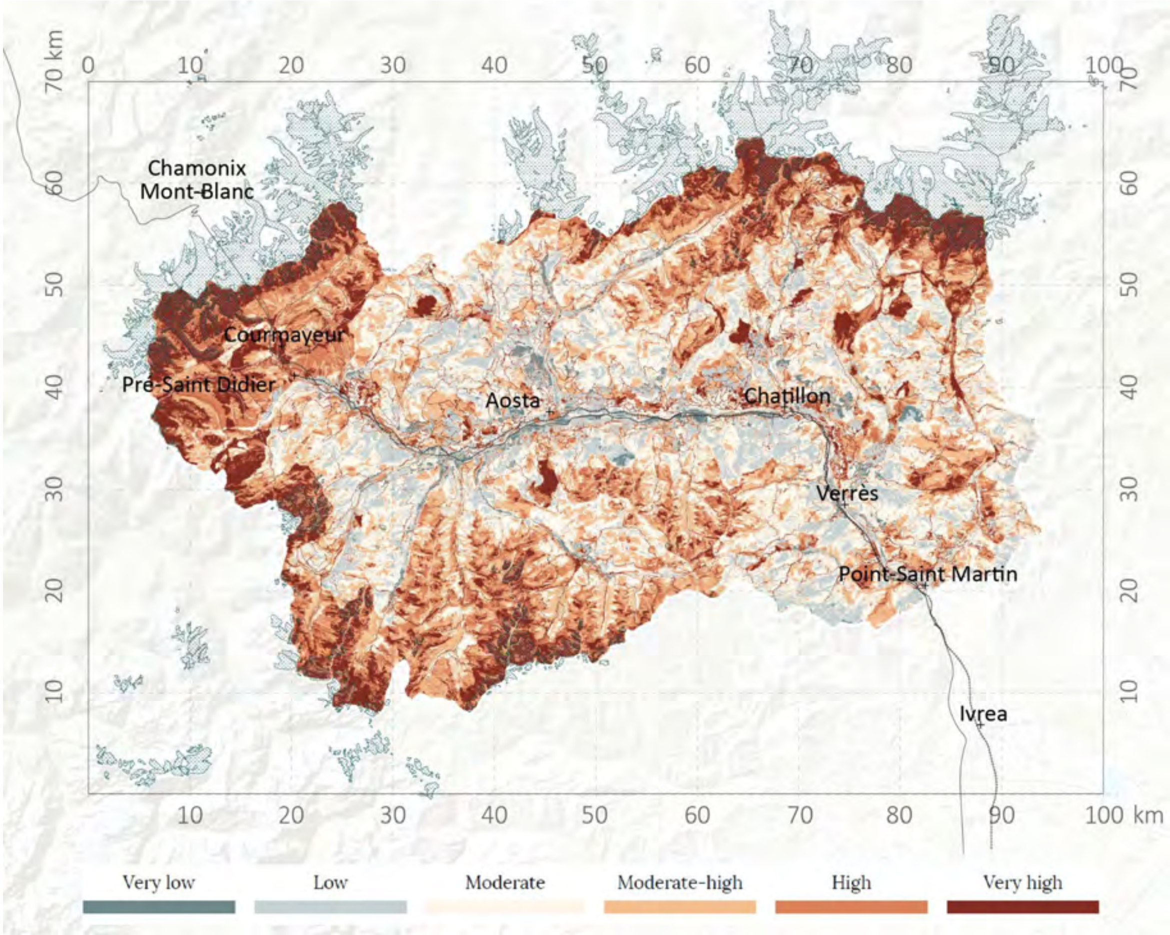

Figure 7. Glacier melting related landslide risk map in Valle d'Aosta region. The map was created through GIS software, interpolating hazard and worth exposed maps (Figures 4 and 6).

One of the areas categorized as high risk is the Lys River Valley, which owes its name to the homonymous river, a left tributary of the Dora Baltea. Gressoney-La-Trinité, the second municipality with the highest risk score, is located in the upper part of the valley, at the foot of the Monte Rosa massif and near the Lys glacier. In particular, in the final stretch, we find a group of small villages on very steep slopes whose development has been strongly conditioned by avalanches and gravitational phenomena that have always characterized this valley in particular. This is the reason why this area is the subject of analysis at the local level in Section 5.

The peculiarities of the Valle d'Aosta landscape and the territorial fragilities that characterize it make it necessary to correlate the areas at landslide risk with these threatened values. The aim of this analysis was to provide further information and tools aimed at protecting the regional territory and its landscapes, as well as support for planning choices concerning protection against the risks arising from possible gravitational movements and landslides that could occur in deglaciated areas. The Territorial Landscape Plan (Piano Territoriale Paesistico, PTP) of Valle d'Aosta was used for the identification of the different landscape units (Figure 9).

