# Global Drivers, local consequences: assessing geodiversity and geosystem services for global change adaptation and sustainable development of Mountain Regions – Examples from the Monte Rosa W-Alps

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# Dedication

This thesis is dedicated to the loving memory of my sister.

(1997-2021)

# Acknowledgements

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# Abstract

This study investigates effective approaches to conserve geodiversity and the associated services of geosystems in mountain regions, which are particularly susceptible to the effects of climate change and human activities. It involves extensive data collection from online sources and local authorities, focusing on the identification and documentation of geosites in the Alagna Valsesia region of the Western Italian Alps, situated within the Sesia Val Grande UNESCO Global Geopark. A key aspect of this research is the adoption of an evaluation method, developed by Suzuki and Takagi in 2018, for assessing geosites. This method is specifically applied to study geomorphological landscapes and geological processes that have natural or cultural significance. The practicality of this evaluation approach is demonstrated through its application to eight selected geosites in Alagna Valsesia. The findings provide a clear overview of the current state of these geosites, highlighting their promotional strengths and weaknesses, and offering a valuable framework for the planning and development of geotourism sites.

A central element of the research is a comprehensive analysis of geosystem services in Alagna Valsesia. This includes creating a detailed map (1:10,000 scale) that illustrates the distribution of services provided by the area's geodiversity. The map serves a dual purpose: it demonstrates how unique landforms contribute to societal services and outlines the risks posed by morphodynamic processes to human activities. This geosystem services map is proposed as a tool to aid in the effective planning and management of mountainous areas, particularly those affected by climate change and human intervention, within the context of sustainable development.

The study employs the Drivers-Pressures-State-Impact-Response (DPSIR) framework, a widely used method in environmental policy and management. This framework helps in understanding the complex interactions between geodiversity and the provision of geosystem services in mountain landscapes. Through the review of relevant literature and policy documents, a DPSIR framework is developed, characterizing the impacts of various factors such as tourism, infrastructure development, and natural phenomena like climate change on key geosystem services. This framework operates on two levels: initially identifying the components of DPSIR, and then delving deeper into the cause-effect relationships between different aspects of geodiversity and their cascading impacts on geosystem services. This approach helps to identify knowledge gaps, particularly concerning the effects of natural processes and human interactions on geodiversity and geosystem services. The study reveals negative impacts on geodiversity and a range of geosystems, suggesting that these issues can be effectively addressed only with targeted policies. The two-step DPSIR approach developed here is seen as beneficial for modeling other complex systems where management is hindered by knowledge gaps. The research findings indicate that climate change, as a driving factor, has significantly impacted geodiversity and the provision of geosystem services in the area. Glacial and fluvial processes, as pressures, have markedly affected these services. The state of geosystems has been reduced due to a variety of morphogenetic agents, processes, and human activities, particularly those supporting the skiing industry. The study highlights only the negative impacts, showing changes in landforms and loss of geodiversity. In terms of response, it proposes actionable insights for policymaking and conservation efforts.

These insights not only highlight the current challenges faced by these unique geosystems but also offer practical strategies for their preservation and sustainable development. This study, therefore, contributes significantly to the field of geodiversity conservation and serves as a model for similar analyses in other vulnerable regions worldwide.

# Table of Contents

# List of figures

# List of tables

# Chapter 1 Introduction

## 1.1 State of the art

Geodiversity is the intricate relationship between geology, soil, and geomorphology, and their role in shaping natural and cultural landscapes and their functioning within the global system is a matter of critical significance. Geodiversity encompasses the complexity and variety of rocks, minerals, landforms, and the processes that shape them, making it more than a simple inventory of Earth's geological characteristics (Gray, 2004). Geodiversity is regarded as an invaluable element and strongly correlates with biodiversity. The bedrock, soils, and terrain, all products of geological formations and processes, are fundamental in determining the distribution of plants, animal habitats, and hydrological systems, thus establishing a direct connection between geosystem and ecosystem services. The composition of certain geological factors that create a favorable non-living environment supports biodiversity (Bravo-Cuevas et al., 2021). The Earth's geodiversity crucially participates in the supply of geosystem services; these are the essential benefits humanity gets from the geosphere and its processes. Similar to the ecosystem services concept which acknowledges the contributions of the living part of nature (Millennium Ecosystem Assessment, 2005), geosystem services aim to highlight the services provided by the abiotic, non-living parts of the environment, particularly those stemming from the subsurface (Frisk et al., 2022). Since in the recent literature there is more than one single understanding of geosystem services concept, it is specified that in this thesis the most comprehensive definition of geosystem services is chosen; namely the one including both surface and subsurface abiotic features. The importance of nature conservation extends beyond the environment, encompassing both human welfare and monetary aspects. The spiritual, cultural, and artistic advantages that individuals get from the preservation of nature are invaluable and at risk of being jeopardized if the environment deteriorates. Particularly, in the case of abiotic nature elements of particular interest are considered to be geoheritage (for example geosites that provide important geoheritage) and to prevent their loss discipline of geoconservation has been introduced. Geoheritage comprises those elements of natural geodiversity which are of significant value to humans for non-depleting purposes which do not decrease their intrinsic or ecological value (Sharples, 2002). Geosites are defined as “site location area or territory in which it is possible to identify a geological or geomorphological interest for conservation” (Wimbledon et al., 1995), or, more recently, as “key localities of particular geological interest” (Brilha et al., 2018; Newsome & Dowling, 2018).

Geoconservation involves the protection of those elements of geodiversity that have geoheritage value principally for scientific reasons, but also for supporting educational, cultural, aesthetic, spiritual and ecological values (Crofts et al., 2015; Gray et al., 2013). Nature conservancy also delivers concrete services, such as regulating natural hazards and providing minerals and energy (Tognetto et al., 2021; Van Ree & Van Beukering, 2016).

Recent studies have provided evidence that presents new knowledge, and a deeper understanding of the effect geodiversity will have on the evaluation of ecosystem services and neglecting it would limit the comprehension of how nature influences human welfare (Alahuhta et al., 2018; Fox et al., 2020; Salminen et al., 2023). Impacts caused by human activities are of great concern to geodiversity, especially sources of pollution, urban expansion, or resource exploitation and thus to the sustainability of these geosystem services (Balaguer et al., 2023; Silva et al., 2019). The importance of understanding how this aspect relates to the broader concept of the Anthropocene should not be overlooked, given that the Anthropocene is widely seen as a pivotal epoch either at the geological or in the social framework. In the context of the Anthropocene, it is essential to acknowledge and identify the impacts of human activities that contribute to the formation of a global stratigraphic boundary. This recognition could also extend to future efforts aimed at discerning these impacts by linking them to specific decades, either contemporary or recent, which are proposed as the onset of the Anthropocene. Currently, there lacks a universally accepted and clear definition of the Anthropocene, as well as agreement on its chronological boundaries. Nevertheless, it is possible to discern a number of global environmental changes that collectively suggest a new epoch markedly influenced by human activity (Lewis & Maslin, 2015). Moreover, this directs to the significant considerable influences on geodiversity for various human activities and natural processes such as: tectonic activity, erosion, climate change caused by human influence (Burek & Prosser, 2008; Steffen et al., 2015; Viles & Cutler, 2012). It is crucial to understand that changes in geodiversity can have a direct impact on the services the geosystems provide and thus leading to significant effects on human well-being (Barbier et al., 2011).

Despite the fact that there are an increasing number of scientific evidence on the subject, the complex linkages between geodiversity, geosystem services, human activities and natural processes continue to be overlooked due to the lack of studies in this environmental field. DPSIR framework can be used to understand these complex linkages more accurately and many cause-effect relationships developed in the environmental and socioeconomic changes (Smeets & Weterings, 1999; Zare et al., 2019). The study has two broad objectives: (i) to understand the dynamics and (ii) set management strategies of conservation and monitoring of geodiversity and sustainable provisioning of geosystem services. Moreover, under these objectives, this research has high potential to influence policy decision making as the increased anthropogenic pressures are mounting in the geosystems and ecosystems (geo-ecosystems).

## 1.2 Research Problem

Although, researchers increasingly comprehend that natural geodiversity is a fundamental influence on the formation of both natural and cultural landscapes and as is directly involved in maintaining biodiversity alongside geodiversity's direct provision of geosystem services, there is an obvious knowledge gap including where information is disseminated on the inter-relationships between geodiversity, geosystem services, human activities, and natural processes. Recent studies (Alahuhta et al., 2018; Salminen et al., 2023) indicate that geodiversity must be integrated into the assessment of ecosystem services. However, explicit anthropic and natural drivers of geodiversity and their respective geosystem services are uneasy to pinpoint.

Also, the application of the DPSIR framework represents a novel approach in the context of geodiversity research. While the DPSIR framework has been widely used in environmental sciences to structure cause-and-effect relationships for various ecosystems (Maxim et al., 2009; Smeets & Weterings, 1999), its explicit application to geodiversity, geosystem services, and their interlinkages with anthropogenic activities and natural processes is less explored. This gap is significant, given the increasing recognition of geodiversity contributions to biodiversity and ecosystem service provision (Crutzen & Stoermer, 2021; Gray et al., 2013; Hjort & Luoto, 2010; Steffen et al., 2011).

Furthermore, the DPSIR framework underlies the capacity to enhance the management of geodiversity amidst the complexities of the Anthropocene epoch. Recognized for the profound influence of human activities on natural processes, the Anthropocene epoch demands a refined and nuanced approach to environmental stewardship (Crutzen & Stoermer, 2021; Steffen et al., 2011). Thus, the criticality of embedding geodiversity considerations within the DPSIR framework to elucidate the multifaceted drivers of geodiversity alterations and their consequent impacts on ecosystem functionality and geosystem service delivery (Gordon et al., 2012; Smeets & Weterings, 1999). Such an integration not only augments the geological and ecological (geo-ecological) discourse (Gray, 2013; Martínez-Harms & Balvanera, 2012) but also establishes foundational principles for the development of effective conservation and management strategies aimed at countering the negative ramifications of anthropogenic environmental disruptions (Haines-Young & Potschin, 2010; Selman, 2004). This approach fosters a comprehensive understanding that bridges the gap between geodiversity and ecosystem services, advocating for a holistic environmental management approach crucial in the Anthropocene epoch (Waters et al., 2016; Zalasiewicz et al., 2010).

Consequently, the pressing research problem emerges: How do anthropogenic activities and natural processes impact geodiversity, and what are the subsequent implications for the functioning and sustainability of geosystem services? Addressing this problem is crucial for the academic understanding of geo-ecological dynamics and imperative for formulating effective conservation and management strategies in the face of escalating human-induced environmental changes.

## 1.3 Research Objectives

The objectives of a research study function as guiding principles, providing clarity and direction for the investigation's progression. They ensure that the investigation maintains a clear and specific direction, has a meaningful purpose, and produces significant effects or outcomes. Within the framework of our research, it is crucial to establish precise objectives that address the fundamental research issue that has been established. Therefore, the aims of this research are multi-faceted.

First, the study seeks to explain how human activities such as tourism, recreation, and infrastructure development, as well as natural processes like erosion, weathering, and climate change, exert influence on geodiversity. This is vital for understanding the complex interplay between human actions, changes in the environment, and geodiversity. Second, the investigation aims to understand the implications of changes in geodiversity on the functionality of geosystem services. As a result, this will contribute to our understanding of the potential consequences that changes in the geosphere can have on human well-being, ecosystem balance, and the interplay between nature and human activities. Third, utilizing the gained insights, the study aims to formulate and recommend sustainable management policies, strategies, and initiatives to alleviate the adverse impacts of human and environmental activities on geodiversity and geosystem services. Last, through the utilization of the DPSIR framework, the study aims to offer a methodical and organized examination of the interconnectedness, interplay, and impact of diverse factors on geodiversity and the resulting geosystem services. This study aims to address the existing information gap and significantly contribute to the development of evidence-based policy decisions and the implementation of comprehensive conservation initiatives.

## 1.4 Research Significance

Certainly, the significance of the subject matter should not be underestimated, particularly in the research field of geodiversity and geosystem services. The research contributes to scholarly understanding about the interrelation between geodiversity, geosystem services, human activities and natural phenomena. On this basis, comprehensive and complex interconnection of the subject matter are being addressed in the research. Also, the research highlights aspects that tend to be unclear or have not been researched in depth. This work has considerable value as it provides insights into the environmental consequences of human-nature interactions, with particular focus on terrestrial ecosystems, providing an extensive examination of the impacts of human and non-human factors on the physical environment. In the current era of rapid global environmental change, which has been largely attributable to human activities, it is essential to understand the dynamics of the environment in order to tackle the challenges the Anthropocene epoch throws down for academicians and scientists, as well as policymakers and stakeholders, conservation practitioners, and communities.

Furthermore, the focus of this research on the DPSIR framework presents a novel approach compared to its peer studies. The research introduced itself as a key, rational methodology that can be implemented and modified by future research studies improving the scope of research tool kit available to assess similar environmental components. Additionally, the study points out the significance of changes in geodiversity for the functioning and provision of geosystem services, also highlighting the relationships with societal well-being. This study establishes a clear link with socio-economic outcomes to emphasize that the protection of geodiversity is not only of concern for the environment but for the regional and societal welfare, economic stability, and cultural preservation.

Moreover, the significance of the research is highlighted by the practical implications. The findings of this research provide evidence that helps to influence policy decisions, conservation initiatives, and community action through practicable management suggestions. Therefore, the research results give the opportunity to fill the gap between the understanding and the practical implementation by actionable insights. Finally, beyond the academic contribution, the research has relevance for a variety of stakeholders including policy makers and local communities, influencing the conversation around geodiversity and sustainable provision of geosystem services. Given the grave context in which our planet evolves significant environmental degradation and human intervention and often destruction. The research serves as the foundation and guide to more sustainable and harmonious coexistence with the geosphere.

## 1.5 Innovative Points

This study breaks new ground in the emerging field of geodiversity and geosystem services research in a number of ways. Most importantly, it is developing new understandings and ideas about the subject concerned and thus laying the foundations for further work. Examples of the innovative elements of the study include:

1. Holistic exploration and analysis of pressures: rather than usual studies, the research focuses extensively on the intricate relationship between human activities, for example, tourism, recreation, infrastructure expansion and the role of natural processes. Such a multifaceted manner results into a more enhanced form of comprehension on the forces affecting geodiversity.
2. Application of the DPSIR framework: use of the DPSIR framework is a novel approach in this geodiversity research. By using this tool to examine the complicated cause-and-effect dynamics, this investigation can lend a more structured and more systematic approach to the analysis, which can potentially be used as a guide for future studies.
3. Practical and actionable insights: a key attribute of this research is its non-theoretical nature and strives for sustainable management solutions as an output from the research. This is designed to ensure the importance of the research to a range of stakeholders from policy makers to local communities.
4. In depth knowledge of geodiversity and geosystem services: though previous studies have noted the connection between geodiversity and geosystem services, this study delves into the subject with a depth and breadth that expands upon earlier research in this field. The study offers comprehensive treatment of the causal relationship, particularly as it affects human well-being and balance of ecosystems, makes this study an innovative stature.

Furthermore, these innovative points will set up the research impact in its academic and practical significances in the geodiversity and geosystem services research field.

## 1.6 Research method

The author evaluated the integration on the effects for geodiversity and geosystem services from different actions. The research process was initiated by collecting requisite data from diverse sources which included data from online resources and direct data from the municipality. After conducting data collection, the next step was processing it for data digitization by loading the data gathered into Quantum GIS (QGIS) software, making sure there is no ambiguity in the accuracy of data that have been collected, the data were georeferenced and systematically managed utilizing geospatial information system (GIS) geodatabase. In the subsequent step, we proceeded with mapping the different geosystem services of Alagna Valsesia using the methodology developed by Tognetto et al. (2021) which is based on the classification presented by Gray (2013). To provide a comprehensive understanding of the key aspects of the human-nature linkages, the DPSIR framework (Driving-Pressure-State-Impact-Response) is utilized in this study. An analysis of DPSIR was used, to understand why these changes are happening (drivers); how the human activities inflict pressures on the environment (pressures); the current status of the geo and its subsystems (states); what are the consequences and synthetic measures of the system due to these changes (impacts); plans of action or measures that have been put in place to cope with the issues (response). This approach assists with the understanding of how all the human and natural components or activities fit together in the bigger picture using the concept of geodiversity and geosystem services putting into perspective the nature and human activities. Therefore, the integration of geodiversity and geosystem services takes into accounts the basic building blocks, which can be used to describe the relationship between the natural and human components and provide an integrative approach to our research question.

## 1.7 Organizational Structure of Research

The flowchart of the thesis structure is shown in figure 1-1. The subsequent chapters of this thesis are as follows;

The subsequent chapter 2 offers a comprehensive review of the pertinent literature, ensuring a robust foundation for the research and highlighting gaps in the current knowledge. Chapter 3, the methodology segment, reveals the research techniques and procedures, detailing how data was collected, the strategies employed for mapping geosystem services, and the rationale and application of the DPSIR framework. In chapter 4, the results are systematically presented, laying out the research findings. These results are then dissected in the discussion section, which interprets them in light of existing literature, offering a richer understanding. Finally, the conclusive chapter recaps the salient points of the study, discusses the broader implications of the findings, and suggests areas that could benefit from further exploration. Based on the thesis's main body, recommendations are proffered based on the interpreted findings, tailored for stakeholders, policymakers, or practitioners. The study also acknowledges any potential limitations faced during the research process and outlines avenues for future work. Concluding the document is a thorough list of references, citing all sources and literature that informed the research, accompanied by appendices containing supplementary materials and data.

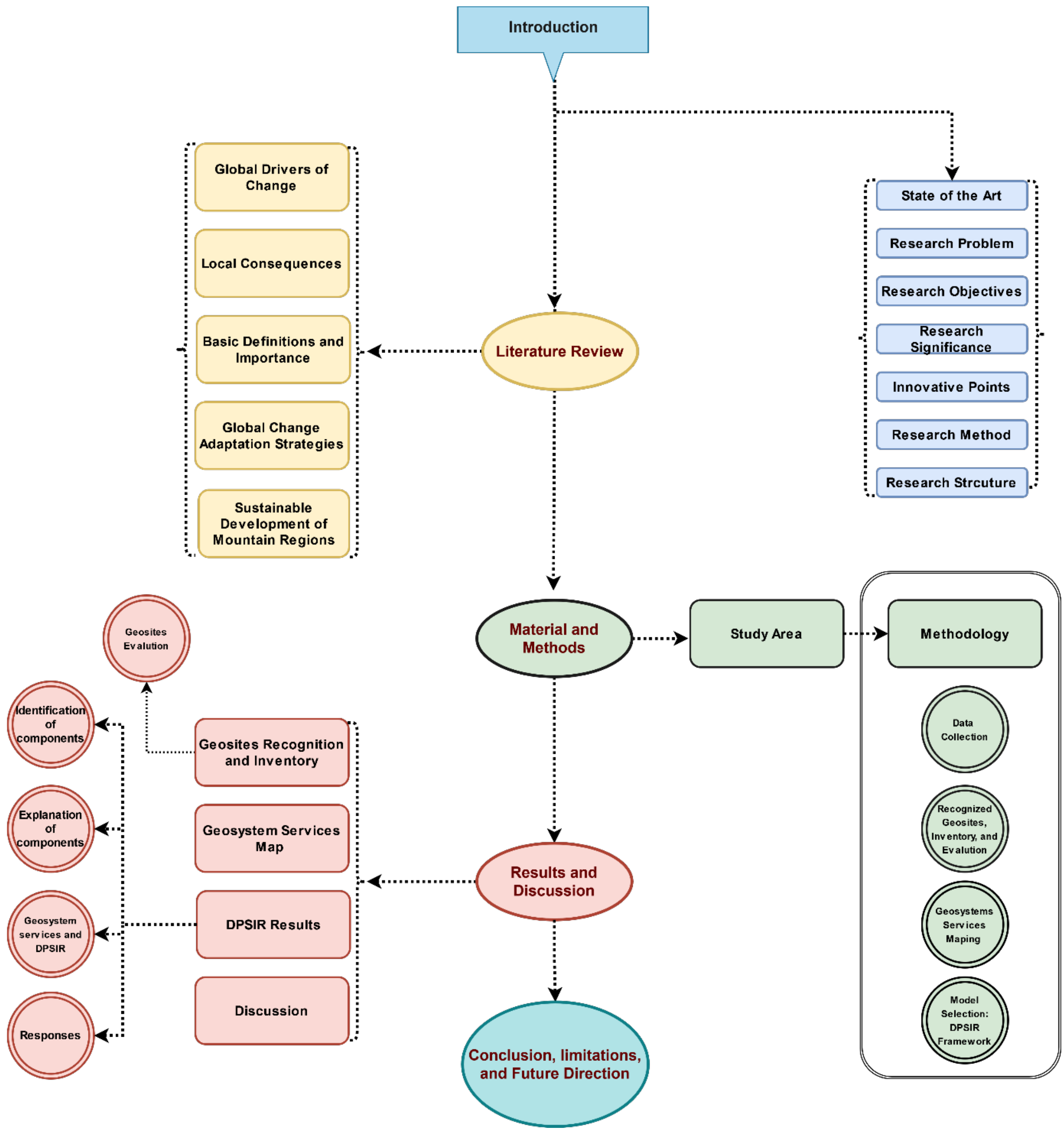


Figure 1-1: Organizational structure of the thesis (Source: Author contribution)

# Chapter 2 Literature Review

Not always are the mountain regions scenic areas but they are unique ecosystems providing a very wide range of services both to the environment and to the people who live in and rely on them. These services providers range from basic services such as fresh water supplies to highly specific ones such as raw materials and they may include climate regulation and a range of opportunities for recreation in addition to others. In the rapidly evolving global economy, the intricate equilibrium among varied geological components which collectively comprise these services is increasingly affected by both global and local changes. The Monte Rosa region in the Western Alps serves as a prime example within this study to illustrate the extensive impact of these changes on such a delicate equilibrium. These impacts of changes are also significant for several different reasons both to the regions themselves and to the world resource of new understanding and conservation techniques that will allow the maintenance of the modern mountain regions and their unique heritage as at present. Climate change, alongside specific human activities such as tourism, alpine sports, and infrastructure development in the Monte Rosa Western-Alps are inextricably linked with global drivers. These local activities can lead to alterations in soil composition, hydrogeological disruptions, and increased erosion, which directly affects the geological variety of the region. These changes in geodiversity, in turn, can influence global biogeochemical cycles and climate patterns, demonstrating the interconnectedness of local actions and global environmental shifts. For instance, tourism and sports increase the demand for transportation and amenities, adding to greenhouse gas emissions that drive global warming. Simultaneously, infrastructure developments can disrupt natural water flow and soil stability, which are already being altered by global climate patterns. These localized human actions reflect and magnify the impacts of broader global drivers, creating a feedback loop that further intensifies the environmental changes observed in mountain regions like the Monte Rosa Western-Alps. These changes in human activity are having huge repercussions on both the conservation capacity and the range of services which they offer the human and geographical world, those being increasing proportions of natural hazards, reductions in the level of biodiversity and increased rates of ecosystem services loss: a greater rate of conservation is required for these new sorts of regions. This review aims to comprehend the interplay between global drivers of change and their impacts at a local level, especially within mountain regions. The objective is to leverage an enhanced comprehension of these regions' climate-related intricacies to advocate for sustainable development approaches. These approaches should harness the often neglected and underutilized geodiversity of mountainous areas, fostering long-term sustainability and protection of these valuable geological resources.