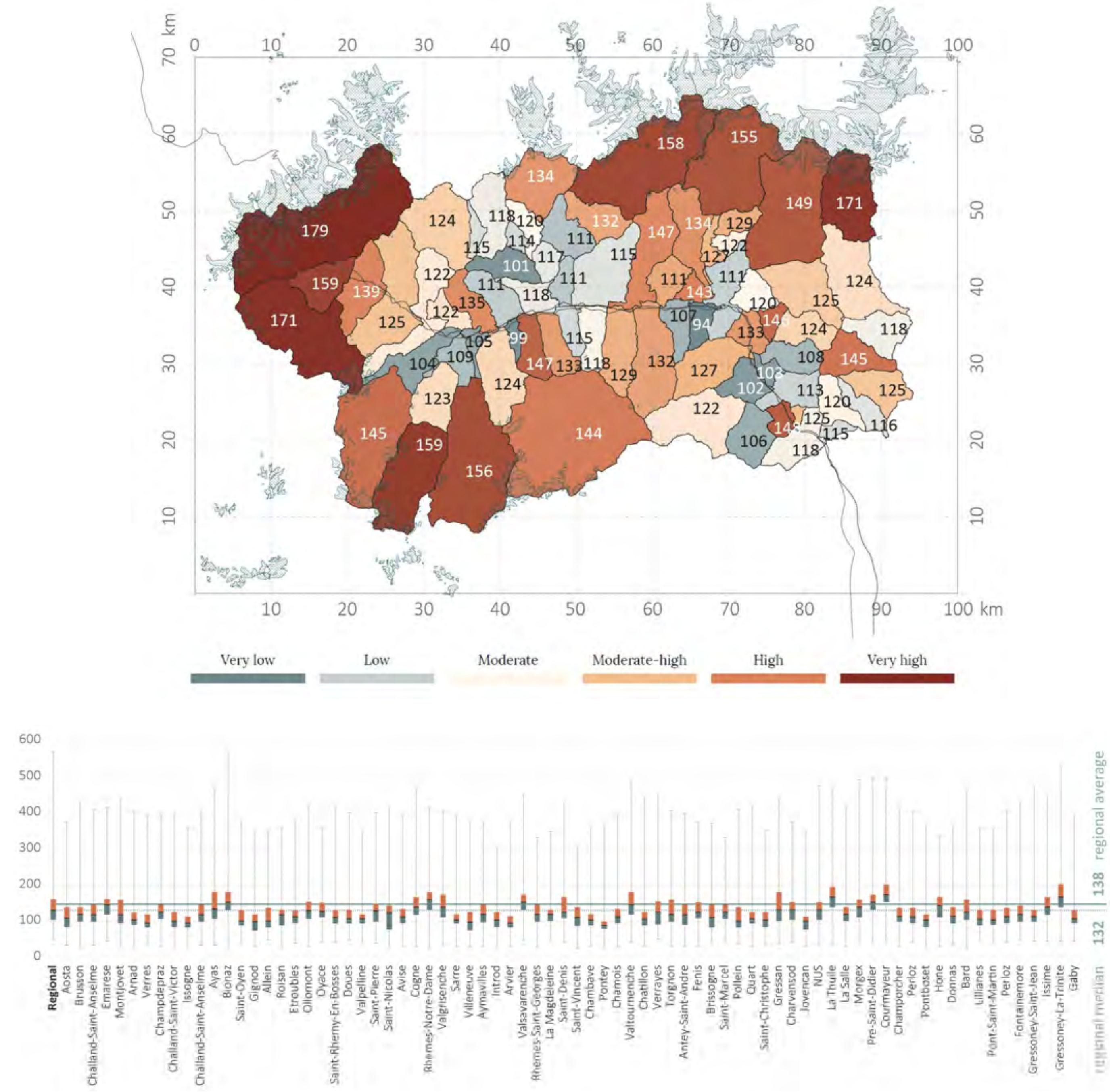

Figure 8. Risk score comparison in Valle d'Aosta municipalities.

The landscape units defined by the PTP were related to the landslide risk map in order to have a first indication of the landscape types with the highest risk, through the averages calculated on the single units. It emerged that the landscape units with values higher than 180 (very high risk) belong to the following types: high-altitude hollow landscapes (AC), glacier landscapes (AG), high-altitude lake landscapes (AL), settlement landscapes on confluences (IK), urban landscapes dominated by natural monuments (UN), valley landscapes with plains (VP), and steep slope valley landscapes (VF). Therefore, predominantly natural areas, glaciers, and high-altitude basins and lakes are followed by settlement landscapes on confluences, urban landscapes dominated by natural monuments, and valley landscapes with plains.

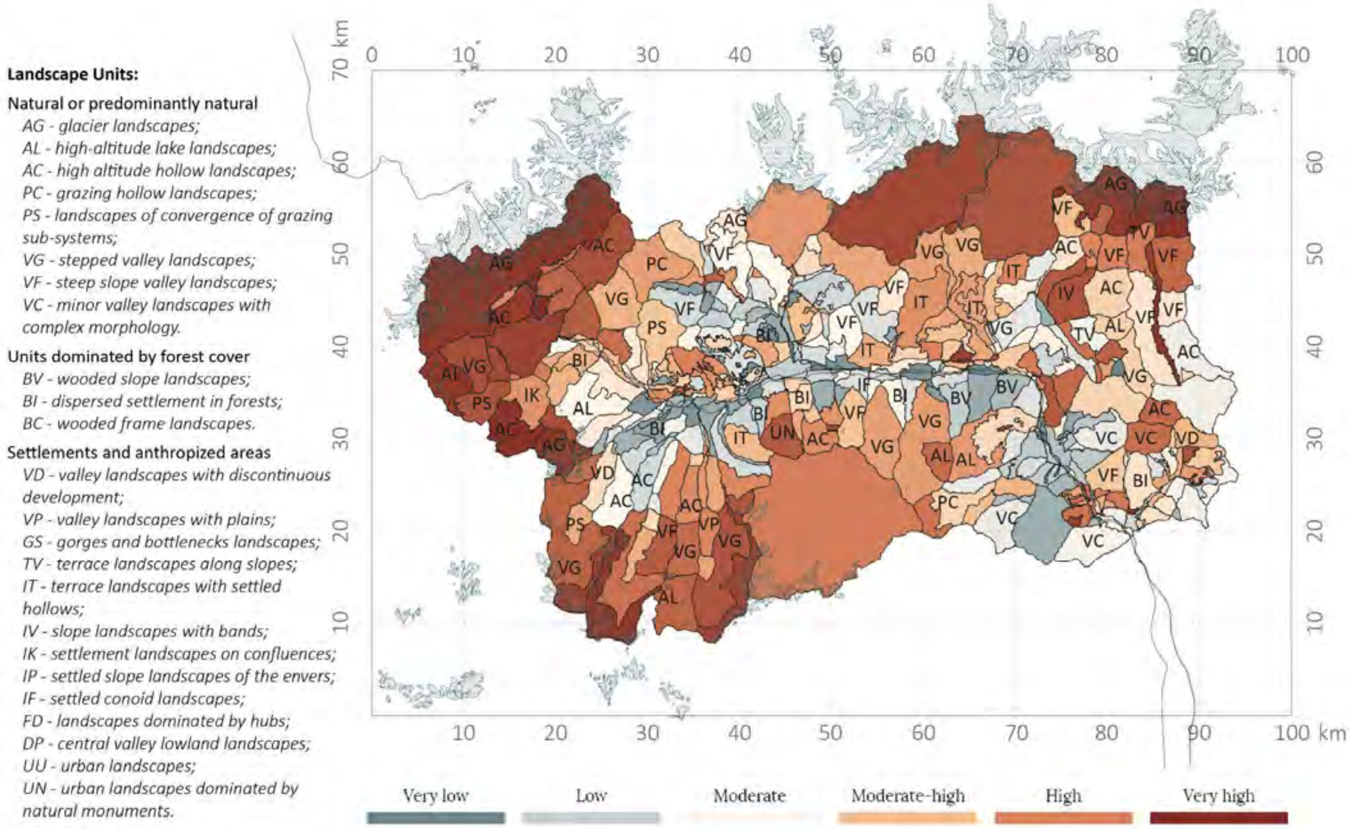

Figure 9. High-risk areas: landscape typologies involved.

5. Local Scale Analysis

The analysis at the regional scale is useful for identifying areas and municipalities needing priority for the design of appropriate mitigation plans. However, this is not exhaustive for the implementation of risk mitigation strategies, which require a more detailed discussion at a smaller scale. For this reason, in this section, the risk assessment is deepened by focusing in the area of the Lys River Valley (Figure 10). Indeed, one of the areas categorized as high-risk in the regional analysis was the Lys River Valley, which owes its name to the homonymous river, a left tributary of the Dora Baltea. Gressoney-La-Trinité, the second municipality with the highest risk score, is located in the upper part of the valley, at the foot of the Monte Rosa mountain range and near the Lys glacier. In the final stretch, we find a group of small villages on very steep slopes whose development has been strongly conditioned by avalanches and gravitational phenomena that have always characterized this valley in particular. In addition, these small towns are fragile, with very old buildings (Walser houses) built using materials such as wood and stone, and have an important identity value and a historical heritage that are highly exposed to natural hazards.

Due to the peculiarities and fragilities of these places, the upper Lys Valley is well suitable as a case study on which to apply the landslide risk estimation methodology. This final analysis focuses on four areas particularly at risk, chosen for an in-depth risk assessment with data improved through a field survey, chosen for their distinct characteristics in order to synthesize all the possible cases in the valley. In this way, the third element involved in risk assessment—vulnerability evaluation—is introduced alongside the hazard and worth exposed elements.