To be able to develop adaptive strategies and promote sustainable practices it is important to understand how global drivers translate down into local consequences. The concept is part of the international agenda to promote resilience and sustainability in fragile ecosystems, by means of numerous international frameworks and agreements, and to nature conservation, which in recent years has begun to increasingly value the concepts of geodiversity and geosystem services as fundamental for the objectives pursued (Frisk et al., 2022). This literature review aims to explore how geodiversity and geosystem services for global change adaptation and sustainable development in mountains depend on the dynamics of global drivers and local consequences, focusing in particular on Monte Rosa W–Alps, by analyzing the adaptive strategies and sustainable processes that have been or could be initiated here (see figure 2-1).

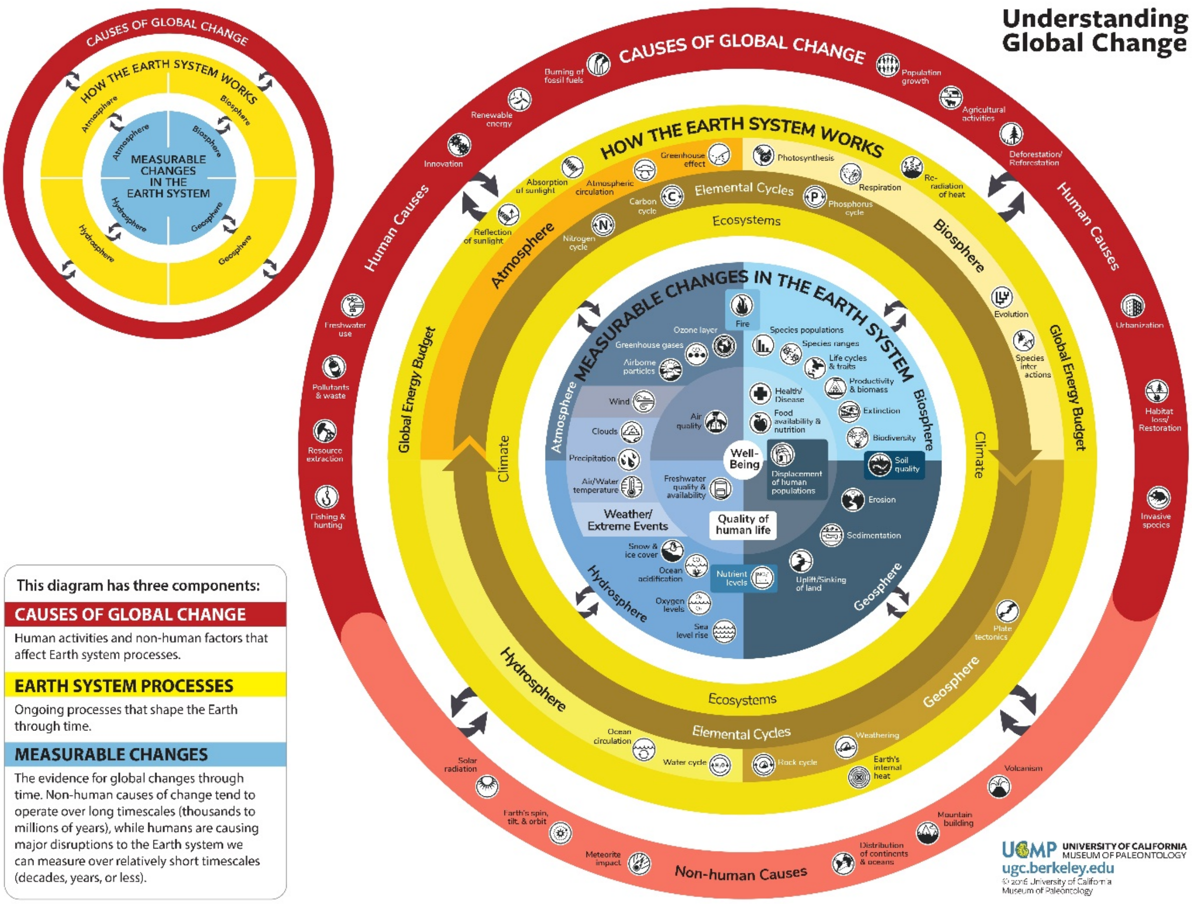


Figure 2-1: Infographic organizing the complexity of global change processes and phenomena (Source: University of California, Berkeley, Museum of Paleontology)

This review is an attempt to summarize current knowledge, identify knowledge gaps and suggest research directions and some policy instruments in the domain of global change adaptation and sustainable mountain development. The literature review that follows seeks to contribute to the study and enhance knowledge in the field, as well as providing practical materials to support stakeholders who need to begin or update the development process of policies and tools in their catchments.

The Monte Rosa W-Alps serves as a lens through which the challenges and opportunities that global changes engender in mountain regions are examined. Insights from recent research, such as Bollati et al. (2023) exploration of geodiversity in pro-glacial areas and its implications for geosystem services, explain the significant relationships between geodiversity, biodiversity, and geosystem services in mountain regions. Moreover, a synthesis of key works on mountain relief formation, geodiversity, and geo-biological connectivity alongside ongoing changes in mountain environments underscores the vulnerability of mountainous places and the critical need for adaptive and sustainable strategies (Stanley et al., 2023). The narrative of global changes, geodiversity, and geosystem services in mountain regions, especially the Monte Rosa W-Alps, presents a compelling case for global change adaptation and sustainable development. This review endeavors to weave together the strands of existing knowledge, shed light on the gaps, and lay down a pathway for future research and policy initiatives to foster resilience and sustainable development in mountain regions amidst a changing global landscape.

## 2.1 Global Drivers of Change

### 2.1.1 Climate change

Climate change significantly impacts mountain regions, altering global temperature patterns affecting precipitation rates, snowfall patterns, and the overall climate regime. Glacial retreat is one of the most visible manifestations of climate change in mountainous areas, which affects geodiversity and has profound implications for geosystem services such as water supply and climate regulation. The changes in temperature and precipitation patterns further affect these regions' biodiversity and ecological balance, influencing their capacity to provide essential ecosystem services. The important interlinkages between climate change, geodiversity, and geosystem services cause a thorough understanding to devise effective adaptation and mitigation strategies. Several recent studies have explored these dynamics in various mountain regions, shedding light on the multidimensional impacts of climate change and proposing adaptive measures to mitigate adverse effects. Palomo (2017) highlights the heightened impact of climate change in mountain regions, evident through glacial retreat and its consequent effects on ecosystem services like water supply. His study further highlights how climate change affects ecosystem services and the well-being of people in high mountain areas through its impacts on food and feed, water availability, natural hazards regulation, spirituality and cultural identity, aesthetics, and recreation. Another assessment by Mark et al. (2017) shows that climate change impacts high mountain ecosystems, such as glaciers and wetlands, and may affect the availability of water resources crucial for human consumption, hydropower generation, and irrigation, particularly showcased in the Andes region.

Mountain regions are the most sensitive to climate change, with the 20th century experiencing above-average warming compared to the global mean. Mountains provide some of the clearest indicators of global warming, making them critical regions for studying climate change impacts (Pepin et al., 2022). The Vanishing Treasures project (2018-2022) aimed to enhance the synergy between climate change adaptation and biodiversity conservation in mountain ecosystems, emphasizing the importance of maintaining ecosystem services and protecting key species to ensure ecosystem functionality amid climate change threats (United Nations Environment Programme, 2021). The multifaceted impacts of climate change on mountain regions underscore the urgent need for adaptive strategies to safeguard geodiversity and ensure the continued provision of essential geosystem services. The findings from these studies and projects contribute to the burgeoning body of knowledge on global change adaptation and sustainable development in mountain regions, setting the stage for further research and policy interventions to foster resilience and sustainable development in these fragile ecosystems.

### 2.1.2 Human activity

The breadth of human activities, including urbanization, agriculture, mining, and tourism, significantly alters mountain landscapes. These activities often result in land degradation, habitat fragmentation, and loss of biodiversity, affecting the geodiversity and the provision of geosystem services in mountain regions (Chakraborty, 2021). For instance, constructing infrastructure for tourism or mining operations can cause soil erosion, disrupt water flow, and lead to the loss of unique geological features. Moreover, pollution emanating from human settlements and activities poses another pressing concern. The cumulative effects of these activities exacerbate the vulnerability of mountain regions to global changes, emphasizing the need for regulatory measures and the promotion of sustainable practices to preserve geodiversity and ensure the continuous provision of geosystem services in mountain regions.

According to Chiarle et al. (2021), local human activities alongside global factors have caused imbalances in mountain regions, leading to significant changes in these environments. A notable impact of rising temperatures, exacerbated by human activities, is the melting of glaciers. This phenomenon causes changes in the pressure on adjacent slopes and increases their instability, leading to mass movements. A study by Stanley et al. (2023) states that geodiversity and geosystem services are foundational for conservation efforts in mountain regions. However, the human dimensions of a mountain's abiotic nature require integrated approaches for effective conservation. The study further explores the potential of public participation in Geographic Information Systems (GIS) in understanding and addressing the impacts of human activities on geodiversity and geosystem services. Tenerelli et al. (2016) highlights the importance of mountain environments for providing cultural ecosystem services (CES), usually defined as the non-material benefits originating from human interactions with ecosystems. These interactions encompass recreational opportunities, aesthetic landscape enjoyment, and inspiration, all affected by human activities in these regions. Furthermore, Pătru-Stupariu et al. (2020) reviewed mountain land use and ecosystem services and acknowledged a wide consensus on the susceptibility of mountain ecosystems to severe impacts on biodiversity and human well-being due to climate and land use changes. These changes, often driven by human activities, underscore the critical need for sustainable land use practices to mitigate adverse effects on biodiversity and ecosystem services in mountain regions.

In summary, the literature underscores the significant impacts of human activities on geodiversity and geosystem services in mountain regions. These impacts necessitate formulating and implementing sustainable practices and regulatory measures to mitigate adverse effects and promote the sustainable development of mountain regions. The discourse also suggests a need for further research to explore integrated conservation and sustainable development approaches in these fragile ecosystems amidst ongoing human activities.

### 2.1.3 Economic Development

Economic development, while essential for elevating the living standards of communities in and around mountain regions, can pose significant challenges. The drive for economic growth often leads to the exploitation of natural resources, potentially depleting geodiversity and hindering the provision of geosystem services. Moreover, introducing non-native species for economic purposes, such as agriculture or aquaculture, can alter the ecological balance, further impacting geodiversity. Balancing economic development with conservation and sustainable management of natural resources is a complex endeavor. It necessitates a multifaceted approach that amalgamates policy frameworks, community engagement, and technological innovations to ensure that economic development does not come at the cost of environmental sustainability.

Mengist et al. (2020) systematically reviewed ecosystem services research in mountainous regions, highlighting economic development's impacts on biodiversity, ecotourism, and other human needs. It also emphasizes the need to evaluate the relative impacts of climate and economic changes on forest and agricultural ecosystem services in mountain regions, showcasing the intertwined nature of economic development and environmental sustainability. According to Martín-López et al. (2019), a significant portion of the global population relies on goods and services provided by mountain regions, including fresh water, raw materials, and recreation such as those defined as geosystem services by Fox et al. (2020). However, these regions worldwide face multiple challenges because of environmental and socio-economic changes, impacting human livelihood, the economy, and ecosystems. Briner et al. (2013) stressed that the provisioning of ecosystem services in mountainous regions is predicted to be influenced by direct biophysical impacts of climate change, climate-mediated land use change, and socio-economic-driven changes in land use. The study underscores the complexity of understanding these factors' relative importance and spatial distribution on ecosystem services derived from forests and agriculture, further accentuating the necessity for multidimensional approaches toward sustainable economic development.

### 2.1.4 Impacts of Global Change

Like many mountainous areas worldwide, the Monte Rosa region grapples with the juxtaposition of its natural splendor against the intensifying impacts of global changes. Zemp et al. (2015) extensive study on global glacier change provides insight into the alarming rates of global glacial retreat driven by escalating temperatures. As these glaciers recede, they unveil previously concealed mineral layers, which profoundly influence the geochemical dynamics of neighboring waterways. This transformation has implications for aquatic ecosystems and human settlements dependent on these water sources. Expanding on the region's biodiverse landscapes, Pepin et al. (2015) elucidated how mountainous species adjust their altitudinal habitats in response to shifting thermal zones. While this migration is an adaptation strategy, it potentially upsets the ecological balance. As species ascend, they intrude into pre-existing ecosystems, inducing new dynamics of competition and predation.

Considering the human dimension, Beniston et al. (2014) highlighted the challenges mountain regions face due to increasing tourism, particularly the rapid expansion of ski resorts. Although these recreational spots invigorate the local economy, their ecological implications, like habitat fragmentation and waste management issues, are of concern. Furthermore, Messerli et al. (2019) addressed the broader implications of infrastructural developments in mountain regions. If uncontrolled, expanding road networks and increasing urbanization might compromise the natural defenses against geo-hazards such as avalanches and landslides. Taking a holistic view, Klein et al. (2019) synthesized the challenges and consequences of global changes in mountain areas. Their comprehensive review underscores the complex balance between conservation imperatives and development pursuits, emphasizing the need for sustainable strategies that appreciate the multifaceted impacts of global change on regions like Monte Rosa.

## 2.2 Local Consequences

The narrative of global drivers such as climate change, human activity, and economic development in mountain regions inevitably transitions into discussing local consequences. The manifestation of these global drivers at the local level brings forth an excess of impacts, particularly environmental degradation, socio-economic ramifications, and changes in land use. The interplay between these factors further stresses the vulnerability of mountain regions, emphasizing the imperative for well-informed, adaptive, and sustainable approaches to mitigate adverse effects and foster resilience.

### 2.2.1 Environmental Degradation

Global drivers, including climate change, economic development, and human activity, are the primary causes of environmental degradation in mountain regions previously discussed. The perturbations induced by climate change, human activities, and economic pursuits manifest in various forms of degradation that imperil geodiversity and undermine the provision of essential geosystem services. Climate change, for instance, accelerates glacial melt, disrupts hydrological cycles, and exacerbates extreme weather events (Kumar et al., 2021). Human activities, such as deforestation, mining, and urbanization, contribute to soil erosion, habitat fragmentation, and biodiversity loss (Scanes, 2018). Economic pursuits often result in over-exploitation of natural resources, depleting the geodiversity (Gray, 2021).

A narrative from various studies delineates the degradation processes and their repercussions on mountain ecosystems (Bamutaze, 2015; Bernhardt et al., 2012). According to Pant et al. (2023) on mountain landscapes, the impacts of global change on ecosystem services (ES), protected areas, and the exigent need for sustainable management strategies are underscored to confront the present and forthcoming challenges in mountain landscapes. Another study by Emmer et al. (2021) elaborates on the geo-hazards and risks in high mountain regions, detailing the retreat and thinning of glaciers, formation of glacial lakes, degradation of mountain permafrost, and alterations to mountain stream hydrology as salient indicators of environmental degradation. The growth of settlements and infrastructure development, along with large hydropower projects, further exacerbate the degradation of mountain environments. Furthermore, a systematic review conducted by Vilakazi and Mukwada (2023) stresses the severe sensitivity of mountain areas, with their unique biodiversity, to climate change and land degradation. It calls for swift actions to curb land degradation in mountain areas, appraising various global strategic methods to mitigate and sustain mountainous areas.

Moreover, a study by Rashid et al. (2022) on ecosystem and hydrological responses in mountain ecosystems explains the threats posed by an increased anthropogenic footprint and climatic changes. These alterations directly impact the livelihoods of communities living in the foothills, manifesting through an upward shift of the tree line, changes in land systems vis-à-vis vegetation dynamics associated with the shrinkage of alpine grasslands, and expansion of scrublands. The degradation of environmental assets in mountain regions adversely affects their capacity to sequester carbon, regulate water flow, and support biodiversity. The resultant disruptions affect the livelihoods of communities in and around these regions, showcasing the interconnectedness of environmental health and human well-being. In summation, the literature presents a nuanced understanding of environmental degradation in mountain regions, highlighting the multifaceted impacts of global drivers. The narrative underscores the critical need for sustainable management strategies to mitigate the adverse effects of environmental degradation and ensure the continuous provision of vital geosystem services for the well-being of the natural and human systems.

### 2.2.2 Socio-economic impact

The socio-economic impacts of global drivers on mountain regions can be profound, often tied closely to environmental degradation and changes in land use. Exploiting natural resources driven by economic development can challenge the traditional livelihoods dependent on these resources. Moreover, the stressors induced by climate change, like altered precipitation patterns and increased frequency of natural disasters, further exacerbate socio-economic challenges. These changes can affect income-generating activities and impose additional costs for adaptation and mitigation, affecting the overall socio-economic fabric of these regions.

Several studies underscore the complex socio-economic dynamics in mountain regions. For instance, utilizing local knowledge alongside modern scientific insights has been suggested as a viable approach to address socio-economic challenges and leverage the unique geodiversity and geosystem services in mountain regions (Schirpke et al., 2021). Mountain landscapes are viewed as social-ecological systems providing multiple ecosystem services that contribute to the well-being of local and downstream communities. These landscapes exhibit rich cultural and biological diversity, and their sustainable management is crucial for promoting environmental stability and community well-being (Schirpke et al., 2021). The socio-economic changes and spatial impacts over the last four decades have transformed mountain areas, and these transformations are closely tied to environmental and socio-economic factors. The pressure exerted by agriculture leads to a trade-off between human activities and resource preservation, highlighting the need for a balanced approach to socio-economic development in these regions (Chakraborty, 2021).

Furthermore, the integration of protected areas and sustainable management strategies is critical to tackling the challenges and leveraging the opportunities presented by mountain landscapes for sustainable development (Stanley et al., 2023). The socio-economic characteristics of mountains, including ethnic diversity, marginality, and migration, are significant factors that need consideration when designing interventions for these regions (Tran et al., 2021). In summary, as shown in fig 2-2, the socio-economic impacts in mountain regions are multifaceted, deriving from global drivers like climate change and economic development. A holistic understanding of these dynamics, community engagement, and integrating modern scientific insights with local knowledge are essential for devising sustainable development strategies to navigate the complex challenges and opportunities mountain landscapes present.

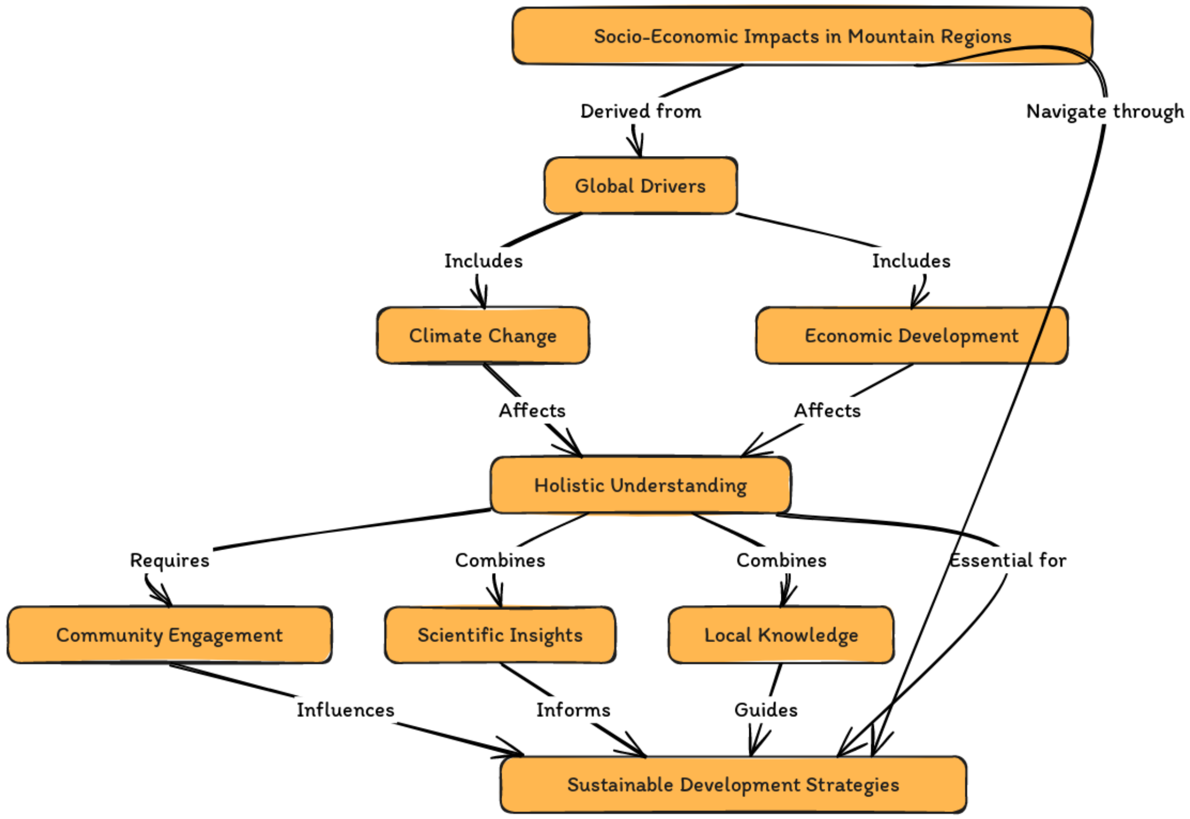


Figure 2-2: Interconnected dynamics of socio-economic impacts in mountain regions (Source: author contribution)

### 2.2.3 Land Use Changes

Land use alteration in mountain regions is a consequential local manifestation of global drivers, leading not only to the conversion of land for agriculture, urbanization, and industrial activities in pursuit of economic development but also to the abandonment of settlements, pastures, and agricultural lands. This abandonment, often spurred by urbanization and migration towards cities for better economic opportunities, contributes to significant socio-ecological changes, impacting biodiversity, landscape integrity, and the preservation of cultural heritage. Both types of land use changes; conversion and abandonment profoundly affect the geodiversity, biodiversity, and provision of geosystem services in these regions. This is particularly evident when combined with climate change-induced variations in vegetation zones and water availability. Furthermore, such land use changes often lead to habitat fragmentation, soil degradation, and increased vulnerability to natural disasters, underscoring the multifaceted impacts of global drivers on mountain regions. Several studies have investigated mountain regions' dynamics and repercussions of land use changes. For instance, a systematic review conducted by Jiménez-Olivencia et al. (2021) on Euro-Mediterranean mountain regions underscore these areas' socio-economic and environmental roles, shaped by the specific limitations imposed by their natural environment. Pătru-Stupariu et al. (2020) review aimed at assessing the impact of land use changes on mountain regions and the related ecosystem services underlines the importance of quantitative methods in evaluating these changes and their effects.

A study by Resler and Gunya (2022) explains the trends of land use and land cover changes in mountain regions worldwide, identifying a pattern of changes that has broader implications for the geosystem services provided by these regions. Moreover, Stanley et al. (2023) stresses the relationship between past and current impacts on ecosystem services and land-use/cover changes, advocating for a holistic assessment of socio-ecological systems to mitigate the effects of global change. An evaluation of recent land-use and land-cover change in a mountain region in Veracruz exemplifies the tangible manifestations of these changes in a specific geographic locale, part of the Sierra Madre Oriental, highlighting the importance of evaluating and understanding these changes in a localized context (Espinoza-Guzmán et al., 2023).

The literature underscores the importance of sustainable land use practices in preserving geodiversity and ensuring the continuous provision of geosystem services in mountain regions. Sustainable land use is characterized by its ability to maintain ecological balance, support biodiversity, minimize environmental impact, and ensure the long-term availability of natural resources. Practices include habitat preservation, responsible resource management, land restoration, and adopting agricultural and forestry methods that align with the ecosystem's capacity. Promoting these practices requires the engagement of local communities, supportive policy frameworks, and the adoption of technological innovations. Through a well-coordinated approach that incorporates these elements, we can effectively address the challenges of land use changes while leveraging the unique opportunities afforded by the geodiversity and geosystem services of mountain regions.

## 2.3 Basic concepts, definitions, and importance

### 2.3.1 Conceptual frameworks for the relationship between environmental elements and anthropogenic activities

In addressing the interplay between humans and the geomorphological environment, the framework as shown in figure 2-3, modified from Panizza (1996) serves as a foundational construct that delineates the multifaceted relationship where human activities both affect and are affected by natural landforms and processes. This duality is further elaborated by Gray

(2013), who recognizes geodiversity as an asset offering technical, scientific, and cultural value, thereby emphasizing the intrinsic worth of the geomorphological environment. Simultaneously, the work of Sharples (2002) highlights the anthropogenic pressures that expedite natural processes, thus underscoring the active role of humans in geomorphological dynamics.

Moreover, studies by Crozier (2010) articulate the provision of ecosystem services by the geomorphological environment as indispensable to human survival and growth. The findings of Bar-Massada et al. (2014) back this up, as they highlight the ways in which human activities can enhance biotic and abiotic processes, which may have important environmental impacts. Such impacts, both detrimental and beneficial, are examined by Slaymaker (2009), who argues for a balanced approach towards managing the geomorphological environment to sustain its resources. Furthermore, the vulnerability of human societies to environmental hazards is a point of convergence in the literature, with Latrubesse et al. (2009) exploring the susceptibility to natural disasters as a consequence of both natural and human-induced factors. This notion is complemented by Smith (2013), who presents a nuanced understanding of risk as a product of the interaction between natural hazards and human vulnerability.

In considering the socioeconomic dimensions of this framework, Gray (2019) emphasized how geodiversity can translate into economic and cultural prosperity. Such socioeconomic benefits are integral to the broader conversation about geoconservation, as posited by Contillo et al. (2022), who advocates for the preservation of geomorphological integrity within the discourse of sustainable development. By modifying the framework based on Panizza (1996), we can understand the intricate dynamics of human-geomorphological interactions and assess the subsequent impacts and risks. It calls for a diligent approach to managing our geomorphological heritage (considering both natural resources and related services), as reinforced by Alexandrakis et al. (2019) in their comprehensive analysis of risk assessment for natural hazards (related pressures on human activities).

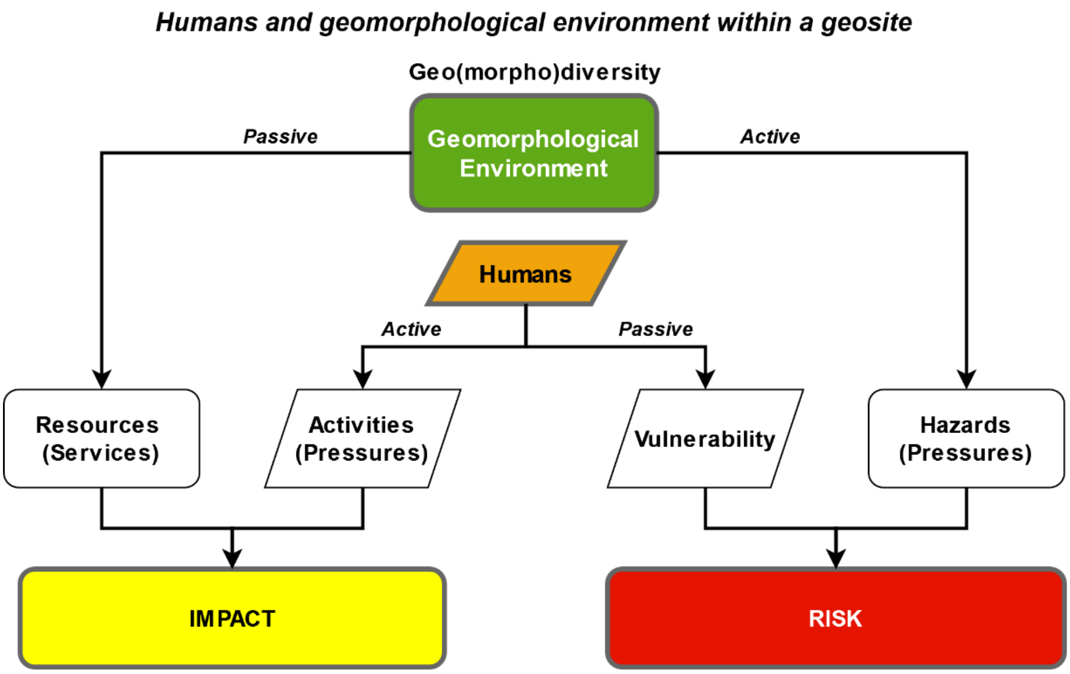


Figure 2-3: Diagram of the relationships and interactions between humans and the geomorphological environment (modified from Panizza, 1996)

Furthermore, in the domain of geomorphology and its intersection with tourism, Pralong and Reynard (2005) have constructed a conceptual framework as shown in figure 2-4, that explains the multifaceted interactions between natural geomorphological processes and the socio-economic factors driven by tourism. Their study proposes a global model that considers the intrinsic and derived value of geomorphological sites, integrating aspects such as natural processes, associated hazards, and the subsequent risks that shape the transformation of these geosites into tourism products. The framework defines how socio-economic drivers exert pressures, altering the state of natural sites, leading to changes that necessitate risk management and can result in various impacts on both the natural and socio-economic systems.

Additionally, the classification proposed by Pralong and Reynard (2005) of geomorphological sites based on their scenic, scientific, cultural, historical, and economic value allows for an analysis of the degree of exploitation, impacts, and the overall sustainability of tourism development. They argue that a profound understanding of these elements is essential to foster a tourism development that is both economically viable and environmentally sound, providing an anticipatory reference point for the sustainable management of geomorphological sites within the broader context of tourism and recreation. Within the modified conceptual framework, classification of single element of the sketch map has been proposed by attributing different colors related to the DPSI framework described in section 2.3.5.

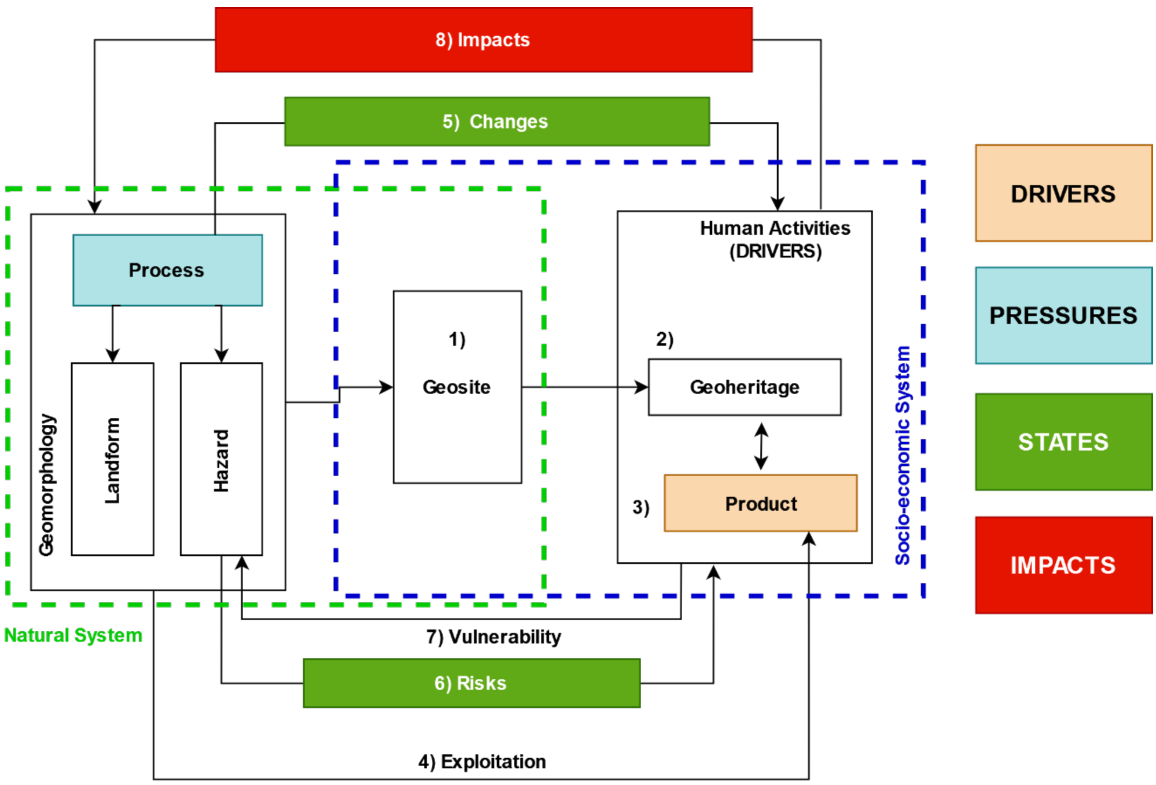


Figure 2-4: Conceptual framework for the relationships between geomorphology and tourism (modified from Pralong and Reynard 2005)

### 2.3.2 Geodiversity and geosystem services: Overview

The fundamental characteristics of the many ecosystems and landscapes of our globe can be attributed to its fundamental geodiversity. Geodiversity encompasses the complexity and variety of rocks, minerals, landforms, and the processes that shape them, making it more than a simple inventory of Earth's geological characteristics (Gray, 2004). According to Prosser et al. (2006), this enormous array is a dynamic continuum that reflects millennia of geological processes and the history they tell rather than a static image.

Any geological landmark, no matter how little, like a grain of mineral, may provide a tale about how Earth has changed over geological time. The face of the world has been molded by the movement of tectonic plates, water erosion, the push and pull of glacial ice, and volcanic heat, which have combined to create a complex tapestry of characteristics that affect ecosystems, climate, and even human civilizations (Knight & Harrison, 2013). Moreover, geodiversity's significance goes beyond its inherent worth. It creates the foundation and substrate on which ecosystems are constructed, affecting hydrology, plant and fauna distribution, and soil properties. Indirectly, geodiversity is essential to Earth's biodiversity because it shapes ecosystems and biological niches (Knight & Harrison, 2013). In addition to these, geodiversity has significant cultural, artistic, and spiritual ramifications. Numerous societies have held sacred mountains and mineral springs in high regard, imbuing them with religious or spiritual meaning. Throughout history, innumerable artists, poets, and intellectuals have drawn inspiration from the striking artistic splendor of some geological structures, such the Grand Canyon or the Giant's Causeway.

In the modern period of swiftly changing environmental conditions brought on by human activity, it is critical to comprehend and protect geodiversity. Numerous distinctive geological features and the priceless knowledge they contain run the risk of disappearing forever as urbanization grows and resource extraction increases. Therefore, conservation efforts must concentrate on both the underlying geodiversity and the living biodiversity.

### 2.3.3 Importance of Geosystem Services

Geosystem services, which arise from the complex network of geodiversity, are evidence of the concrete advantages that civilization enjoys from the Earth's geological resources. Although the idea of ecosystem services, a term used to describe the advantages of biological systems has been more popular in recent years Costanza et al. (1997), geosystem services are relatively new to be acknowledged as having equal significance.

Fundamentally, geosystem services show how geological and geomorphological elements contribute to human welfare. This can include providing services like mining and fossil fuel extraction, regulating services like natural water filtration in limestone regions, and cultural services like tourism and the preservation of significant cultural or spiritual value found in landscapes (Brilha et al., 2018). For example, mining districts are more than just mineral-rich areas. They represent regions where rich resources have been concentrated by geological processes over millennia, creating economic centers and forming trade routes and human settlements (Hooke, 2006). Aside from the material, the aesthetic and recreational benefits of distinctive geological formations, including landmark landforms or geoparks, attract millions of tourists each year, boosting local economies and encouraging respect for the planet's geological past (Newsome & Dowling, 2006). The fact that water is necessary for life further emphasizes the significance of geosystem services. Aquifers are fundamentally geological in origin, and they supply freshwater to a large proportion of the global population. Geological processes and characteristics control their size, flow, and rates of recharge. Analogously, the indispensable geosystem services include the natural purification processes that happen when water percolates through particular types of rock, providing clean drinking water (Brauman et al., 2007). Furthermore, it is impossible to overstate the protective functions that some geological features provide. Mangroves, for instance, are naturally occurring barriers against tsunamis that shield coastal settlements and lessen the possibility of disaster because of their unique sedimentary roots (Barbier et al., 2013).

It is essential to acknowledge, value, and preserve these geosystem functions. It is critical to comprehend the many ways that geodiversity enhances and supports our lives as civilization continues to expand and exploit resources at a rapid rate. The development of sustainable policies that guarantee the continuation of these services for the next generations is only possible with this acknowledgement.

### 2.3.4 Geodiversity role in ecosystem functioning and human well-being

Because of its very nature, geodiversity has a significant impact on both the natural world and human society. Ecosystems are shaped by the subtleties of geodiversity, and the benefits that are obtained from geosystems have a real influence on human welfare. The fundamental element of ecosystem function is geodiversity. The bedrock, soils, and terrain that determine the kind and distribution of plants, animal habitats, and hydrological systems are all products of geological formations and processes. For example, karst characteristics found in limestone terrains support certain ecosystems that are suited to these kinds of conditions (Ford & Williams, 2013). The mineral content of soils, which is directly impacted by the parent rock, defines their fertility and, in turn, the kinds of plants that may grow there. Naturally occurring in geological depressions, wetlands are essential for the cycling of nutrients, the purification of water, and the provision of habitat for a wide variety of plant and animal life (Mitsch & Gosselink, 2015).

There is a complex link between human well-being, geosystem services, and geodiversity. Geosystem services fundamentally offer resources necessary for survival. This comprises metals for building and technology, freshwater from aquifers, and fossil fuels for energy (Bobylev et al., 2022). Geodiversity has a profoundly positive impact on human lives that goes beyond survival. Unique geological elements in a landscape have aesthetic, spiritual, and cultural significance. As pilgrimage destinations and sources of inspiration for artists and authors throughout history, places like the Grand Canyon and Mount Everest are rich in cultural and spiritual significance (Joye et al., 2013). A further factor in the welfare of humans is the protective function of some geological formations. For example, sand dunes and coastal mangroves serve as natural barriers against storm surges and tsunamis, safeguarding human populations and inland areas (Barbier et al., 2008). There is no denying the correlation between ecosystem function and human well-being, which is rooted in geodiversity. Geodiversity shapes and supports healthy ecosystems that offer recreational opportunities, resources, and defense against natural dangers. Essentially, maintaining a sustainable future for ecosystems and the human civilizations they support is the main goal of geodiversity conservation, rather than only protecting rocks and landscapes (Tewksbury et al., 2014).

### 2.3.5 An overview of the DPSIR Framework

A systematic method is essential to study the complex interactions between environmental factors, human activity, and the resulting consequences. The DPSIR (Drivers, Pressures, State, Impact, and Responses) Framework, which has gained popularity in environmental sciences and policymaking, is useful in this regard. The DPSIR Framework, which was first created by the European Environment Agency (Smeets & Weterings, 1999), offers a comprehensive method for comprehending the relationship and causation of environmental events. It illustrates how different social "Drivers," like population expansion or technology breakthroughs, result in "Pressures," like pollution or over-extraction. These factors affect the "State" of the environment, which has an array of "Impacts" on ecosystems and human welfare. Society creates "Responses" to decrease or adapt to these consequences (Svarstad et al., 2008).

This structured approach is very useful when attempting to navigate challenging environmental situations. For example, the DPSIR framework can pinpoint an economic factor (such as fast industrialization) contributing to a region's declining freshwater quality. This driver may then create pressure (such as industrial effluents) that is changing the state of freshwater sources and affecting human health, prompting responses like stricter water quality regulations (Atkins et al., 2011). The DPSIR framework may be applied to a wide range of tasks, including in-depth geo-ecosystem evaluations and assessments of climate change. While addressing the pressing problems (Pressures or Impacts), its structure makes sure that the larger influences (Drivers) are not missed (Kelble et al., 2013). This all-encompassing strategy guarantees that treatments (Responses) address the underlying issues rather than just acting as band-aid fixes. Furthermore, the DPSIR framework provides insights into how societal and natural activities impact geodiversity and geosystem services, as well as how they may be preserved or restored, when applied to this domain (Gari et al., 2015). Essentially, the DPSIR framework provides a systematic mechanism for creating sustainable and effective solutions in addition to illuminating the routes of environmental change.