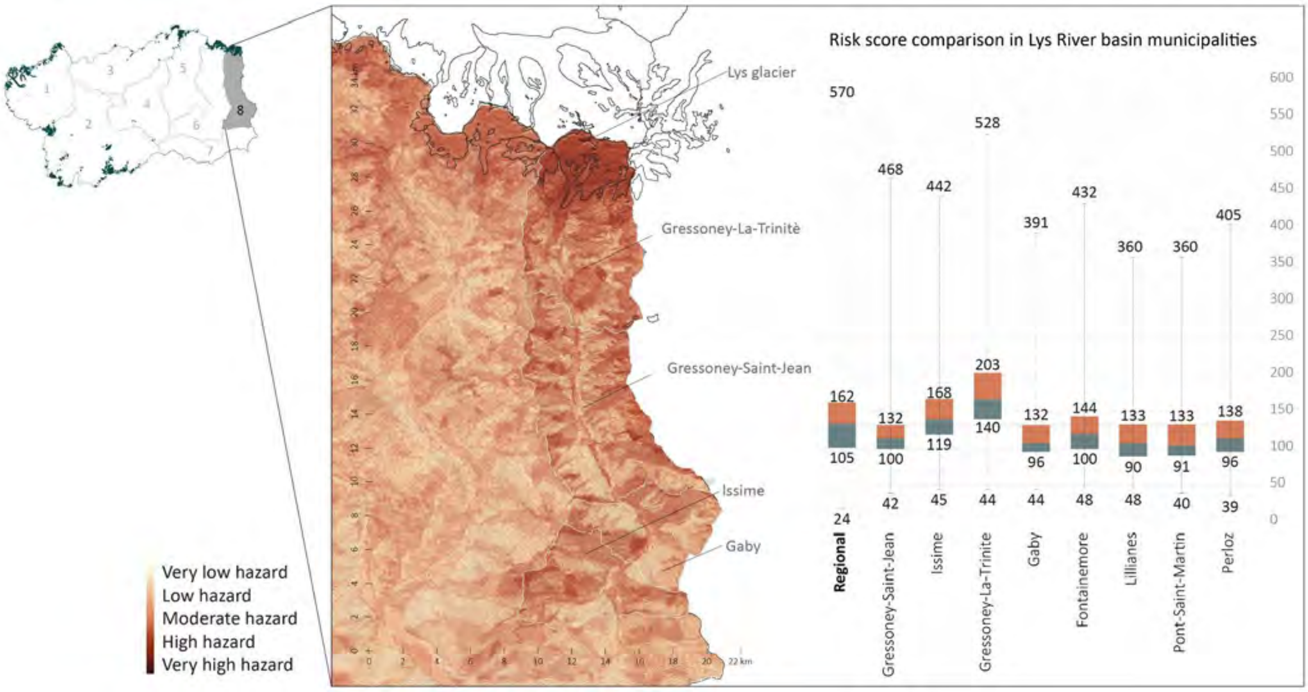

Figure 10. The Lys Valley: the risk map and its representation as a box-plot for the municipalities.

5.1. Vulnerability Analysis

The first step of the local scale analysis consists of estimating the vulnerability of the buildings, based on data collected during a field survey. Four different areas were selected for an in-depth risk analysis (Figure 11), each chosen for its unique characteristics to cover a broad range of cases across the valley:

1. Alpenzu Walser village (Area 01): an Alpine pasture at the edge of the forest;
2. The locality of Noversch (Area 02): a historic settlement on the valley floor;
3. Gressoney-La-Trinitè (Area 03): the town centre, with receptive activities and a ski area;
4. Locality Orsia (Area 04): dispersed houses on the slopes at the end of the valley.

For each location, an estimation of the vulnerability of the buildings was made consisting of five parameters: age and state of conservation, road access and reachability, exposed slope facade and protections, number of floors and building size and use, functions and the presence of people, as summarized in Table 3. Each parameter was assigned a score ranging from 1 (low vulnerability) to 3 (high vulnerability) for each building. The final sum of these scores gives the Total Vulnerability. The highest value found was 15 (historic houses, hardly accessible, unprotected, and still inhabited), while the lowest value was 7 (new houses, located along the main infrastructure, with little exposed facades). The nine scores obtained were then grouped into three categories:

- V scores 7, 8, and 9 > moderate V;
- V scores 10, 11, and 12 > medium V;
- V scores 13, 14, and 15 > high V.

The second step involves determining the worth exposed, which takes into account the presence of people in the buildings considered. This factor, called "temporal spatial probability", refers to the likelihood that people will be in the area affected by the hazard at the time of its occurrence. The strong seasonal nature of these tourist areas must be considered, as the timing of the potential event is crucial in this context. For the preliminary assessment, the highest value was assigned to public facilities, shops, restaurants, hotels, and mountain huts, as these typically host the largest number of people. A medium value was assigned to houses permanently or occasionally inhabited, while the lowest value was given to uninhabited structures like barns, sheds, garages, etc.