Systems analysis is the source of the DPSIR (Drivers, Pressures, State, Impact, and Responses) framework, which offers an organized method for comprehending the dynamics of socio-ecological systems. When the European Environment Agency (EEA) first created it in the 1990s, the goal was to utilize it as a tool to combine various environmental data types and facilitate decision-making by classifying the cause-and-effect links in environmental concerns (Smeets & Weterings, 1999). The DPSIR framework has had several modifications throughout time. Its order and structure have been modified in light of the particular environmental problem at hand. For example, some adaptations suggest feedback loops to show the complex interdependencies of socio-ecological systems, whereas the standard model presents a linear progression (Svarstad et al., 2008). The simplicity and flexibility of the DPSIR framework is its main advantage. Because of its universality, it may be used in a wide range of environmental contexts, including freshwater management, climate change adaptation, and biodiversity protection. In addition, it provides policymakers and the public with an organized method for comprehending and explaining complicated environmental issues (Potschin-Young et al., 2018). The DPSIR framework has its detractors even though it is widely used. Some contend that because of its linear structure, socio-ecological systems' complexity is oversimplified. According to Kelble et al. (2013), the classical representation of the framework might not be sufficient to fully capture the feedback and non-linear dynamics present in these systems. Furthermore, even while DPSIR offers an organized classification, it might not always provide clear instructions on how to rank the drivers or pressures that have been discovered or take appropriate action. If it is not used as a meaningful instrument to encourage positive environmental action, it might end up being just another academic exercise (Binder et al., 2013).

There is a growing need to improve and modify instruments like the DPSIR framework due to the changing issues brought about by changes in the global environment. To better reflect the human-environment interaction, future versions may incorporate socio-economic aspects in a more complex way and be more inclusive of feedback mechanisms.

### 2.3.6 Earlier Uses in Geospatial and Environmental Studies

The DPSIR framework has been extensively used in many environmental and geospatial research due to its systematic approach to comprehending environmental concerns. Research attempting to identify the factors contributing to biodiversity loss has benefited greatly from the application of the DPSIR paradigm. The DPSIR model, for example, was utilized in research on Mediterranean wetlands to comprehend the stresses (such as agricultural development) affecting these important habitats, the ensuing state changes, and the wider effects on bird biodiversity (Alcaraz-Segura et al., 2008). The framework has been useful in clarifying the socio-economic factors that contribute to pollution in freshwater systems, the resulting alterations in water quality, and the wider implications for the health of people and ecosystems. This has had a significant impact on how water management strategies are implemented across Europe (Atkins et al., 2011).

Urban sprawl, deforestation, and changes in land use have all been studied using the DPSIR paradigm in geospatial research since the development of Geographic Information Systems (GIS) and satellite remote sensing. Researchers have mapped and evaluated the forces driving land transformation, the strains placed on natural landscapes, and the ensuing geo-ecological and socioeconomic effects by combining DPSIR with GIS. This has led to changes in land use and land cover. For example, this integrated method was employed in research conducted in Southeast Asia to study the land cover change impact analysis on land degradation (Rahmawaty et al., 2022). The effects of climate change on coastal regions have been visualized using geographic tools in conjunction with the DPSIR framework. Sea level rise, the stresses it places on coastal ecosystems, and the ensuing socioeconomic effects it has on nearby towns have all been predicted in studies (Tol et al., 2008).

Although the implementation of the DPSIR framework in geospatial and environmental research has provided valuable insights, several objections continue to exist. The framework has occasionally been criticized for being very basic and unable to adequately represent the intricacies and feedback loops present in socio-ecological systems. Moreover there are limitations in using the DPSIR framework in the geospatial research because there is the risk of putting too much emphasis on spatial elements coming from the interpretations of features (Tognetto et al., 2021) and on visual representation of the relationship between entities coming from the graphic application of the DPSIR (Argent et al., 2016).

### 2.3.7 Advantages and Drawbacks of the DPSIR Framework

In environmental and socio-economic research, the DPSIR (Drivers, Pressures, State, Impact, and Responses) framework has become widely used as a tool for comprehending the complexities of socio-ecological systems. Similar to every conceptual framework, it has some limitations along with clear benefits.

*2.3.7.1 Advantages*

- Organized Approach: The DPSIR framework's organized design is one of its main advantages. It provides a methodical way to analyze intricate socio-ecological interactions by dissecting environmental challenges into its component parts (Drivers, Pressures, etc.) (Potschin-Young et al., 2018).
- Wide Range of Applicability: The DPSIR framework may be used in a variety of environmental contexts due to its generic design. The paradigm provides a broadly applicable way to comprehend the underlying processes, regardless of whether one is researching biodiversity loss, land use change, or water quality (Gari et al., 2015).
- Socio-economic and Environmental Data Integration: The DPSIR framework promotes a comprehensive knowledge of environmental concerns by fostering the integration of socio-economic drivers and environmental conditions. According to Turnhout et al. (2013), this is crucial in a world where natural and human systems are intricately entwined.

*2.3.7.2 Drawbacks*

- Oversimplification: A prevalent criticism of the framework is that complicated, frequently non-linear socio-ecological interactions may be oversimplified due to its linear structure. The DPSIR in its traditional version may overlook complex feedback processes since the world seldom operates in simple cause-and-effect sequences (Binder et al., 2013).
- Possibility of Fragmented Solutions: By grouping problems into distinct categories, it is possible to provide solutions that only address peripheral factors (like pressures) rather than the underlying causes (like drivers) of the problems (Kelble et al., 2013).
- Interpretative Variability: Because the DPSIR categories are general, different research may interpret them in different ways. When tackling identical situations, this might result in uneven approaches and perhaps different findings (Niemeijer & de Groot, 2008).
- Possible Anthropocentric Views Bias: By emphasizing human-driven pressures and reactions, the DPSIR model may unintentionally ignore processes that are exclusively geo-ecological or intrinsic geo-ecological values that are not immediately related to human benefits (Spangenberg et al., 2014).

## 2.4 Global Change Adaptation Strategies

According to the global change framework shown in the figure 2-1, In the face of global changes, predominantly due to climate fluctuations and anthropogenic activities, societies grapple with the significant challenge of adaptation. A substantial body of literature has been dedicated to exploring various adaptation strategies that can mitigate the impacts of these changes and foster resilience in different ecosystems and human societies.

### 2.4.1 Policy Frameworks

The complicated dance between global change and human response underscores the profound significance of policy frameworks in anchoring adaptation strategies. These frameworks provide a structured and strategic approach, instrumental in forging pathways to address the multifaceted challenges presented by global changes. Robinson et al. (2023) have been pivotal voices in championing the transformative potential of effective policy frameworks. Their comprehensive analysis explained how such frameworks can serve as powerful catalysts, energizing national and grassroots actions when devised with clarity and foresight. Furthermore, they emphasized the potency of aligning domestic policies with global accords, such as the Paris Agreement. Such synchronization, they argued, creates a cohesive global front, amplifying resilience against the impacts of climate change and promoting shared accountability. The nexus between traditional wisdom and modern policy frameworks has also been an area of keen academic interest. Zurba and Papadopoulos (2023) explored this intersection, asserting that a goldmine of adaptive strategies within indigenous knowledge systems exists. Rooted in the depths of time, these insights, which have been shaped and refined across generations, bring a wealth of pragmatic solutions often harmonized with local ecosystems. By weaving this knowledge into contemporary policy frameworks, policymakers can tap into a holistic and integrative approach, marrying the best of traditional wisdom and modern science.

However, the essence of any effective policy framework is not just its strategic depth or integrative approach but its human-centric focus. Birkmann et al. (2022) provided a compelling narrative, spotlighting the socio-economic dimensions often intersecting global change impacts. Their research underscored that a resilient policy framework is mindful of its societal implications. By ensuring policies are crafted with an eye on the most vulnerable and marginalized populations, such frameworks transcend mere strategic documents, evolving into powerful tools for social justice, inclusivity, and equity. Building upon this, Al Sayah et al.

(2023) highlighted the need for continuous evolution and flexibility within policy frameworks. As global change is an ever-evolving phenomenon, policies must be agile, responsive, and open to revisions based on emerging data and realities. Such dynamism, they argued, ensures that policy frameworks remain relevant, impactful, and truly representative of the diverse challenges and opportunities that global change presents. In conclusion, the literature provides a resonant affirmation of the cardinal role of policy frameworks in global change adaptation. As the world grapples with the significant challenges of a shifting climate and its cascading impacts, these frameworks stand as beacons, guiding collective efforts toward a resilient and inclusive future.

### 2.4.2 Community-based Adaptation

With its essential focus on ground-level, localized strategies, community-based adaptation has become a cornerstone of global change adaptation discourse. Its essence lies in the premise that the most affected by changes–local communities–possess invaluable insights and knowledge that can guide effective and sustainable adaptation measures. Shammin et al. (2022) investigated the mechanics of community-based adaptation, highlighting its inherent strengths. They observed that community-driven endeavors, rooted in local realities, inherently cultivate a deep sense of ownership among participants. This ensures more robust engagement and boosts the longevity and sustainability of implemented strategies. They emphasized that such initiatives, informed by centuries of traditional knowledge and experience, offer a rich repertoire of techniques and methods that resonate with local ecosystems, cultures, and economies. Mfitumukiza et al. (2020) study offered an illuminating insight into the tangible benefits of community-based adaptation. Their in-depth exploration of coastal communities in Southeast Asia revealed adaptive practices that have stood the test of time. These communities, facing the relentless challenge of rising sea levels, have ingeniously leveraged mangrove reforestation and sustainable aquaculture to mitigate impacts. Mangroves, with their ability to act as natural buffers, have protected these communities from storm surges and enhanced local biodiversity, while sustainable aquaculture practices have ensured economic viability. Their findings drive home the point that community-based adaptation is not just about survival but also about thriving in harmony with nature.

Nevertheless, as with every strategic approach, community-based adaptation presents inherent complexities. Forsyth (2013) offered a complicated analysis of this method’s potential challenges and details. They pointed out that while local communities possess a wealth of knowledge, a gap in technical expertise, resources, and broader policy support often exists.

Bridging this gap is essential to ensure that local efforts are scaled effectively, benefit from advancements in science and technology, and are synchronized with regional and national adaptation strategies. They advocated for a collaborative approach wherein policymakers, scientists, and local communities work together, ensuring that grassroots solutions benefit from external expertise and resources while retaining their local essence. In a subsequent study, Rahman (2021) discussed the importance of documentation and knowledge dissemination in community-based adaptation. He argued that many invaluable local adaptation practices remain undocumented and, thus, unknown to the broader world. By systematically documenting and sharing these practices, communities can preserve their knowledge and inspire and guide other communities facing similar challenges across the globe.

With its inherent strengths and challenges, community-based adaptation is central to the global adaptation narrative. As the world faces unprecedented changes, local communities' wisdom, experiences, and insights offer a beacon of hope and a roadmap for sustainable and inclusive adaptation.

### 2.4.3 Technological Innovations

The interplay between technology and adaptation strategies has emerged as a keystone of modern efforts to confront and mitigate global change. Highlighting the magnitude of this transition, Rosenzweig et al. (2014) stress the potential advantages of the digital revolution, which has accelerated the development and adoption of technological solutions. Particularly transformative in this era is satellite-based remote sensing. According to Pettorelli et al. (2014), this technology provides real-time, granular data on environmental patterns, offering invaluable insights to farmers, policymakers, and communities. Such technological interventions facilitate crucial decisions on water usage, crop selection, and harvesting timelines, potentially ensuring more resilient agricultural systems. Urban environments are not exempt from the influence of technological advancements. Bibri and Krogstie (2017) discusses the rise of smart cities and urban centers enhanced by many sensors and underpinned by artificial intelligence. These cities promise sustainability and an elevated quality of life for their inhabitants. This transformation reshapes urban planning, positioning technology as a cornerstone of future city development.

While the agricultural and urban sectors have seen significant technological advancements, biological engineering offers another dimension of innovation. In a study by Qaim (2020), the potential of drought-resistant crops and genetically modified organisms (GMOs) is underscored, hinting at a future where agriculture thrives even in challenging climatic conditions. However, the rapid pace of technological evolution is not devoid of ethical concerns. Jasanoff (2016) offers a cautionary perspective, emphasizing the responsibility that comes with innovation. Ensuring that technology does not inadvertently compromise biodiversity, cultural values, or further societal disparities is paramount. In conclusion, technological innovations present a promising horizon for confronting global change. However, as scholars like Rosenzweig and Jasanoff point out, this horizon is multifaceted, necessitating a balanced approach that integrates the boon of technology with ethical and equitable considerations.

## 2.5 Sustainable Development of Mountain Regions

Mountain regions, often called the world's "water towers" because of their crucial role in freshwater supply, present unique challenges, and opportunities for sustainable development. Given their fragile ecosystems, cultural richness, and strategic importance, academic literature increasingly emphasizes crafting sustainable strategies tailored to these regions.

### 2.5.1 Sustainable Tourism

The globalized world has ushered in an era where mountain regions, previously considered remote and inaccessible, are now increasingly popular tourist destinations. This is particularly true for the Monte Rosa W-Alps, boasting breathtaking landscapes and unique geological features. Understanding the balance between tourism management and environmental preservation becomes crucial, given the important relationship between geodiversity and sustainable tourism. A comprehensive analysis by Newsome et al. (2012) highlights potential environmental degradation caused by unregulated mountain tourism, a pressing issue for sensitive geosystems like the Monte Rosa W-Alps. The challenge lies in harmonizing economic growth with environmental conservation in the sustainable tourism model. A more specialized form of tourism, geo-tourism, brings a fresh perspective to this dynamic. Newsome and Dowling (2006) describe geo-tourism as sustainable tourism with a particular emphasis on showcasing a region's geological and geomorphological features. Geo-tourism can significantly bolster conservation efforts by diversifying tourist activities and educating visitors on geological significance.

Supporting the case for a tourism model that prioritizes natural and cultural preservation, Walden-Schreiner et al. (2018) found that tourists tend to have higher regard for local customs, traditions, and environmental guidelines when their visit has an instructive element, such as geo-tours. Furthermore, Koens et al. (2018) study stresses local communities' indispensable role in steering sustainable tourism strategies. When communities are actively involved, tourism tends to tread lightly on the environment while generating socio-economic benefits. Given the Monte Rosa W-Alps' significance as a tourist destination, understanding its place in the broader sustainable tourism discourse is crucial. As global trends influence tourist preferences, regions like Monte Rosa require a refined approach to sustainability. Marrying geodiversity with community involvement and education is a promising strategy for ensuring sustainable tourism in mountain regions worldwide.

### 2.5.2 Conservation Strategies

The important link between geodiversity and biodiversity is essential for sustainable conservation in the Monte Rosa W-Alps. This region is a testament to the delicate balance between unique geological formations and vibrant ecosystems, necessitating thoughtful, context-driven conservation measures. Corroborating the notion of anthropogenic impacts on geosystem services, a study by Schild (2020) discussed how human activities, such as tourism and infrastructural developments, bring about economic gains while potentially aggravating soil degradation and habitat fragmentation. Building upon the importance of designated conservation zones, DeFries et al. (2007) have emphasized the value of protected areas in preserving biodiversity. Applying this to the context of Monte Rosa, it becomes apparent that preserving its geodiversity would greatly benefit from a concerted effort involving the local communities. These communities, enriched by generations of lived experience in the region, can provide invaluable insights as caretakers of the geological and ecological treasures Monte Rosa boasts.

Highlighting the significance of a collaborative approach, especially when geological processes cross political boundaries, Zbicz (2003) underscores the concept of transboundary conservation. Transboundary conservation refers to environmental preservation efforts that span national borders (Erg et al., 2015; Harris et al., 2001; Zbicz, 2003), addressing processes like glacial dynamics and water flow that are inherently cross-border in nature. This concept underscores the need for international cooperation to effectively manage and protect interconnected ecosystems. Furthermore, in line with the insights provided by Comer et al. (2015), an integrated approach that includes a detailed assessment of geodiversity within conservation planning can pave the way for more effective preservation strategies in areas like Monte Rosa. The Monte Rosa W-Alps is an invaluable lens through which we can perceive and understand the broader global challenges associated with conservation. As worldwide dynamics influence conservation paradigms, the insights gained from Monte Rosa reiterate the importance of considering both geodiversity and biodiversity when devising sustainable solutions for mountain regions across the globe.

### 2.5.3 Local Sustainable Practices

The Monte Rosa W-Alps, characterized by its distinct geodiversity and cultural richness, is a testament to how local sustainable endeavors can illuminate the path for broader regional initiatives. Understanding the local implications is crucial for devising sustainable solutions in the milieu of evolving global dynamics. Expanding upon the research of Woltjer (2014) on the role of terraced farming in mountainous regions, Plieninger et al. (2015) examined terraced agricultural landscapes. Their findings indicated that these terraced constructs, meticulously shaped over centuries, epitomize human innovation and act as bulwarks against soil erosion, thereby fostering soil conservation. Moreover, these terraces establish micro-environments suitable for diverse crops, bolstering local biodiversity and food security.

Diving deep into the pastoral traditions of mountain regions, Fernández-Giménez and Fillat Estaque (2012) discussed transhumance's role. This age-old practice of herders seasonally migrating livestock between varying altitudes facilitates grassland rejuvenation and underpins balanced grazing, preserving fragile mountain ecologies. Complementing this, Timothy (2011) accentuated traditional crafts' ecotourism prospects in mountainous regions. Communities like Monte Rosa's communities craft a sustainable tourism model that lauds their heritage. They ensure environmental preservation while championing artisanal activities, from cheese-making to weaving. The Monte Rosa W-Alps exemplify mountain communities' adaptability and profound symbiosis with the environment. Local practices, perfected across generations, chart the course for sustainable regional development, weaving a tale of the harmony between geodiversity, cultural heritage, and sustainability. As global paradigms shift, Monte Rosa's localized narratives offer invaluable lessons and optimism for sustainable mountain growth.

### 2.5.4 Local Adaptation and Sustainable Development Initiatives

The Monte Rosa region encapsulates the delicate beauty of mountain ecosystems, facing the dual challenge of natural climate variations and human-induced pressures. In a comprehensive assessment, Zemp et al. (2015) provided an extensive overview of global glacial changes, and their findings resonate with the changes observed in the Monte Rosa region. Their report elucidates the swift retreat of glaciers, revealing previously concealed mineral deposits. As these glaciers recede, they profoundly affect water systems in volume and geochemistry, impacting aquatic life, water quality, and human communities reliant on these resources. Parmesan and Yohe (2003) conducted a broad study on how global temperature changes influence species distributions in the terrestrial context. Their findings align with those posited for the Monte Rosa region by hypothetical researchers Ollivier and Fontaine. Climatic shifts drive species to seek refuge in cooler, higher altitudes, but this migration may result in geo-ecological imbalances, potential biodiversity losses, and increased competition.

The impact of human actions on mountainous regions is not to be underestimated. Beniston (2003) provided an in-depth look at the implications of tourism in alpine regions. While economically beneficial, ski resorts can drastically alter landscapes, leading to habitat fragmentation, pollution, and other environmental disturbances. Similarly, expanding infrastructure such as road networks poses risks, not just ecologically but also regarding safety against natural hazards like landslides. Synthesizing these insights, Messerli et al. (2019) have articulated the global challenges faced by mountain regions. Their work emphasizes the need for a balanced approach, harmonizing development and conservation. Drawing from such broad studies, it becomes evident that places like Monte Rosa require integrated and adaptive strategies. These strategies should be rooted in robust scientific research and involve stakeholders at every level, ensuring the preservation of these fragile ecosystems in the face of inexorable global changes.

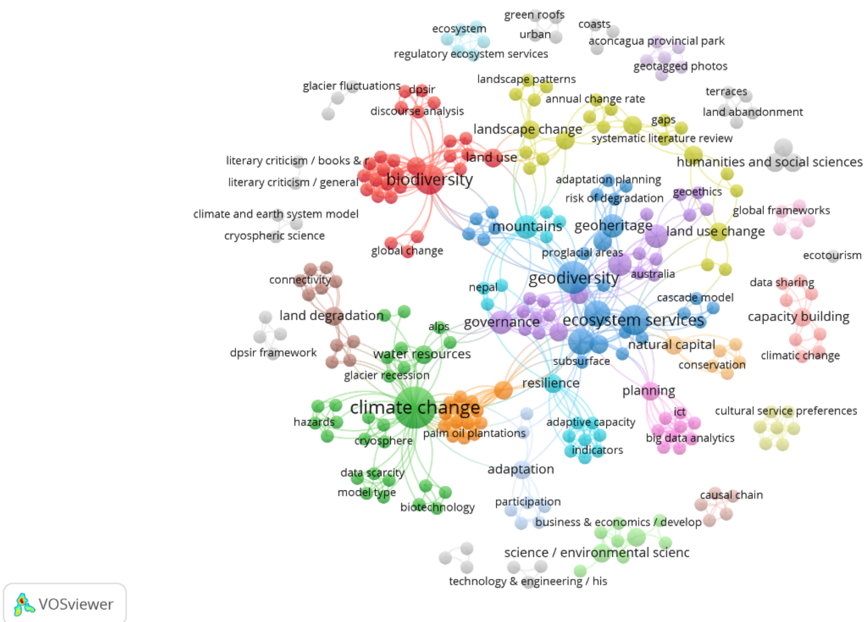


Figure 2-5: Visual mapping of keyword co-occurrence highlighting research trends and interconnections in geodiversity and sustainable mountain development studies (Source: author contribution)

# Chapter 3 Materials and methods

## 3.1 Study Area

Alagna Valsesia, known as the Walser green paradise, is a small town in the region of Piedmont in the province of Vercelli, geographical location of the study area is shown in figure 3-1. It is located in the alpine valley of Valsesia which is part of the Pennine Alps (Piana et al., 2017) and is characterized by the intrusion of various lithotypes belonging to the Monte Rosa crystalline massif and to the ophiolite-bearing Piedmont area (Dal Piaz et al., 2003) and covers an area of about 133.17 km$^2$ (ISTAT, 2022). In fact, the area is part of Sesia Val Grande UNESCO Global Geopark (SVUGGp), where the altitude is highest in Geopark, at 4554 meters asl is the top of Monte Rosa, the second highest massif in the Italian Alps, helping to contribute to its unique geomorphological dynamics and significant geodiversity (Guerini et al., 2023).

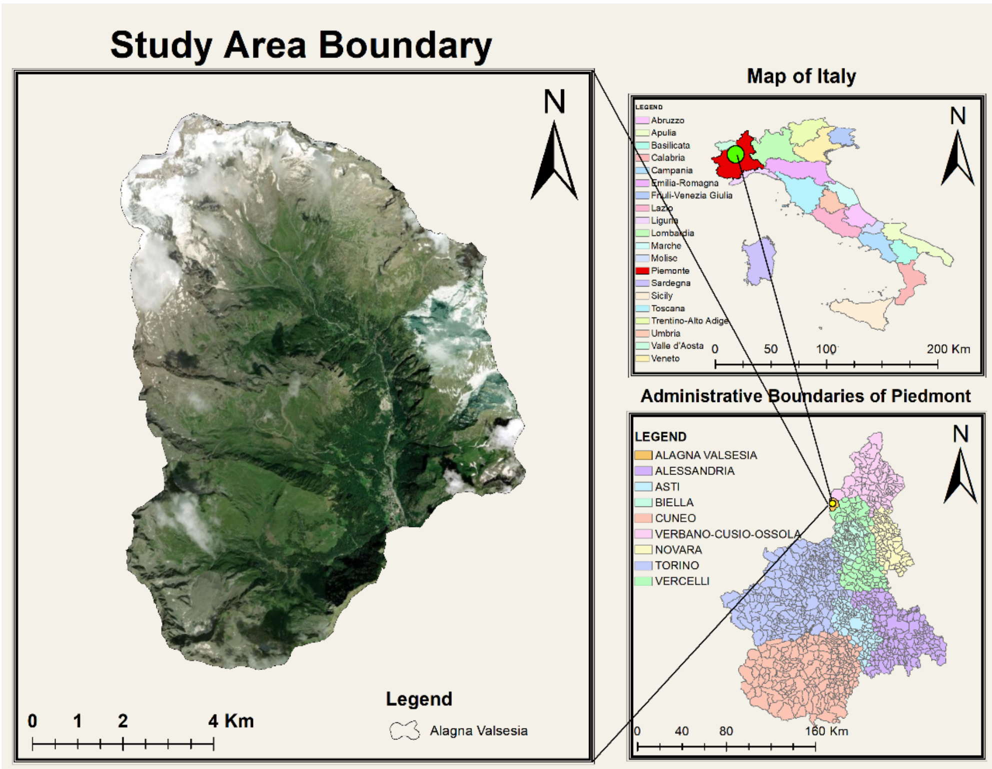


Figure 3-1: Location map of the study area (Source: author contribution)

In addition, as shown in figure 3-2, most of the area is underlain by granite and gneiss formation which is an inheritance from the variscan orogeny that took place during the Paleozoic (Coward & Dietrich, 1989). The Alpine orogeny, which occurred in the Tertiary era, further unfolds the region through tectonics. The latest tectonic activity, during the Tertiary era, created a complex and rugged geological structure that is now referred to as the Alps. Furthermore, the location is home to the Monte Rosa massif, which lies within the Sesia Zone. The region called Sesia Zone produced high-pressure metamorphic rocks because of the Alpine collision.

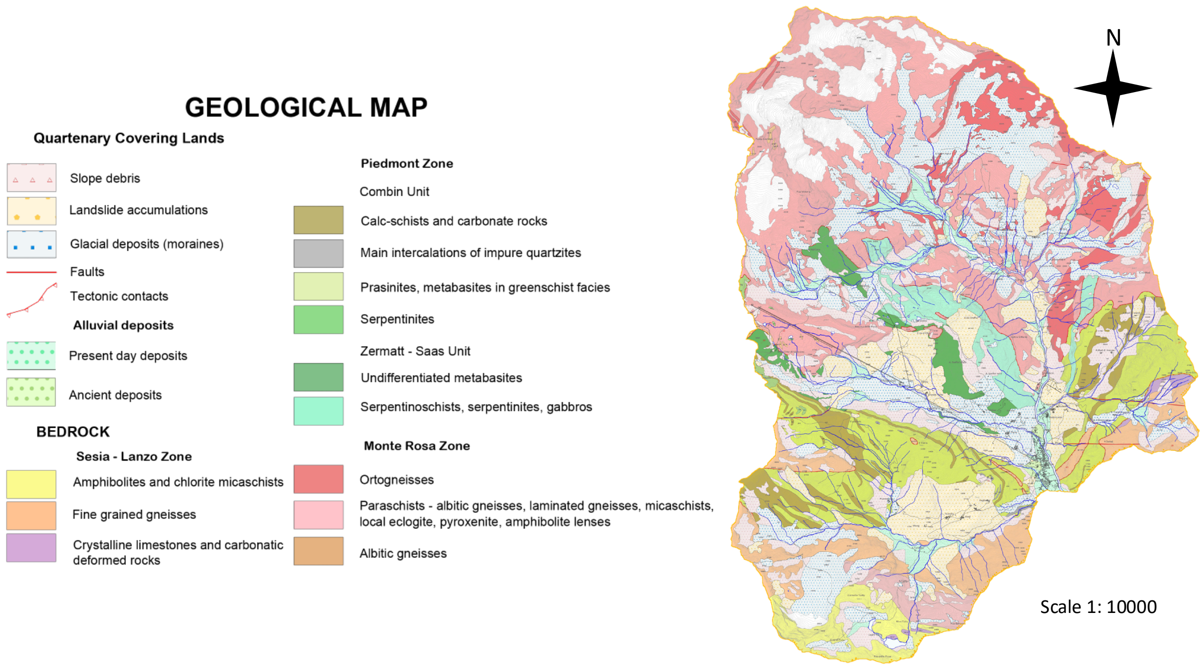


Figure 3-2: Lithological and structural components of geodiversity modified Geological map of Alagna Valsesia (modified from Bartolini et al. (2022)).

As shown in figure 3-3, Alagna Valsesia region portrays many interesting characteristics from a geomorphological point of view. The geomorphological features have been produced in the two million years or more by a variety of natural processes. During a number of recent quaternary glaciations, some of which later being named the Riss Ice Age in the region has created large landform features. One of the main features created by glaciations is the glaciated landscapes. The glaciated landscapes represent a series of cirques, U-shaped valleys, and moraines. Additionally, the actions of the Sesia River and its tributaries have been fundamental to the geomorphology of the area, creating the valleys. Alluvial plains and river terraces have also been formed through fluvial action, which are habitats for human settlement and agriculture practices. There is a wide variety of periglacial landforms situated in Alagna Valsesia. Therefore, these explain the existing dynamic interrelation involving glacial action and the underlying geological formations, and plainly explain the formation of unique landforms and deposition patterns. In particular, the complex geomorphological framework determined a great landscape variety that contributed to the geological heritage; most of the recognized sites in Alagna Valsesia have indeed, their primary interest in geomorphology (Perotti et al., 2020).

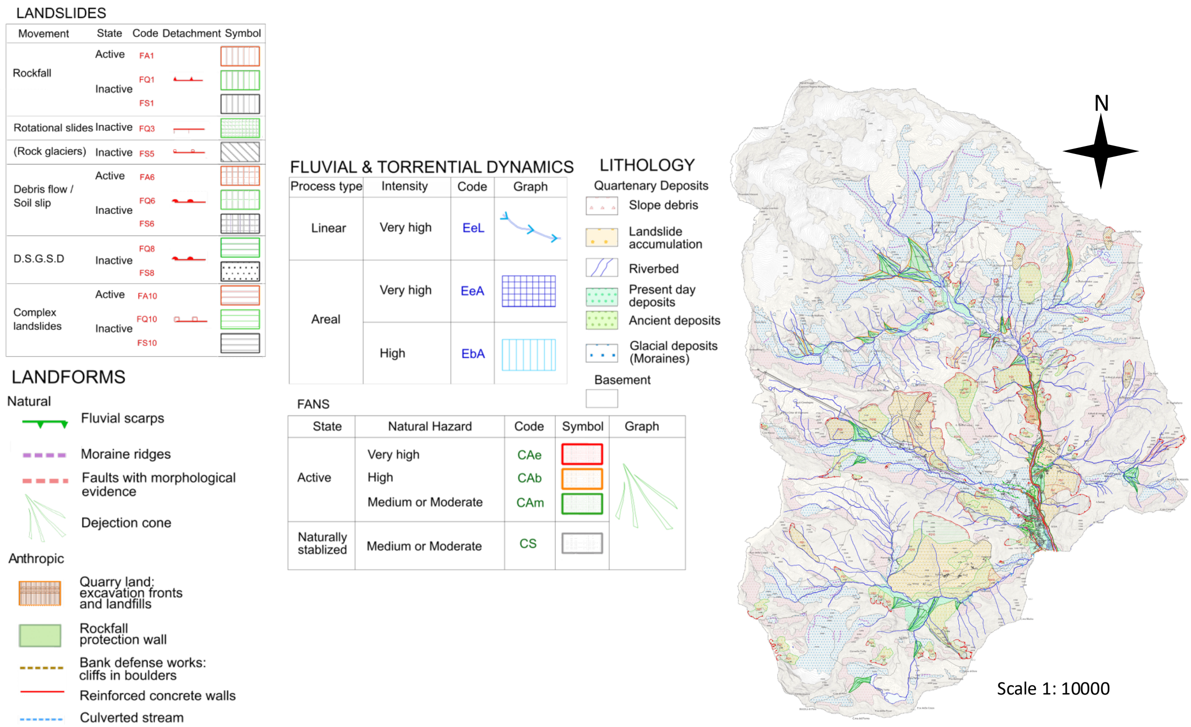


Figure 3-3: Geomorphological components (landforms and processes, either natural or anthropic) of the geodiversity modified Geomorphological map of Alagna Valsesia (modified from Bartolini et al. (2022)).

Furthermore, The Alagna Valsesia region is a geographical wonderland, as well as a cultural wonderland. During the 13th century the Walser people of German ancestry, migrated to the region. With the Walser came a vast array of culture and architectural styles that were specifically designed to complement the surrounding environment. Walser homes, identifiable by their wooden log encasements and stone roofs, provide a look into the historical and cultural history of the surrounding region. Alagna Valsesia has become a popular vacation destination in recent years because it offers a mix of opportunities to enjoy the natural beauty of the Alps as well as its culture traditions. Activities often performed are skiing, mountaineering, and trekking. The regional infrastructure has been built to better valorize eco-tourism, that aims to safeguard the natural and cultural heritage. The high geodiversity makes study area a prominent place for the mapping of geosystem services (Tognetto et al., 2021), a shared research topic for several examples of the study's impacts on nature under changing climate (Colombo et al., 2019; Giardino et al., 2020; Quaglia et al., 2020), and finally a strong point for geotourism (Perotti et al., 2020) and geoeducational activities (Giardino et al., 2022).

## 3.2 Methodology

The research workflow included data collection, digitization, mapping geosystem services and model selection and application, as shown in Figure 3-4.

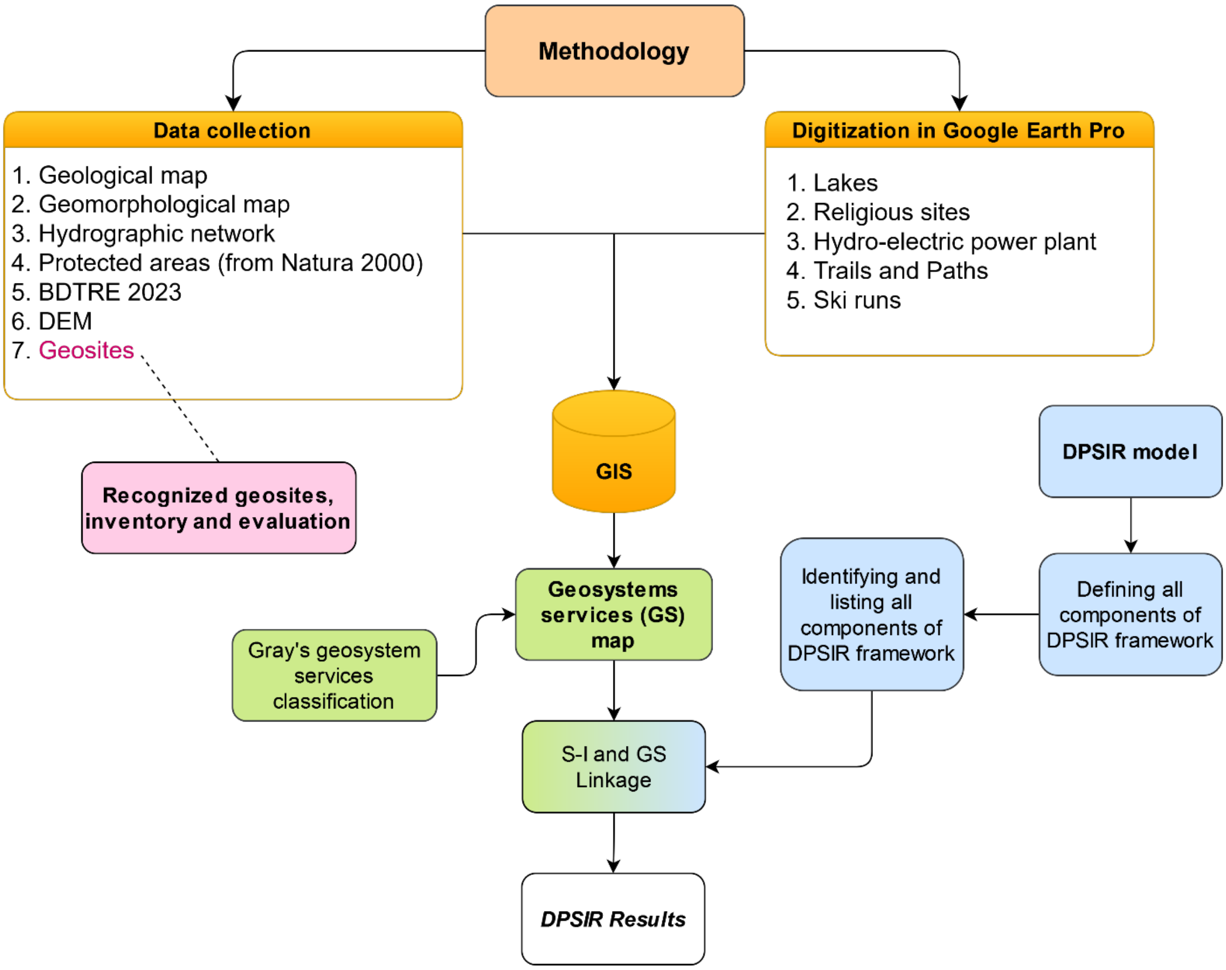


Figure 3-4: Flowchart of applied research methodology (Where S-I is states and impacts and GS is geosystem services). Description of each step is provided in the following text. (Source: author contribution)

### 3.2.1 Data collection

The data collection techniques implemented in this study include acquiring information from online resources and municipalities. The creation of cartographic products within a Geographic Information System (GIS) utilizing Quantum GIS (QGIS) software was the primary focus of the data collection methods. Data for this study was obtained from online databases and was also requested directly from the municipality. Various online databases were extensively searched, among which Geoportale Piemonte came out to be a very important source. Principal focus was given to select data that is GIS compatible or georeferenced to develop cartographic models. In addition to internet data, the information was also actively sought among the municipalities through informal inquiry. The data collected from the municipality included the geological and geomorphological maps which were important for our research since it offered a comprehensive and a regional perspective. The digitization of various features in Google Earth Pro was done by the author, as shown in Table 3-1. Various services were derived from various important features, and these played a vital role in the production of a geosystem services map. After acquiring the necessary data, it was then imported into a GIS geodatabase. A geodatabase is a digital container of knowledge and allows for easy access, processing, and analysis of data. The QGIS software was used for the processing of the data due to being an open-source platform while providing the extensive availability of features offered with a very easy to navigate interface.

The author has shown the commitment to ethical considerations throughout the process of collecting data. By getting the permissions required; by observing confidentiality and data protection principles when using data sources, and only using the data that was collected responsibly. The author has made the entire data collection process transparent by providing a description of data sources in Table 3-1 and how they have been collected to avoid any copyright issues. All of this allows others to review or replicate the findings of this study.

Table 3-1: Summary of data collection

| **Database** | **Scale/Resolution** | **Source** | **Link** |
|---|---|---|---|
| Geological map | 1:10,000 | PRGC Alagna | - |
| Geomorphological map | 1:10,000 | PRGC Alagna | - |
| BDTRE 2023 | 1:10,000 | Regione Piemonte | BDTRE |
| Regional hydrographic network | 1:10,000 | CSI Piemonte | Geoportale |
| Protected areas | 1:250,000 | Regione Piemonte | Natura 2000 |
| DTM | 5m | Regione Piemonte | DTM-5 |
| Lakes | 1:10,000 | Digitized | - |
| Ski runs | N/A | Digitized | - |
| Religious sites | N/A | Digitized | - |
| Hydro-electric power plant | N/A | Digitized | - |
| Trails and paths | N/A | Digitized | - |

- URL not available for data obtained from municipality or authors own contribution

*N/A = not applicable

### 3.2.2 Recognized geosites, inventory and evaluation

This study's method for recognizing, inventorying, and evaluating geosites relies on comprehensively integrating existing literature and applying a brief evaluation scheme developed by (Suzuki & Takagi, 2018). Within the recognition phase, the initial action was to identify those geosites which were referred to by scientific publications, as well various literature reviews were made to obtain a general understanding of significance of each site. This was a fundamental preparatory stage to develop the inventory phase, in which geosites were collected and categorized. The cataloging has been made by extracting data from published documents, which had information about the geological parameters and the characteristics of each geosite relevant to the subsequent analysis.

The root of this method follows the geosite assessments that are based on the model first introduced by Suzuki and Takagi (2018). This model provides a well-structured framework as shown in Table 3-2, including 18 scores divided into six major categories to evaluate the various attraction and accessibility of various geosites for both academic and tourism purposes. The scoring which represents 1-4 scale is derived from a set of pre-established criteria obtained from scientific literatures, on-site observations and/or past experiences, publicly available resources including web sites and guidebooks.

The scheme for evaluation has certain primary scores that relate to various aspects of the site which include Ved (educational value), Vsc (scientific value), Vtr (tourism value), Vsa (safety and accessibility), Vcs (conservation values and site sustainability), and Vti (tourist information). Clarity of geological information, scientific value of the site, aesthetic significance, risks, conservation, and quality of information established are calculated before giving the approximated values. Apart from the scheme presented here, there is special interest put on each geosite’s didactic potential, scientific communication clarity and integration of the global visibility in the digital domain.

Upon completion of the scoring process, each geosite is meticulously analyzed, and every category is given an average. That average is then rounded to the one decimal place allowing for the most accurate reflection of geosite performance. This averaging applies to multiple geotopes or related features within a single geosite if necessary. The collected results are visually represented through a radar graph, which facilitates a multidimensional view of the geosite’s attributes. The graph portrays the data and color-codes to distinguish between the site's inherent natural values and the values associated with human activity. By pairing the axes into educational, natural heritage, and geotourism clusters, the graph delineates the varying perspectives of the geosite's attributes, hence providing insights into which values merit preservation and how they may contribute to the site's sustainable use whether through educational means, geological conservation, or as part of a cultural-historical narrative that benefits local communities.

Through this structured approach, the present study harnesses existing literature and is an innovative evaluation tool to systematically gauge geosites, thereby facilitating their effective management and incorporation into the geotourism framework, particularly for sites aspiring to align with the Global Geoparks Network under UNESCO label.