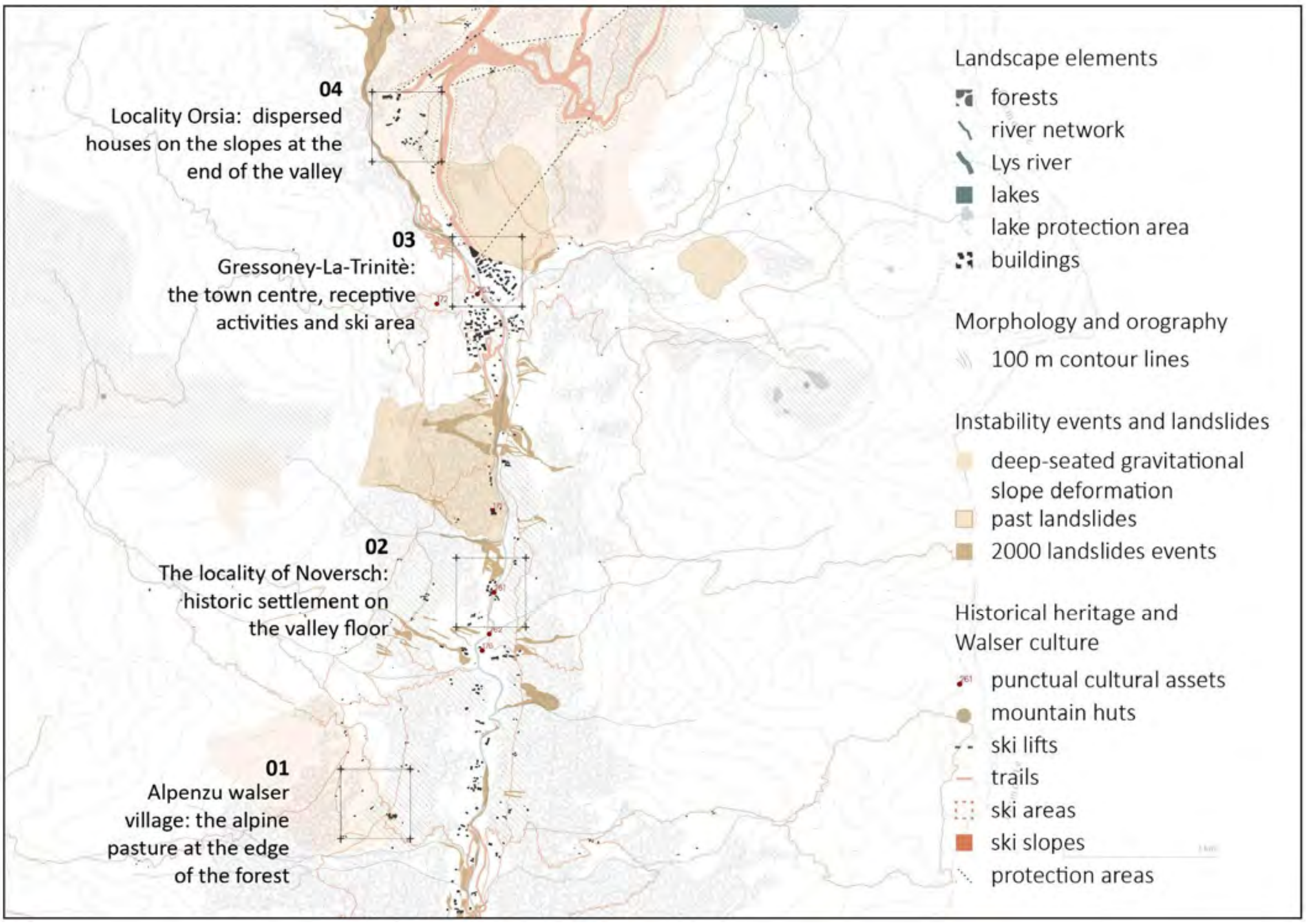

Figure 11. Positions of the four case studies for the local scale analysis representing the landscapes of the Lys Valley. Data obtained from regional geoportals and databases of the Autonomous Region of Valle d'Aosta.

Table 3. Vulnerability criteria and scores used in the local-scale vulnerability analysis.

Vulnerability Criteria	Scores 1 (Moderate)	2 (Medium)	3 (High)
Age and state of conservation	recent construction	built in the 20th century	historic house or Walser house
Road access and reachability	located along the main road	accessible by car	only accessible on foot through a hiking trail
Exposed slope façade and protections	small facade with few openings	facade with various windows	large, unprotected facade, many openings
Number of floors and building size	one floor	two floors	three or more floors
Use, functions, and presence of people	uninhabited/barn, shed, garage function	inhabited regularly or occasionally	hotel, hut, shop, or public service

Subsequently, with the obtained data, it was possible to calculate the potential damage to buildings by multiplying the vulnerability (V) and worth exposed (W) values. Finally, through combining the potential damage with the hazard values, the total landslide risk assessment was derived.

5.2. Results

The first site analyzed was the Walser village of Alpenzu Grande (Figure 12), located in Gressoney St-Jean, sits on a natural balcony offering views from the Monte Rosa massif to the entire valley. The village has a rich history, with evidence dating back to 1200. It showcases the distinctive Walser architecture, introduced by Germanic settlers in the 13th century, including the traditional "stadel" buildings on mushroom-shaped columns. Alpenzu Grande is situated on a southeast facing plateau within a protected zone of the Piano Territoriale Paesistico (PTP), the steep slope and its location in a deep-seated gravitational slope deformation area contribute to a high vulnerability to landslides. Additionally, the cultural value and age of the buildings increase their susceptibility to damage.

The second area analyzed was the one of Noversch (Figure 12). It is a small agglomeration within the municipality of Gressoney-Saint-Jean, located approximately 2 km away from it. Situated in the lowest part of the valley where the river Lys flows as a torrent, Noversch comprises 14 buildings: 10 residential, 2 for agricultural and productive use, and 2 unused. Of the residential buildings, four were constructed with load-bearing stone walls, while the remaining six are primarily wooden, making them more vulnerable. Notably, eight of these buildings were built before 1919, including several Walser "stadel" houses built by the Zumstein family, which are considered "structurally exemplary." The village is split by the stream, connected by a stone bridge with a round arch built in 1540. The historical buildings on the orographic left are particularly vulnerable due to poor accessibility in the event of a landslide. Noversch also suffered significant damage during the flood that devastated Valle d'Aosta in 2000.

Gressoney-La-Trinité, situated at an altitude of 1627 m at the top of the valley crossed by the Lys stream, lies in a flat area beneath the Lyskamm glacier and the Monte Rosa massif (Figure 12). Renowned internationally as a mountaineering and winter sport destination, it is part of the Monterosa Ski area, boasting 150 km of slopes, making it one of the largest in Europe. The village features the parish church of the Holy Trinity, dating back to 1671, built on the foundations of a 15th-century structure. The tourist-oriented area near the ski lifts is populated with modern hotels and residences, which are less vulnerable due to their construction and accessibility but have a high exposed value in terms of human lives and monetary worth. Despite its location in a moderate hazard area, resulting in a medium final risk value for most buildings, the presence of a deep-seated gravitational slope deformation area on the left orographic slope and a past landslide event nearby must be considered.

The fourth analyzed area was Orsia (Figure 12). Orsia is a village in the municipality of Gressoney-La-Trinité, situated just over 1 km from the town centre at an altitude of nearly 1800 m. The village features houses scattered along the steep slopes of the Lys valley. While accessible by the main road, many houses on the slopes can only be reached on foot, increasing their vulnerability. The area contains a few recently built hotels, but it primarily comprises well-preserved Walser houses and old staddle. The damage estimate is high due to the average exposed value, as the buildings are mainly year-round residences or second homes, combined with their high vulnerability. The final risk estimate is significant, particularly because these houses are located in a high-risk area on a deep-seated gravitational slope deformation zone.


(**a**) (**b**)

(**c**) (**d**)

Figure 12. The four sites analyzed: Alpenzu Grande (**a**), Noversch (**b**) Gressoney-La-Trinité (**c**), and Orsia (**d**). Photographs by the authors.

The local-scale risk assessment results (Figures 13 and 14) indicate that despite some buildings being located in medium or moderate hazard areas, they exhibit high potential damage or total risk due to high vulnerability values. This increased vulnerability is attributed to their location above deep-seated gravitational slope deformations or near previously occurred landslides, making them more susceptible to reactivation.

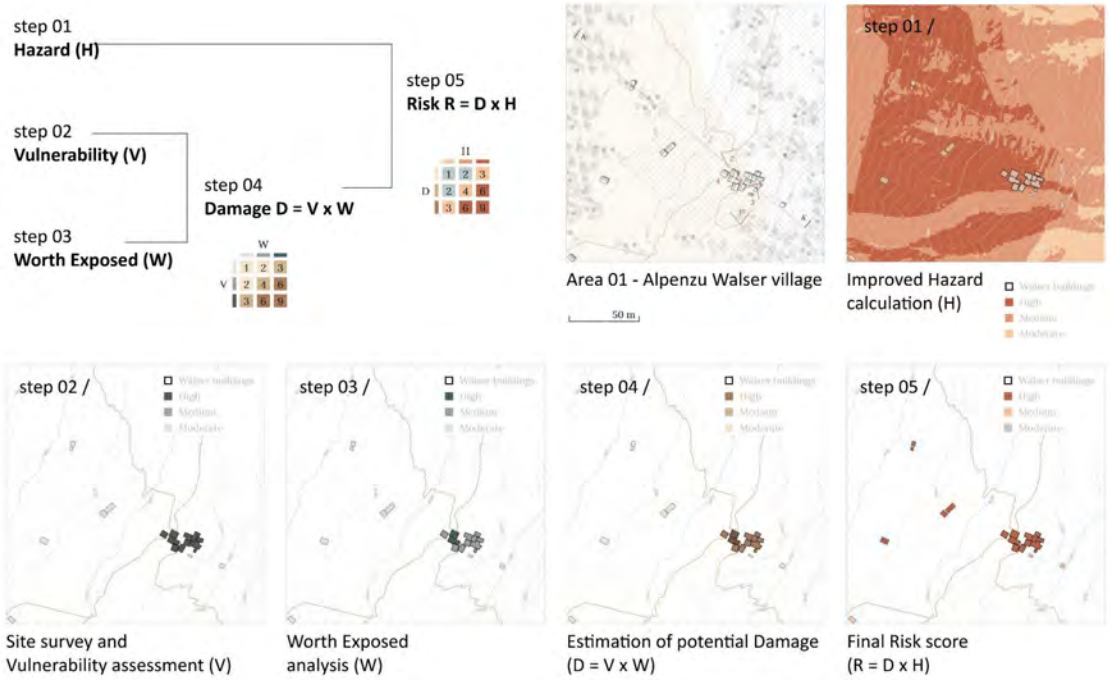

Figure 13. Local-scale analysis workflow for the Alpenzu Grande (Area 01) site: improved hazard calculation with a more detailed DTM (2 × 2 m) and assessed vulnerability and worth exposed values for the area to compute potential damage and assess the final risk score.