Table 3-2: Evaluation criteria for the geosites (Source: Adopted from Suzuki and Takagi (2018))

| ID | Score name | Scoring criteria | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Ved | **Educational value** | | | | |
| Ved1 | Ease of understanding the geosite's story | Difficult to understand even with an explanation from a geoguide | Understandable with an explanation from a geoguide | Understandable with an explanation board or other information sources | Easily understandable without additional explanation |
| Ved2 | Representativeness | None (for scientists only) | Low/somehow typical | Moderate | High |
| Ved3 | Ease of understanding information panels at the geosite | No information panels | Content is complicated or not sufficient | Moderately understandable | Understandable to anyone |
| Vsc | **Scientific value** | | | | |
| Vsc1 | Research significance | Low | Moderate | High | Very high |
| Vsc2 | Clarity and non-obsolescence of scientific story on information panels, guidebooks, and web sites | None | Partly explained | Explained | Well explained |
| Vsc3 | Rarity in the region | Not rare | Locally rare (e.g., within a geopark) | Regionally rare | Nationally or internationally rare |
| Vtr | **Tourism value** | | | | |
| Vtr1 | Emotional/esthetic value such as beauty or impressiveness | Low | Moderate | High | Very high |
| Vtr2 | Other natural/anthropogenic values | None | Not important | Important | Important and well-known |
| Vtr3 | Other tourist attractions in the vicinity | None | Exist but not valuable | Exist | Famous attractions exist |

| | | | | | |
|---|---|---|---|---|---|
| Vsa | **Safety and accessibility** | | | | |
| Vsa1 | Safety condition of geosite and footpath | Relatively dangerous (e.g., helmet and trekking shoes are required) | Moderate risk of danger | Low risk of danger | Safe area |
| Vsa2 | Travel time from the base (information) point on the area's attractions | More than 2 h | 1–2 h | 30 min to 1 h | <30 min |
| Vsa3 | Walking time from bus/train stops or parking lot | More than 30 min | 15–30 min | 5–15 min | <5 min |
| Vcs | **Conservation and site sustainability** | | | | |
| Vcs1 | Current state of conservation | Not conserved | Partly conserved | Moderately conserved | Well conserved |
| Vcs2 | Legal protection | Not protected | Existing plans for protection (e.g., geopark area) | Partly protected (national park) | Protected (world heritage, natural/cultural monument) |
| Vcs3 | Site sustainability | Difficult to be preserved | Could be damaged by long-term natural processes or human activities | Could be affected by natural disaster or social/political situation | Low risk of potential destruction |
| Vti | **Value of tourism information** | | | | |
| Vti1 | Information panels of the approach to geosite | No information | Limited information (with a risk of getting lost) | Information that helps with moderate ease of access | Information that helps easy access |
| Vti2 | Geosite information on web sites, pamphlets, guidebooks, etc | No information | On either web sites or pamphlets | On both, web sites and pamphlets | On web sites and pamphlets and in guidebooks |
| Vti3 | International usefulness of information panels and web sites (multilingual) | No information | One language only | Two languages | More than two languages |

### 3.2.3 Geosystems services mapping

A method that is exact and well-structured is required in order to understand geosystem services, as well as their distribution and effect in a particular geographic region. For the purpose of this investigation, we made use of the geosystem services mapping method developed by (Tognetto et al., 2021). This method is based on classification methods and taxonomy of geosystem services by (Gray, 2004; Gray et al., 2013), which helped map these vital natural elements. His study showed the significance of categorizing geosystems' multiple functions to better understand their roles and their consequences on the natural world and humans. Gray divided geosystem services into regulating, provisioning, supporting, cultural, and knowledge services. The application of this method was carried out in several steps. At first, we divided all the possible geosystem services in Alagna Valsesia based on Gray's classification. Among the 25 types of geosystem services, we identified 14 types of geosystem services in Alagna Valsesia. After that, as displayed in Table 3-1, the data from different sources were utilized to digitize these services in GIS environment. GIS analysis created spatially explicit layers representing various geosystem services in the study area. Further, we utilized Google Earth Pro to pinpoint all the sites that provide services to society, then exported all the sites to GIS. Finally, to generate geosystem services map, the Lines, Points, and Polygons layers were joined to create a final geosystem services map as shown in Table 3-3.

Table 3-3: Table showing detailed geospatial data used to generate geosystem services map

| **Layer** | **Data type** | **Feature type and extension** |
|---|---|---|
| DTM | Raster | Raster (tiff) |
| Geological map | Vector | Polygon (shp) |
| Geomorphological map | Vector | Polygon (shp) |
| BDTRE 2023 | Vector | Polygon (shp) |
| Regional hydrographic network | Vector | Linear (shp) |
| Protected areas | Vector | Polygon (shp) |
| Religious sites | Vector | Point (kmz) |
| Hydro-electric power plant | Vector | Point (kmz) |
| Trails and paths | Vector | Linear (kmz) |
| Ski runs | Vector | Polygon (kmz) |
| Lakes | Vector | Polygon (shp) |

### 3.2.4 Model selection: DPSIR framework

Environmental studies have long developed conceptual frameworks to simplify complex human-nature interactions. The State-Response (S-R) model, pioneered by Canada in 1979 (Rapport, 1979), paved the path for later, more comprehensive, and integrated models. Pressure-State-Response (PSR) model developed by (OECD, 1993), provided the foundation for these frameworks. The 1999 European Environment Agency Driving-Pressure-State-Impact-Response (DPSIR) model was the culmination of these frameworks.

The DPSIR framework is being more widely accepted in environmental sciences which represents a spatial depiction of cyclical natural systems (Cooper, 2013; Gari et al., 2015; Wang et al., 2018). Instead of just observing environmental state and impacts, DPSIR considers the underlying drivers of human activities, the different stresses put on the environment, how that drives a change in state, the impact on geo-ecosystems and how society and politics reacts accordingly.

Our research utilized the DPSIR model because it readily covers the important drivers of the economy, the society, the environmental resources, and the geodiversity and it provides the explanation of the diverse relationships between the different aspects. It is clearly explained and defined in our research how the relationship between the human activities and the natural elements of the geodiversity translates into the geosystem services and providing the benefits to the society, thus making the DPSIR concept as a suitable model.

#### *3.2.4.1 DPSIR application*

Our initial step was to accurately define the components of the DPSIR, which are outlined as follows:

- Drivers refers to the comprehensive social, economic, and natural forces that initiate environmental system changes. These are the fundamental factors that cause environmental conditions to change. In other terms, drivers are the underlying mechanisms that activate the system.
- Drivers lead to pressures; both natural and human-induced. These pressures stress the environment, causing change.
- States refer to the conditions of the environment under the influence of the identified pressures. They represent the quality and quantity of environmental components and the status of human-made structures. The state of an environmental system is a direct

result of pressures and serves as a snapshot of the environmental conditions at a given point in time.

- Impacts are the consequences of these state changes on the human and geo-ecological environment. The impacts can manifest in geo-ecological, economic, or social dimensions. The aforementioned entities symbolize the consequences resulting from alterations in the environmental condition and their impact on geo-ecosystems, human well-being, and socio-economic circumstances.
- Responses are the tactics, activities, or interventions by stakeholders including government, communities, and policymakers to minimize or adapt to the observed impacts. Responses may include legislative changes, regulatory measures, or behavioral adjustments to reduce pressures, improve the environment, or mitigate damage.

In identifying and selecting the drivers and the corresponding PSIR components for this analysis, author initially undertook a thorough literature review and examination of environmental reports pertinent to the study area, identifying a preliminary list of environmental and human-induced changes. Subsequent consultations with the mayor of Alagna Valsesia and representative of Monterosa 2000 ski resort provided invaluable insights, refining our understanding of the region's key drivers and the ensuing pressures, states, impacts, and responses. This process was complemented by an analysis of historical data (reports and photographs), allowing us to discern trends and further refine our selection of DPSIR components. This multi-pronged approach, combining literature review, expert knowledge, established a solid foundation for mapping the complex interactions between environmental dynamics and human activities within the study area.

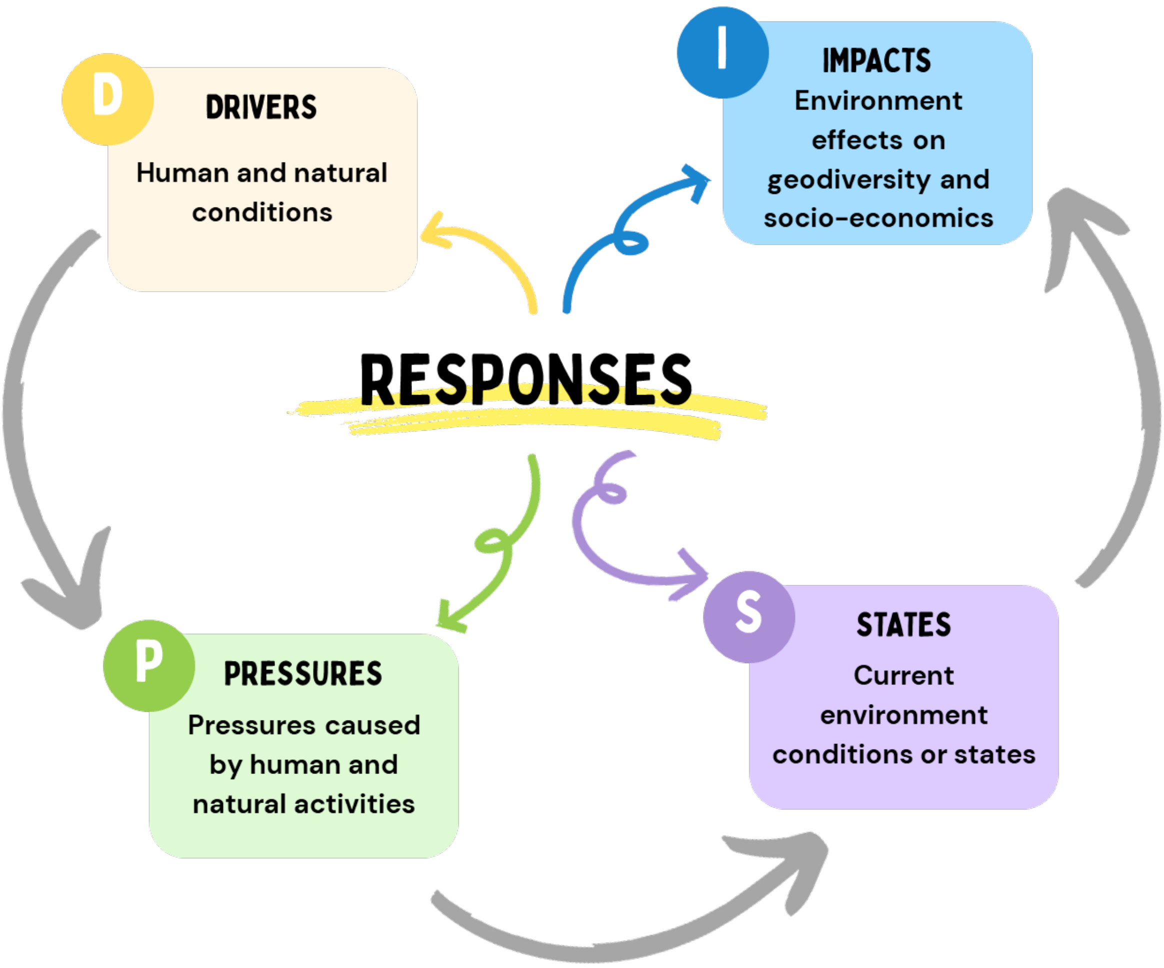


Figure 3-5: Illustration of DPSIR approach applied in this study

Later on, author defined each component of the DPSIR framework and identified the associated drivers, pressures, states, impacts, and responses, drawing upon both a comprehensive literature review and insights from selected experts in geodiversity, ecosystem services, and environmental management from the earth sciences, management, agricultural department of University of Torino (UNITO) and from the institute of geoscience and georesources of the national council of Italy (CNR) and the Italian glaciological committee (CGI). These experts were chosen based on their academic credentials, professional experience, and contributions to the field. Their input was obtained through the informal offline and online meetings, which were specifically focused to elicit detailed information on how natural and anthropogenic factors influence geosystem services. The findings were then systematically linked and visually represented to highlight the affected geosystem services, showcasing the interplay between these factors and the resulting states and impacts.

# Chapter 4 Results and Discussion

## 4.1 Geosites recognition and inventory

In our research on the Alagna Valsesia area, by utilizing the existing body of the literature we have identified eight distinct geosites within the study area. These geosites were identified based on a range of criteria including the scientific significance of the geomorphological features as well as their educational value, their aesthetic appeal, and accessibility. Each geosite is representative of a unique aspect of Alagna Valsesia's geological diversity and showcases a broad range of different features ranging from stratigraphic sections and mineral deposits to glacially sculpted landscapes and tectonic structures. The thoroughness of this selection process is indicative of the abundant geological heritage present in the area and further perpetuates the looming necessity for its preservation. Importantly, the recognition of these geosites is of immense significance to the thesis, as it develops a framework to allow future geoconservation efforts and extends the geotourism potential of the study area.

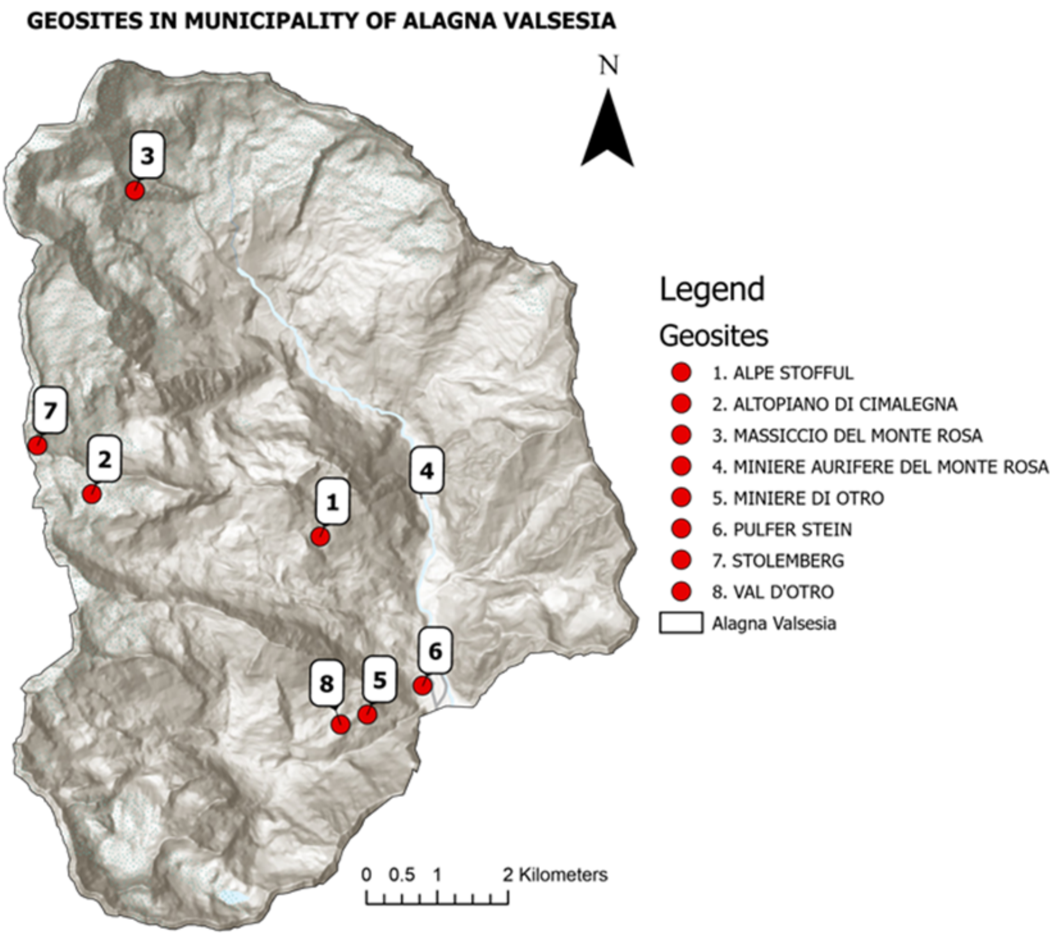


Figure 4-1: Recognized geosites in the municipality of Alagna Valsesia

As shown in figure 4-1, the Alagna Valsesia area, where the recognized geosites are located, is shown visually to complement the extensive research that has taken place on these sites. In the figure is a map of where the geosites are located within the area. In figure 4-2, there is also photographic evidence of the geosites as another visual representation.


Figure 4-2: Photographs of the recognized geosites in Alagna Valsesia; 1) Alpe Stofful, 2) Alto Piano di Cimalegna, 3)Massiccio del Monte Rosa, 4) Miniere Aurifere del Monte Rosa, 5) Miniere di Otro, 6) Pulfer Stein, 7) Stolemberg, 8) Val d'Otro

Once all the eight geosites within the study area were selected from the existing database of geosites in Monte Rosa from a previous study by Perotti et al. (2020). Geosites were selected considering their geographical locations and primary significance, ensuring that the chosen locations span the entire study area and offer comprehensive coverage of its diverse geological characteristics. Moreover, an extensive inventory of these geosites was developed based on the existing literature. This inventory process involved a systematic compilation and documentation of each geosite, cataloging essential information such as geosites name, description, geological unit, elevation, first and second scientific interest, importance, and primary and secondary interest. The results of the inventory of geosites are presented in figure 4-3.

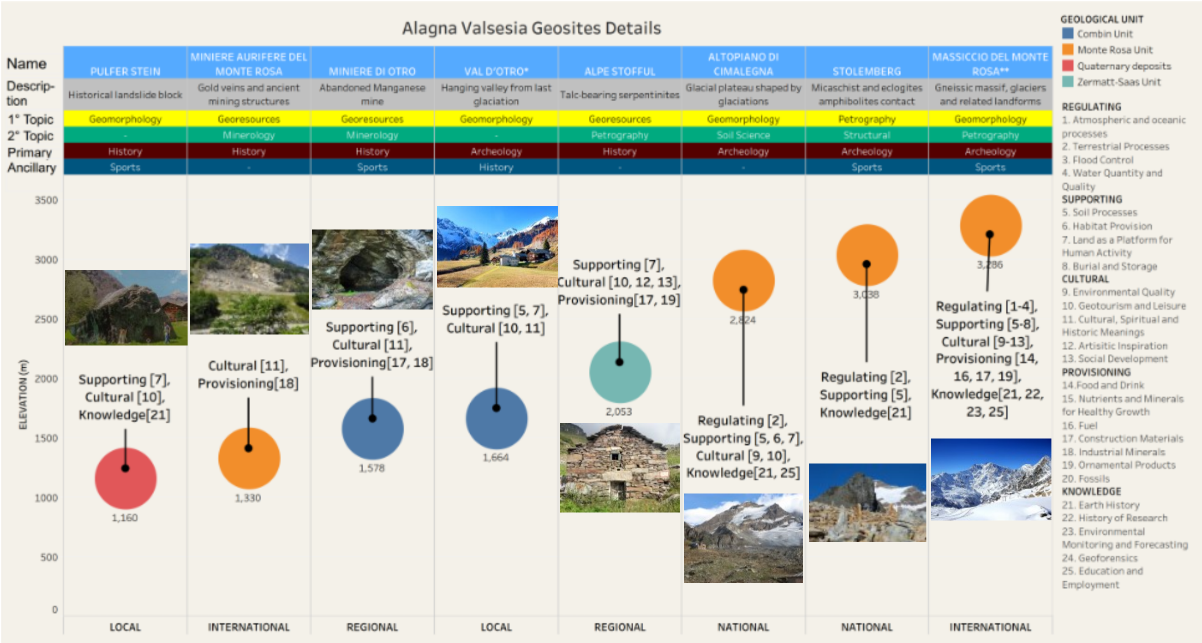


Figure 4-3: Inventory of geosites and their classification based on geosystem services by Gray, 2013

### 4.1.1 Geosites evaluation

Figure 4-4 presents the results of the geosite assessment for the eight identified geosites in the Alagna Valsesia region using the Suzuki and Takagi (2018) model. When evaluating the quality of geosites, the system considers several factors of great depth. In order to accurately assess each geosite, the following aspects are broken down into a list that includes a geosite's educational value (Ved), scientific value (Vsc), tourism value (Vtr), safety and accessibility (Vsa), conservation value and site sustainability (Vcs), and tourist information (Vti).

Distinctive criteria as shown in table 3-2 is used to measure the quality of each geosite, and the result is displayed on a radar chart (see Fig. 4-4). The geosites that earn this score are the ones that are the closest to the outer edge of the radar chart. The coordinates of the geosite on the chart show how well that geosite performed in each of the subject criteria. The numbers by the coordinates show the rating for each criterion; for example, a 3.8 next to Altopiano Cimalegna is the numerical rating that the geosite received for scientific value.

The radar charts show a visual distribution of how each geosite scores across all criteria. A geosite with a larger enclosed area on the radar chart indicates a higher overall rating across all assessed criteria. This visual representation allows for a quick comparison between the geosites in terms of their overall value and can help identify strengths and weaknesses of each site.

When comparing the eight geosites in Alagna Valsesia, starting with educational value, sites like Miniere Otro, Val d'Otro and Massiccio Monte Rosa stand out with relatively high scores, suggesting they offer robust educational experiences, due to their clear geological features and historical significance. However, Stolemberg and Alpe Stofful have a lower score, which indicates fewer educational resources and less obvious educational aspects within the site. In terms of scientific value, Miniere Aurifere has a high score, followed by Altopiano Cimalegna, Massiccio Monte Rosa, and Stolemberg indicating significant geological importance and uniqueness. Whereas Pulfer Stein and Alpe Stofful with lower scores, lack unique scientific features. The tourism value is particularly high for Altopiano Cimalegna, Miniere Otro and Alpe Stofful suggesting these sites are well-frequented by tourists due to their beauty and recreational possibilities. On the other hand, Miniere Aurifere has moderate appeal, which points to a need for better tourism infrastructure and enhancement. Concerning safety and accessibility, Pulfer Stein, Miniere Aurifere and Altopiano Cimalegna turn out to be more accessible and safer compared to others, indicated by their higher scores. While Stolemberg scores the lowest and this affects its potential for tourism and education if visitors cannot easily and safely access the site. Miniere Otro, Val d’Otro and Massiccio Monte Rosa also have room for improvement in this area. For conservation value and site sustainability, Stolemberg scores highly, suggesting effective conservation measures are in place, whereas Miniere Aurifere needs more robust conservation strategies to ensure its preservation. Lastly, when it comes to tourist information, Miniere Otro, Val d’Otro and Massiccio Monte Rosa geosites score particularly high. While remaining geosites have an average score, therefore suggesting that while there are some informational resources available across the sites, there is an opportunity to enhance the educational materials and resources to better inform visitors about the geological and natural importance of these areas.

Overall, Altopiano Cimalegna and Massiccio Monte Rosa stand out as well-rounded sites with high educational, scientific, tourism and conservation values, though they may benefit from improved safety measures and enhanced tourist information. Stolemberg tends to require the most attention across all criteria to reach its full potential as a geosite. Each site has its own strengths and weaknesses, and a comparative approach helps to identify where investment and improvement could most effectively enhance the value and experience of each unique geosite.

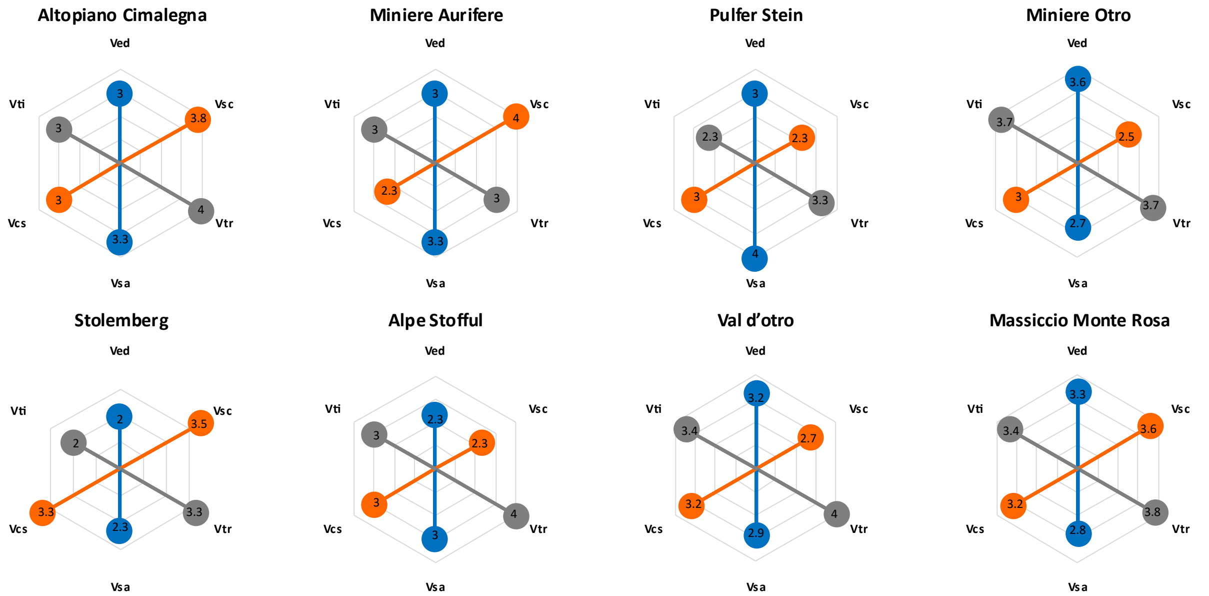


Figure 4-4: Comprehensive evaluation results of 8 selected geosites in Alagna Valsesia: a radar chart analysis comparing educational, scientific, tourism, safety, conservation, and informational values.

Utilizing the bar graph in figure 4-5, the geosite can be depicted in a spatial sequence that aids in understanding the interplay between natural elements and human influences within a specific locale. It should be recognized that the obtained results are comparable exclusively for sites that fall into similar categories.

Geosites that have the highest scores in the overall assessment may be assigned as potential geotourism sites or may require additional management measures to enhance their condition as necessary. Conversely, sites where tourism or educational visits could potentially harm scientifically valuable attributes should remain closed to the public. Our assessment initiates with the components of natural heritage (indicated by the orange axis in Fig. 4-4) to ascertain a site's suitability for such uses and to identify alternative measures or appropriate actions to minimize the risk of harm. As a result, sites that are highly significant from a scientific standpoint (Vsc) yet have low scores in conservation and sustainability (Vcs) should be given priority in terms of protection, which might include limiting access and usage. When organizing any on-site activities, it is crucial to check safety and accessibility conditions, which can often be enhanced by constructing parking lots, walkways, or fences, although such infrastructure should be designed to be as non-intrusive as possible.

In the current analysis, the Altopiano di Cimalegna and Massiccio Monte Rosa emerged as the top-ranking areas in the assessment results (as seen in Fig. 4-5), with Val d'Otro and Miniere Otro also scoring notably high. These sites stood out across four key metrics: elements of natural heritage (Vcs, Vsc) and convenience and attraction for geotourism (Vtr, Vti). Their prominent position is largely due to the ease of accessibility and the rich geodiversity they offer. On the lower end, Stolemberg received the minimal overall score, reflecting its limited educational value and less accessible location, despite its high conservation status. Alpe Stofful was similarly positioned low, with its deficiencies in natural heritage and educational resources overshadowing its geotourism potential. The modest scores for Alpe Stofful are thought to stem from underdeveloped geopark facilities and a weak presentation of its scientific and educational aspects.

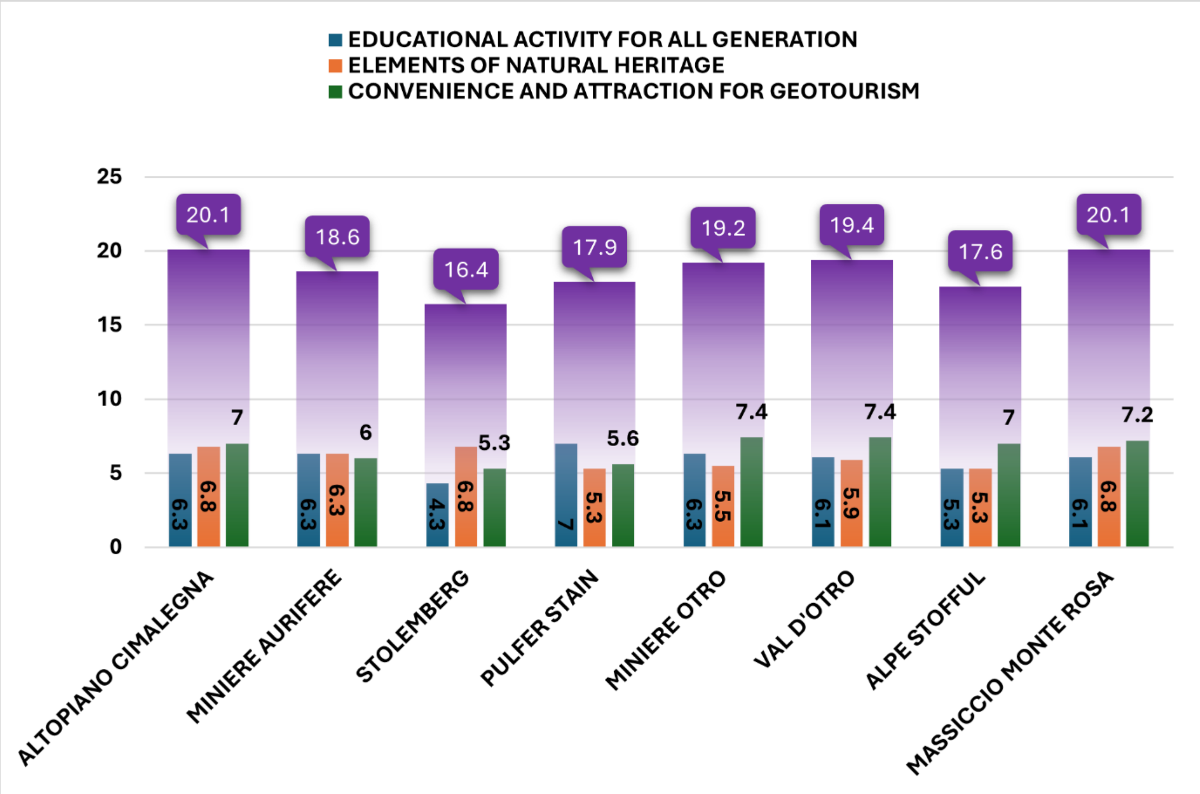


Figure 4-5: Differences in the evaluation results of the selected geosites (Ved + Vsa = Educational activity for all generation; Vsc + Vcs = Elements of natural heritage; Vtr + Vti = Convenience and attraction for geotourism)

## 4.2 Geosystems services map

As shown in Figure 4-6, the Geosystem Services Map created during this study shows the geodiversity aspects that provide geosystem services in Alagna Valsesia. Defined as regulating, supporting, provisioning, cultural, and knowledge services, each contributes differently yet substantially to the environment and wellbeing of society.

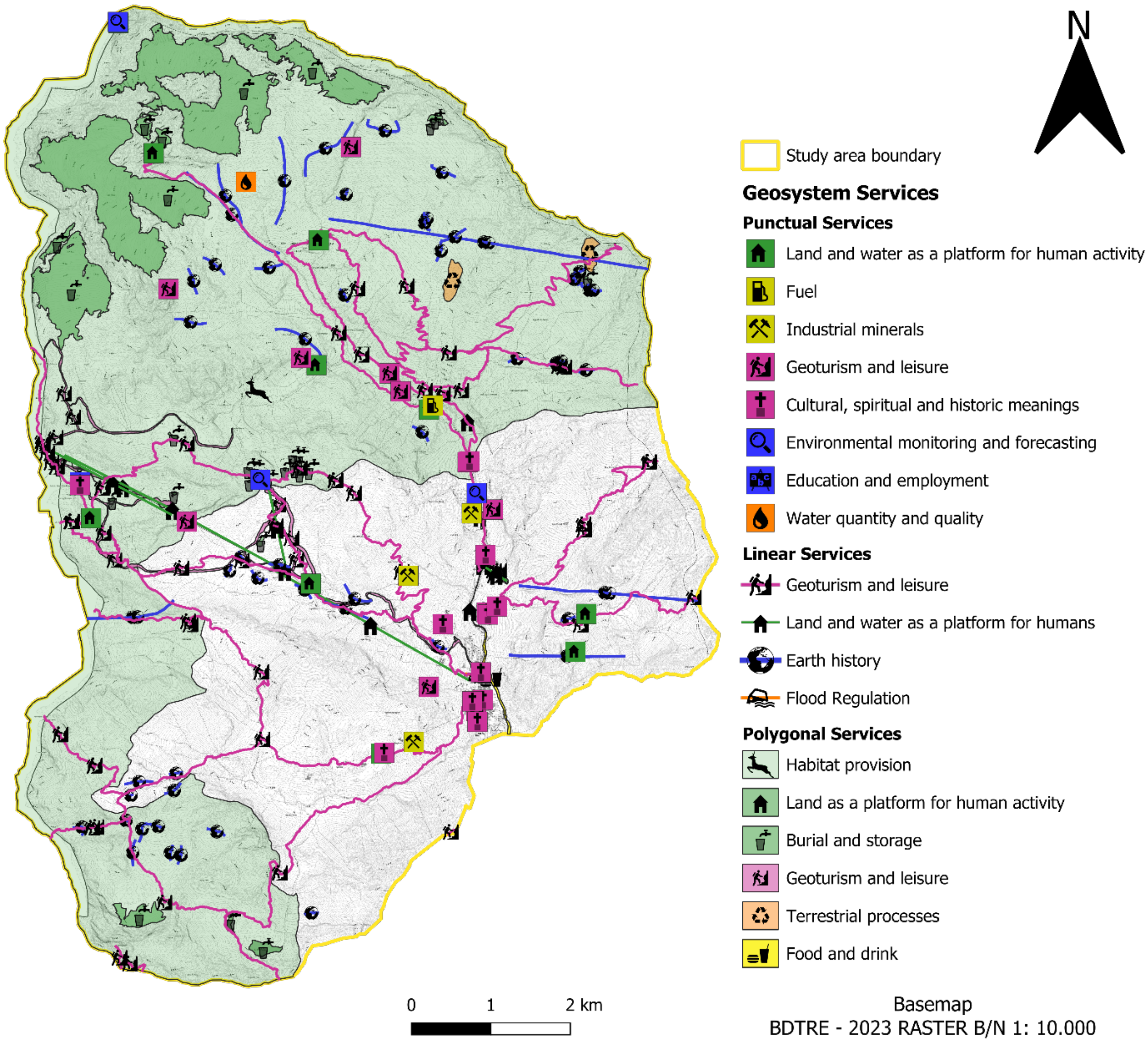


Figure 4-6: Map of geosystem services in Alagna Valsesia

Further, Figure 4-7, details the distribution of geosystem services in the study area, divided into Regulating, Supporting, Provisioning, Cultural, and Knowledge services.

- Regulating services: the study area has three regulatory services, accounting for 2.07% of geosystem services. Despite their tiny share, these services balance natural processes including terrestrial processes, flood regulation, and water quality regulation, affecting the entire geo-ecosystem.
- Supporting services: Supporting services make up approximately 25.21% of geosystem services and include services like habitat provision, land and water as a platform for human activity, and burial and storage sites. These services are essential for all geo-

ecosystem functions, human activities, and create the framework for all other services. The area's strong supporting service presence reflects a healthy underlying environment.

- Provisioning services: these services account for 2.07% of the total distribution. These services include food and drink, Fuel (hydroelectric power energy), and industrial minerals. The count is insignificant, but these services contribute to the local economy and maybe larger economies, therefore, should not be underestimated.
- Cultural services: Similar to supporting services, cultural services account for 25.21% of all services and include services related to geotourism and leisure, and cultural, spiritual and historic meanings. These non-material services improve spirituality, cognition, introspection, recreation, and aesthetics. Their presence in the study area highlights the cultural heritage, recreational, and tourist relevance.
- Knowledge services: The knowledge services, accounting for 45.45% of all services, is the most abundant category in our study area. These comprise earth history, geoforensics, and education and employment. The analysis of these geosystem services is undertaken to determine their inherent worth and potential knowledge for future generations. This could include unique geodiversity, biodiversity, significant geological formations, or other scientific areas of interest. The high percentage of knowledge services in the study area indicates the considerable potential for academic research and conservation efforts.

Supporting, cultural, and knowledge services are widely spread throughout our study area, whereas regulatory and provisioning services are limited. This highlights the complexity and richness of the area's geodiversity, its scientific, cultural, and supportive importance, and key conservation areas.

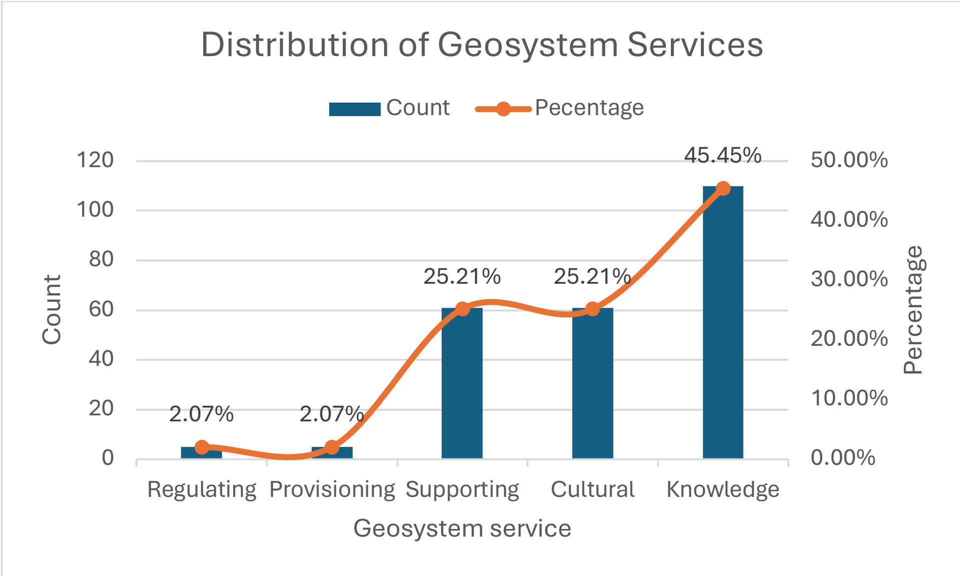


Figure 4-7: Distribution of geosystem services in Alagna Valsesia

Table 4-1, quantifies and distributes geosystem services in the research area by feature type: polygonal, linear, and punctual. It shows the count and physical size (area for polygonal, length for linear) of each geosystem service. Notably, the table indicates a large representation of supporting services in polygonal features, whereas cultural and knowledge services dominate in linear features, revealing geosystem service spatial distribution and popularity. However, the point features cannot be represented in length or area, thus, based on number of occurrence, cultural and supporting services are widely spread in the area.

Table 4-1: Geosystem services distribution and quantification by polygonal, linear, and punctual features in Alagna Valsesia

| **Polygonal features** | | | **Linear features** | | | **Punctual features** | |
|---|---|---|---|---|---|---|---|
| Geosystem service | Count | Area ($m^2$) | Geosystem Service | Count | Length (m) | Geosystem service | Count |
| Regulating | 2 | 136975 | Regulating | 2 | 624 | Regulating | 1 |
| Supporting | 33 | 53413929 | Supporting | 18 | 18462 | Supporting | 10 |
| Provisioning | 1 | 35588 | Provisioning | - | - | Provisioning | 4 |
| Cultural | 10 | 460490 | Cultural | 29 | 89529 | Cultural | 22 |
| Knowledge | - | - | Knowledge | 106 | 48822 | Knowledge | 4 |

## 4.3 DPSIR Results

### 4.3.1 Identification of the DPSIR components

Table 4-2 presents a systematic breakdown of the DPSIR framework as applied to our study area, structuring the complex interplay between environmental dynamics and human activities. It categorically maps out the sequence from drivers to impacts, capturing the progression from initial environmental or human-induced changes to their ultimate consequences. This structured approach enables a clear visualization of the pathways through which different drivers exert pressures on the environment, how these pressures alter the state of the system, and the subsequent impacts that emerge from these changes. Such an organized representation aids in discerning the multifaceted nature of environmental challenges and underpins the need for a nuanced understanding when formulating response strategies.

Table 4-2: List of DPSIR components identified in Alagna Valsesia

| Drivers | Pressures | States | Impacts | Responses |
|---|---|---|---|---|
| Precipitation | The more frequent extreme events by rainfall; The decrease in snow precipitation | Debris flow; Floods; Exposed land | Loss of land and property; Loss of resources; Freeze and thaw cycles | Implementing early warning systems; Enhancing flood defenses; Managing land use to reduce exposure; Promoting resilient infrastructure; Reforestation efforts |
| Temperature | Melting of ice & snow cover | Slope instability; Avalanches | Increased slope angle; Damage to utilities & communication | Developing avalanche control measures; Strengthening slope stability; Adapting building codes for temperature changes; Monitoring and forecasting temperature extremes |
| Glaciers | Glacial and Paraglacial processes; Glacial shrinkage | Moraine formation; Development of torrents; Moraine slope angle increase; Rock instability in moraines; New Lake formation | Changing landform or landscape; Landslides (Rockfall, Debris flow, etc); Increased erosion; GLOF | Monitoring glacier changes; Implementing land use planning in glacier areas; Engineering solutions for unstable slopes; Glacial Lake outburst flood (GLOF) risk management |
| Rivers Torrents | Fluvial Processes | Debris flow; Floods; Temporary regimes | Loss of land and property; Loss of resources; Altering organic material deposition | Enhancing river management and floodplain restoration; Improving sediment management; Establishing buffer zones along |

| | | | | |
|---|---|---|---|---|
| | | | | rivers; Utilizing green infrastructure for flood control |
| Tourism & Recreation | Water use for ski tourism; excessive tourists | Exploitation of natural resources; Water stress | Soil erosion; Increased pollution | Implementing sustainable tourism practices; Regulating tourist numbers; Promoting eco-friendly activities; Enhancing water conservation measures |
| Infrastructure development | Changes in land use and landcover | Artificial (man-made) ground | Change in natural landscape; Loss of geodiversity | Implementing strategic environmental assessments; Promoting green infrastructure; Balancing development with conservation; Reforestation and land restoration |
| Energy consumption | Increased energy demand; Water abstraction | High end consumption; Reduced water quality and quantity; Altered hydrological regimes of streams and rivers | Local economic stress; Loss of hydro-geodiversity | Promoting renewable energy sources; Improving energy efficiency; Implementing water-saving technologies; Encouraging low-impact energy consumption |
| Transportation | Environmental pollution | Decreased environmental quality | Increase in extreme events | Developing sustainable transportation systems; Encouraging public transit and eco-friendly vehicles; Implementing pollution control measures; |

### 4.3.2 Explanation of DPSIR components

*4.3.2.1 Drivers of Change in Alagna Valsesia*

1) Precipitation and Temperature Variations

Sensitivity to changes in precipitation and temperature is of paramount importance among the environmental domains. Changes in precipitation patterns such as an increase in the frequency and intensity of rainfall, have significant impacts on the hydrological dynamics of mountain geo-ecosystems. In a similar way, the changing climatology through an increase in temperatures in these regions, affects most of the geo-biophysical processes. These climatic drivers drive a lot of environmental changes thus the need for careful monitoring and forecasting in designing and implementing adaptive management strategies.