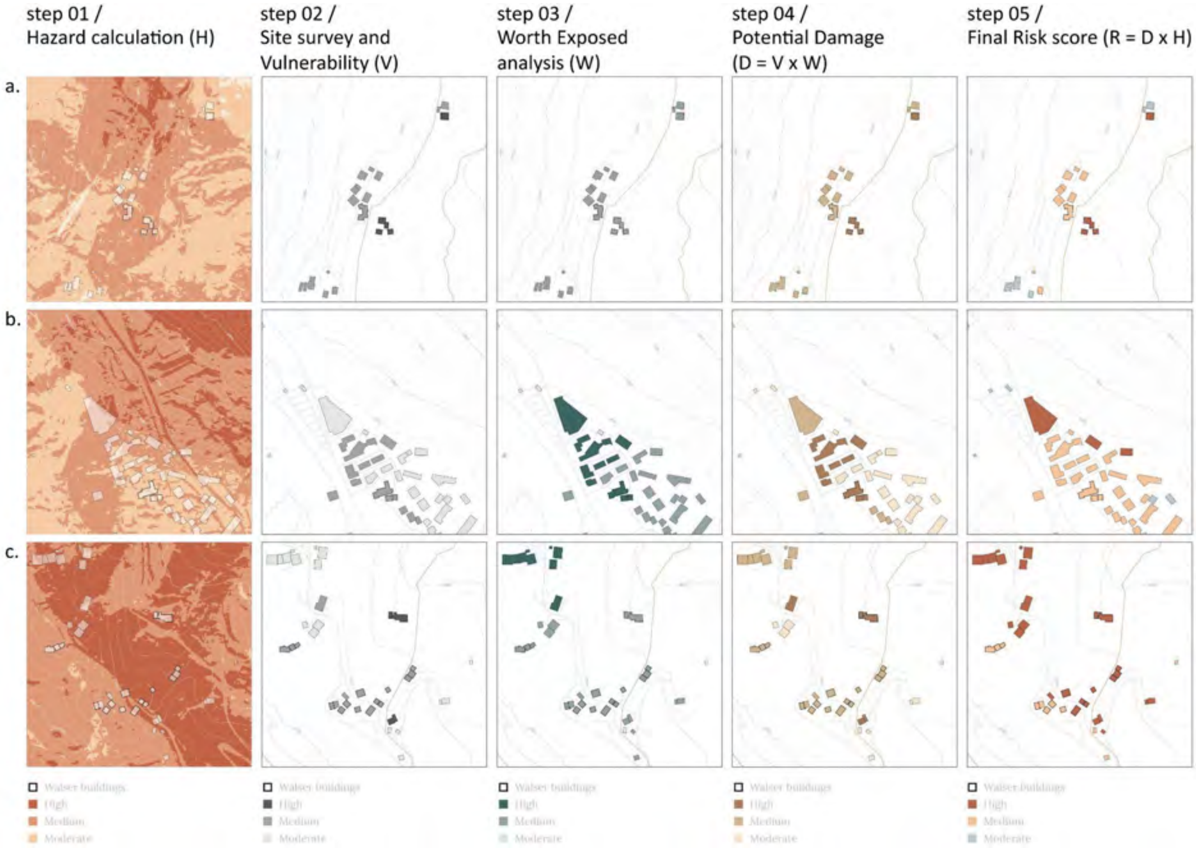

Figure 14. The local scale analysis results (improved hazard calculation, assessed vulnerability and worth exposed values, and final risk score) for Noversch (**a**), Gressoney-La-Trinitè (**b**), and Orsia (**c**). Analysis made with data collected in the field with the vulnerability scores listed in Table 3.

In particular, Alpenzu (Area 01) and Orsia (Area 04) are on the edge of areas affected by gravitational slope deformations, a common issue in the region characterized by scattered houses or small historical centres. Area 03 in Gressoney-La-Trinitè experienced an evacuation in 2018 due to an unstable boulder, affecting residents, tourists, and services, and disrupting transportation routes. Area 02, Noversch, was impacted by the 2000 floods, where intense rainfall exceeded regional averages, causing soil saturation and slope sliding.

The analysis underscores the importance of detailed vulnerability estimation in assessing potential damage and total risk. At-risk municipalities should enhance their documentation with information on building materials, age, floors, and inhabitants to improve risk assessments. The presence of Walser houses and historical settlements increases vulnerability and risk, highlighting the need to prioritize safety and heritage protection in building renovations. Comprehensive risk analysis should guide new construction locations, especially considering tourism development in the Lys Valley.

6. Discussions

In Valle d'Aosta, perhaps more than in other regions, there is a strong awareness that landscape and environmental protection are intrinsically linked to economic and social development. Within this perspective, the approach shifts from mere limitations and passive defence to proactive actions aimed at recovery and enhancement, which the regional and local authorities can actively promote, guide, and support. The methodology developed in this work provides a tool to identify sensitive sectors of the territory prone to instability and pinpoint areas where specific geological–hydraulic phenomena are likely to occur.

The results of this study can significantly aid policymakers and urban planners in the development of targeted risk mitigation strategies. The regional-scale risk maps enable the clear identification of areas requiring immediate intervention, while the local-scale assessments provide detailed insights essential for site-specific planning. These findings are particularly useful for enhancing spatial planning in Valle d'Aosta and facilitating the design of effective disaster risk management policies. Furthermore, the classification of risk by municipality and landscape typology offers actionable insights for prioritizing resource allocation.

By integrating the hazard, exposure, and vulnerability assessments, this study complements existing risk models, such as those employed in the Territorial Landscape Plan of Valle d'Aosta. The refined resolution of the risk maps (10 m × 10 m) surpasses the coarser generalizations in previous studies, enabling more precise identification of risk zones. Even if we must underline that the objective of this first phase of this work was to provide a useful tool for large-scale planning that can later coordinate more specific actions on areas particularly at risk, to obtain more precise estimates, it is necessary to employ greater expertise and conduct more detailed analyses of the substrate, geological components, and other potential risk factors

The approach also aligns with frameworks like PermaNET and GlaRiskAlp, enriching their applications by addressing the specific impacts of glacier melting. In addition, the presented work complements existing studies on rockfall susceptibility along the regional road network of Valle d'Aosta [94–96]. The presented results and methods can also be related with other works focusing on rockfall susceptibility and rockfall hazard estimation in northwestern Italian Alps [97,98].

While the presented methodology demonstrates significant potential, several areas for future research can be identified.

Modelling of triggering factors. It must be specified that in this the work, the knowledge of the mechanisms and contexts of landslide activation is not detailed enough to identify a dominant factor; therefore, the influence of each factor is equal. Giving weight to the various hazard indices according to the type of event that may occur could provide useful information, especially regarding the choice of mitigation measures to be implemented. This work can be the basis for detailed geological and geomorphological investigations, which can only be carried out in field surveys. Through careful on-site work, factors such as the removable debris potential could be determined; unstable material, identified; and the thickness and grain size of the glacial till, estimated. It could also be assessed whether this material is able to be conveyed to accumulation areas by analyzing the degree of connection of the runoff network, and the possible presence of factors that may lead to sudden water releases (proglacial lake basins, abnormal increases in runoff during rainfall, snow or glacial masses susceptible to rapid melting). Finally, it would have been useful to assess the degree of fracturing of the rocks by means of various geomechanical surveys.

Dynamic data updating. Updating data is also a very important element of this work. The identification of a risk situation is never a definitive operation that is carried out once and is effective forever, but rather a work in progress. An ideal update frequency is suggested in the previous sections. The data can be subdivided into those points that are static and those that are dynamic and need to be updated regularly. Examples of static datasets are related to geology, soil types, geomorphology, and morphography. The time frame for the updating of dynamic data may range from hours and days, for example, for meteorological data and its effect on slope movements, to months and years for land use and population data.

Improve knowledge in the mechanism of rock instability. Additionally, a more in-depth study of landslide-triggering factors could help identify key elements necessary for calibrating the method, enhancing the framework's precision. This would also support the establishment of thresholds for various parameters used in the analysis. When defining these threshold parameters, the availability of historical events in the area can provide valuable data to further refine and calibrate the indices. Finally, it is essential to consider data timeliness to ensure that all information is temporally aligned for consistency across analyses.

Socio-Economic Impacts. This study can also be the starting point for an economic estimate of the assets subject to natural hazards. Above, we are talking all about high-altitude ski facilities, and all the tourist and accommodation activities that surround this sector, but also about paths, natural areas that could be damaged, riverbanks to be rebuilt, and so on.

Integration with Machine Learning: Combining the deterministic GIS framework with machine learning algorithms could uncover non-linear patterns in slope instability risks and improve hazard prediction.

Longitudinal Studies: Monitoring changes in risk levels over time, especially in response to ongoing glacier retreat and climate change, could provide valuable insights for adaptive risk management.

Improving coordination. Coordination between different municipalities (and at a higher level between different countries) in landslide disaster risk management is fundamental, including the drafting of emergency plans and the development of structural and non-structural measures. A low level of coordination between single municipality leads to a final representation of the surface process dynamics that is heterogeneous and incomplete and that henceforth generates unsatisfactory basin-scale planning. The approach proposed in this work overcomes most of such weaknesses, at least on a regional scale.

Expansion to Other Regions: Testing the methodology in other mountainous regions worldwide would validate the proposed approach's robustness and highlight necessary adjustments for different geographical and climatic contexts.

Sensibility analysis. Finally, it should also be recalled that estimates of risk are inevitably approximate and should not be considered as absolute values. This is best understood by allowing for the uncertainty in the input parameters, and in reporting the risk analysis outcomes. Furthermore, tolerable risk criteria are themselves not absolute boundaries. The level of risk acceptability is not universally defined: society shows a wide range of tolerance to risk, and the risk criteria are only a mathematical expression of the assessment of general societal opinion.

7. Conclusions

Due to climate change effects, land protection and the need to integrate environmental risk mitigation measures into regional strategies and planning are becoming increasingly important. In this regard, the aim of this work was to provide more specificity to the values of glacier retreat and shrinkage, with the aim of assessing the hazard resulting from these phenomena in relation to the risks arising from possible gravitational movements and landslides that could occur in deglaciated areas. In particular, this work presented a procedure for assessing and mapping landslide susceptibility and the associated risk relating to glacier melting phenomena and consequent slope instabilities. The primary aim of this study was to provide a risk map to support local governments in identifying priorities for the design of appropriate mitigation plans. Valle d'Aosta was chosen as a "testing ground" for glacial risk research, especially regarding the associated landslide risk, which involves all the municipalities in the region.

The assessment was divided into regional and municipal/local analysis.

At the regional scale, the assessment was conducted using nine hazard indices taken from different bibliographic sources and sector manuals, aiming to provide the most complete framework possible. The research adopted a multidisciplinary approach, as required by the complexity of the landslide phenomena, whose occurrence is determined by a series of interrelated factors, categorized into environmental conditions and triggering factors. While numerous methods and examples exist concerning the assessment and computation of individual sub-components, there is still a lack of applications of the entire risk assessment procedure over large areas, where the final result can be directly used for designing risk mitigation policies at the regional and municipal levels. The final result of this first phase is a susceptibility to landslide movements map, which shows the territory's propensity for the occurrence of landslide phenomena in relation to different combinations of predisposing factors.

For the municipal level, the methodology was further refined using higher-resolution data and by integrating in situ analysis in order to properly evaluate vulnerability, whose estimate at the regional scale is very difficult. For the local scale, the developed methodology was tested in the final section of the Lys River valley, categorized as a high-risk area in Valle d'Aosta. In particular, the final stretch of the valley was examined, through five steps: (i) improved hazard calculation; (ii) site survey and vulnerability assessment; (iii) worth exposed analysis; (iv) estimation of potential damage; and (v) aggregated risk score computation.

The risk calculation presented in this paper is part of a broader process within landslide disaster risk management (DRM), in which hazard definition and risk calculation are fundamental phases that allow the development of strategies aiming to strengthen the resilience of a community affected by natural hazards. Changes driven by climate change pose new challenges to territorial planning and governance, requiring intervention in the **connective tissue** between environmental and territorial components, evaluating their interactions comprehensively. For planners, urbanists, or project developers, this necessitates an enhanced capacity for interdisciplinary knowledge exchange with disaster-related experts and technicians, the consideration of an increasing number of variables (and associated uncertainties), and an expansion of spatial and temporal scales in analyses.

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