2) Glacial Dynamics

The importance of glaciers in Alagna Valsesia, is not only represented by their existence in a form of physical characteristic, but it lies in the complexity of the relationships established by these formations with the larger system in which they are immersed. Glaciers are not to be considered, as a matter of fact, mere static entities to whom warm climates oppose, sometimes on the grounds of sophisticated climate changes. Instead, glaciers are active agents modifying the related surroundings. Through their shrinkage, in fact, glaciers are powerful: as they rearrange landscapes, sizes and dispositions of water bodies, or, on a smaller scale, even local climate conditions. The knowledge of glaciers' dynamics is hence crucial in order to anticipate the impact throughout Alagna Valsesia, where glaciers play such an important role to the changing climate and availability of water.

3) River and Torrent Activity

Rivers and torrents with their nonstop fluvial processes are surely the natural drivers that shape landscapes and because of this they are very important giving the geomorphologic character of their territories where they flow along. The modification of terrestrial and aquatic environment boundaries, driven by water bodies, is of great significance when considering interactions with other environmental elements and human structures.

4) Tourism and Recreation

The impacts of tourism and recreation on socio-economic aspects, particularly in areas of environmental significance like Alagna Valsesia, can be very significant. The arrival of tourists and their involvement in many different activities can affect land use and resource distribution with regard to the needs of the tourist, creating structural alterations with serious consequences. Although tourism offers important economic benefits, tourism can also place heavy pressure on the environment, which may be a case of careful resource management for ensuring long-term sustainability.

5) Infrastructure Development

A major driver of change in the natural landscape is the alteration of natural landscape and the conversion of land for human use, mainly in relation to infrastructure development, which typically has important environmental change implications as a consequence. Development in the form of roads, buildings and other human spread alterations to habitat fragmentation and can alter local geo-ecosystems. Depending upon the scale and type of infrastructure, the implications across a region can be massive for geodiversity at a regional scale and also the integrity of the environment.

6) Energy Consumption

The consumption of energy is associated with the economic growth of Alagna Valsesia and the ski industry. As societies demand more energy, the methods of production and the energy sources used can lead to significant environmental changes. The patterns of energy use influence not only the local but also the global environment, intertwining with broader issues of resource depletion and climate change.

7) Transportation

The transportation sector is a significant driver of environmental change, shaping the development patterns of regions and influencing the mobility of populations and goods. Innovations and expansions in transportation infrastructure and vehicle use can lead to profound changes in environmental conditions, emphasizing the role of transportation planning and policy in environmental management strategies.

#### *4.3.2.2 Pressures Induced by Drivers*

1) Climate-Induced Pressures from Precipitation and Temperature

Alterations in precipitation patterns exert significant pressure on ecosystems through increased instances of extreme weather events. The more frequent and intense rainfall events create pressure on water management systems and natural water courses, potentially leading to erosion and changes in sediment transport. Simultaneously, a reduction in snow precipitation applies pressure on cold-region hydrology and snow-dependent ecosystems.

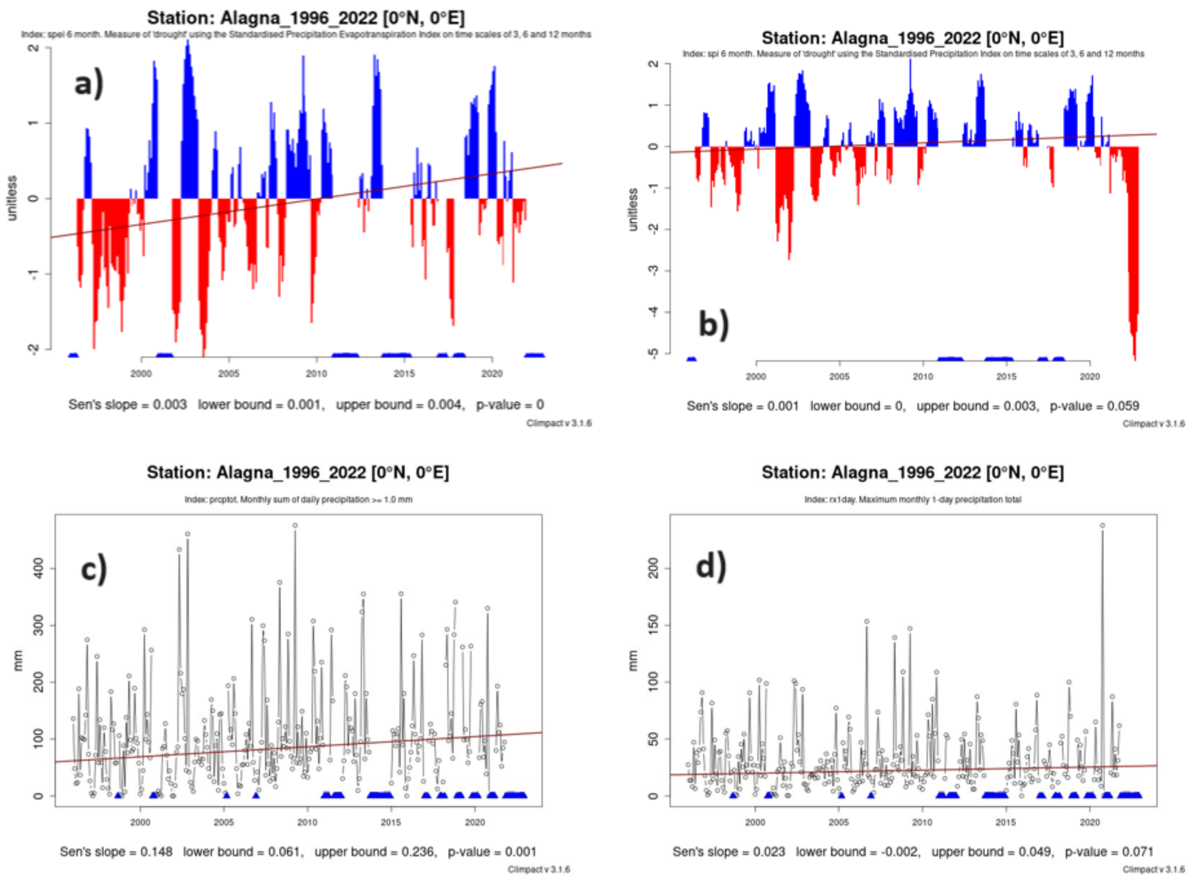


Figure 4-8: a) measure of drought using standardized precipitation evapotranspiration index (SPEI); b) measure of drought using standardized precipitation index (SPI); c) monthly sum of daily precipitation >=1.0mm; d) maximum monthly 1-day precipitation total

The Climpact software (see www.climpact-sci.org) was used to calculate climate indices used in this study. The data related to temperature and precipitation was obtained from Bocchetta delle Pisse weather station. Figure 4-8a indicates that while there have been fluctuations in moisture conditions (with both dry and wet periods), there is a statistically significant, although slight, increasing trend in the SPEI values over the last 26 years for Alagna. This could imply a tendency towards wetter conditions, but given the small slope, this trend is not particularly strong. Whereas figure 4-8b suggests a very slight but not statistically significant trend towards drier conditions at this location over the 26-year period. The particularly long red bar at the end of the series indicates an extreme drought event occurring in the most recent period of the data set. Moreover, figure 4-8c implies a statistically significant increase in monthly precipitation over the period from 1996 to 2022 at the station "Alagna." This increasing trend might be associated with changing weather patterns, which could have implications for water management, agriculture, and climate adaptation strategies in the region. Further, the figure 4-8d shows that there is a slight upward trend in the maximum 1-day precipitation totals per month over the 26-year period, but this trend is not statistically significant. This could imply that while there are months with extreme precipitation events, there is no strong evidence to say that these extremes are increasing or decreasing over time at this location.

Similarly, temperature increases exert pressure on natural systems by precipitating the melting of ice and snow cover. This not only directly affects water availability but also pressures the integrity of habitats that depend on perennial ice and snow for ecological balance.

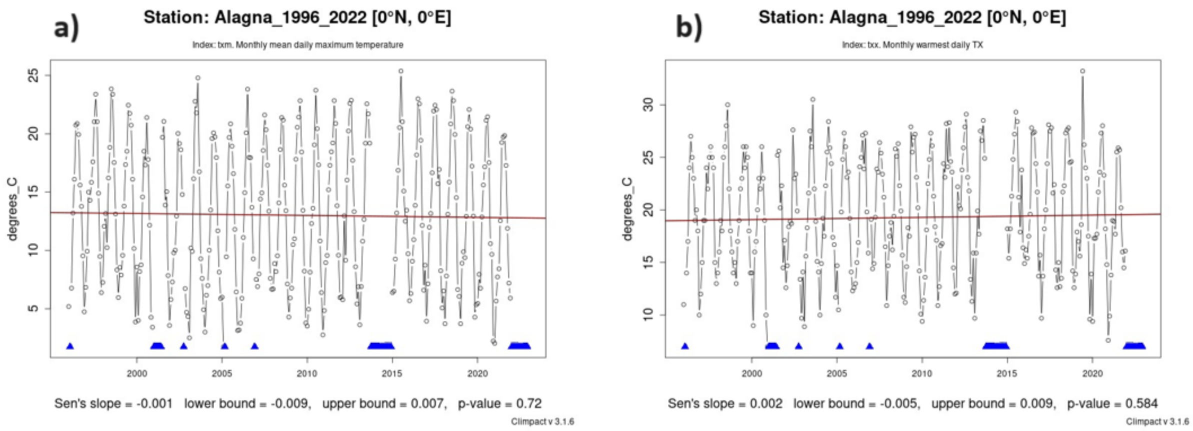


Figure 4-9: a) monthly mean daily maximum temperature; b) monthly warmest daily maximum temperature

Figure 4-9a suggests that there has been no significant trend in the monthly mean daily maximum temperatures at the station "Alagna" over the period from 1996 to 2022. The temperatures have fluctuated, but overall, they have not significantly increased or decreased according to the trend line and the statistical analysis. Figure 4-9b shows while there is a slight upward trend suggested by Sen's slope, the high p-value indicates that there is no significant change in the warmest daily maximum temperatures at the station "Alagna" over the 26-year period analyzed. This means that any observed increase in the monthly warmest temperatures is not statistically distinguishable from random variability in this data set.

2) Pressures from Glaciers

The retreat of glaciers presents direct pressures on both land and water systems. As glaciers shrink, pressures emerge in the form of altered freshwater availability and changes in sediment load downstream. Glacial and paraglacial processes also exert pressure on the stability of landscapes, potentially leading to increased rockfall or landslide activity.

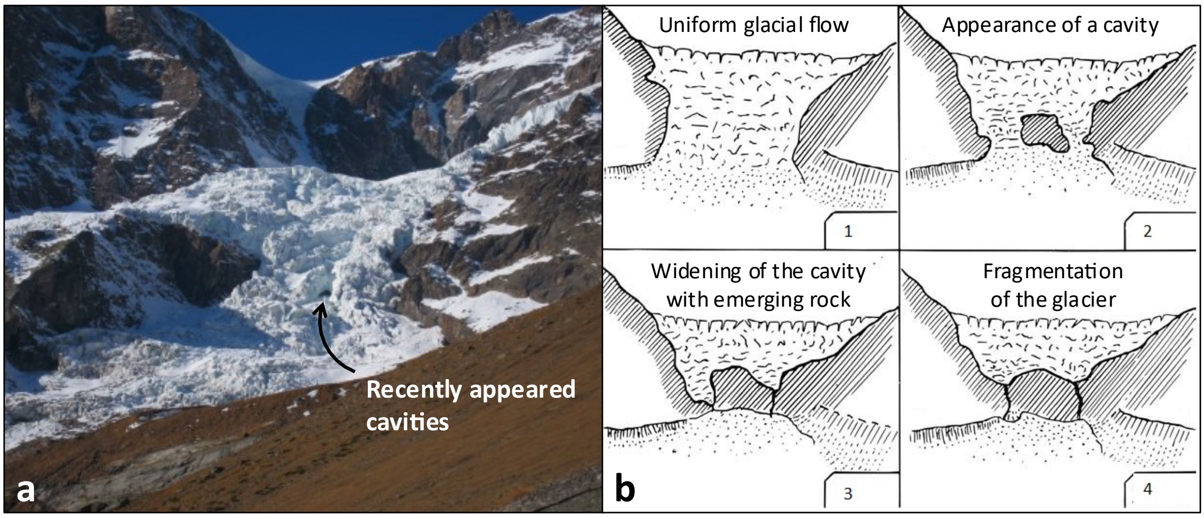


Figure 4-10: Melting of ice at Piode glacier (Image source: Cristina Viani)

As shown in figure 4-10, due to a rise in temperature, the Piode glacier has been experiencing increased melting. This isn't uniform across the glacier; most of the melting and shrinkage is happening at its base. Over time, this localized melting has led to the formation of a cave within the glacier. Moreover, this phenomenon is also causing the glacier to fragment or break apart into smaller pieces.

Increased melting combined with the destabilization of the glacial structure raises concerns for the surrounding areas. One immediate threat is ice falls, where chunks of ice break off and tumble down, which can be hazardous for anything or anyone in their path. Another significant concern is the potential for a Glacial Lake Outburst Flood (GLOF). As glaciers melt, they can form lakes that are often dammed by ice or glacial debris called moraines. If the dam breaks, it can result in catastrophic flooding downstream.

3) River and Torrent Dynamics

The natural processes associated with rivers and torrents exert pressure on the surrounding environments. Fluvial processes can pressure ecosystems through the alteration of river courses, flooding, debris flow and sediment deposition.

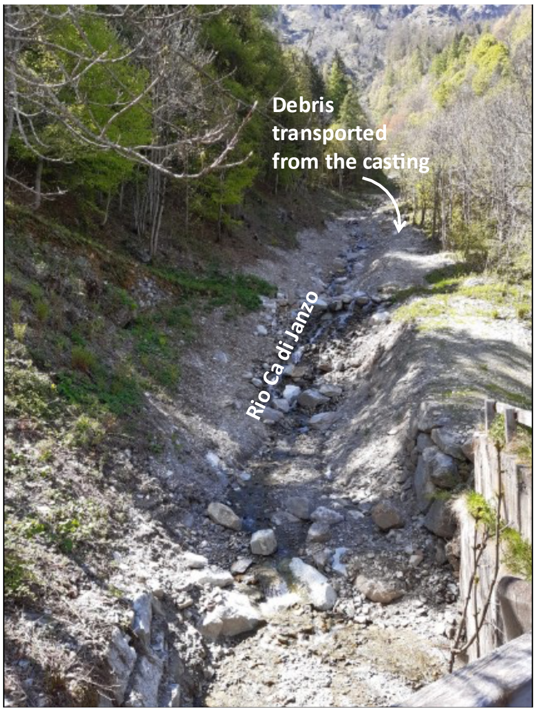


Figure 4-11: Debris flow (Image source: Cristina Viani)

As illustrated in figure 4-11, the Rio Ca di Janzo torrents play a central role in driving fluvial processes in the region. Torrents, being powerful streams of water, have a significant erosive power. In this context, the torrents have led to heightened erosion rates and the increased occurrence of debris flows. Debris flow, a moving mass of rock, mud, and water, can reshape landscapes and deposit sediment in new areas.

Such environmental changes can have direct implications for human activities in the region. Erosion and debris flows can lead to the loss of valuable land and damage critical infrastructure, posing challenges for the local community. Given these impacts, there's a pressing need for interventions. Effective flood management strategies are essential to prevent or minimize potential damage, and measures must be put in place to control runoff, thereby ensuring the safety and sustainability of human activities in the area.

4) Tourism and Recreation Pressures

The pressure from tourism and recreation manifests in the increased use of water resources for activities such as ski resorts and the pressure from foot traffic in sensitive areas. The influx of tourists can apply pressure through resource consumption and the physical impact on landscapes, potentially leading to socio-economic stress on the area.

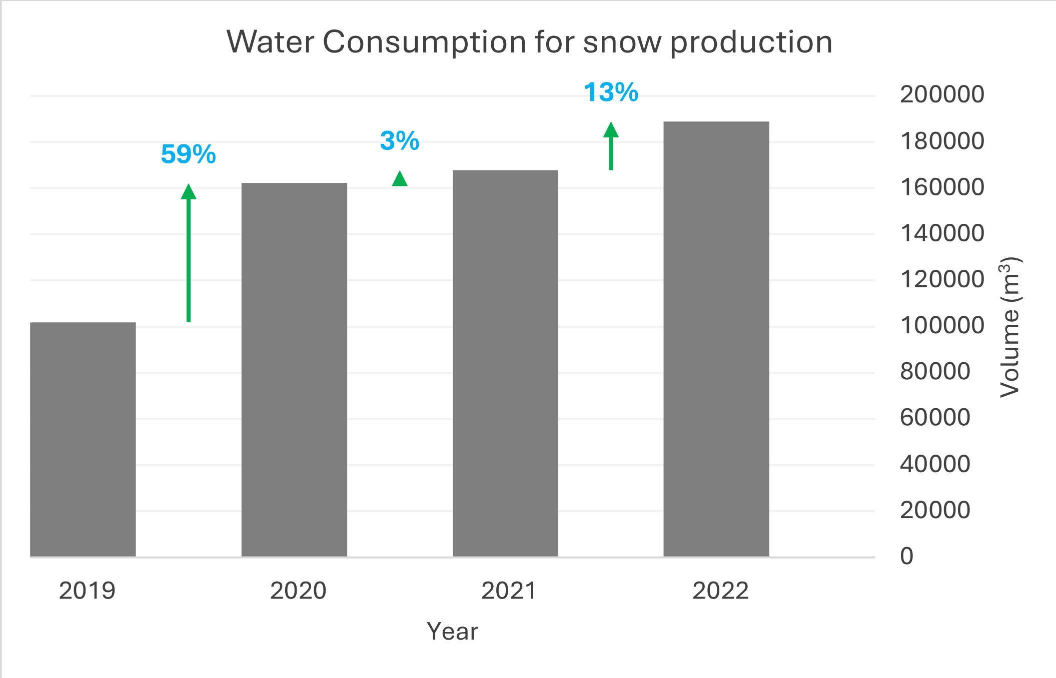


Figure 4-12: water usage for snow production (Source: Monterosa 2000, AWGP)

Figure 4-12 shows the water usage for snow production has been increasing over the specified years, which implies the higher number of tourists visiting the area for skiing activities. The most notable points from this chart are the significant jump in water consumption from 2019 to 2020, highlighted by a 59% increase, and another substantial increase of 13% from 2021 to 2022. Compared to those there was a slight increase from 2020 to 2021 which is mainly due to the smaller number of tourists visiting the area due to COVID-19, ultimately requiring less artificial snow, or a reduction in the operational scale or duration of the ski seasons. It seems that water consumption for snow production is generally on the rise over the years, with 2022 having the highest recorded volume.


Figure 4-13: Number of tourists entering Alagna Valsesia (Source: Monterosa 2000, AWGP)

Figure 4-13 depicts that in 2019, the first period (Jan-Apr) saw 107,096 tourists, while the following two seasons (Jun-Sep and Dec) experienced a significant decrease in number of tourists. In 2020, during the first season the number of tourists entering was 84,552 and decreased in the subsequent season to 31,790, and no tourists at the end of year because of the closure of location due to COVID-19 pandemic. During the year 2021, The first period had no visitors that suggests the impact of COVID-19 pandemic, later the subsequent seasons had 29,634 and 27,204 number of tourists, respectively. After the COVID-19 pandemic, 2022 started with a high number of tourists but comparatively lower than in 2019. However, maintaining the same number of tourists in the subsequent seasons (Jun-Sep and Dec), except the 2020 end and 2021 beginning season. There is a clear seasonal pattern with the peak season (Jan - Apr) typically having the highest number of tourists, except in 2021.

5) Infrastructure Development Pressures

Infrastructure development exerts considerable pressure on the environment, with the extent of this impact varying according to the scale of the projects, the vulnerability of local ecosystems, and the effectiveness of environmental safeguards. Land use changes from construction activities can lead to habitat fragmentation and loss, adversely affecting biodiversity. Similarly, soil sealing from urban expansion reduces the ground's natural absorption and filtration capacities, altering hydrological cycles and potentially exacerbating water management challenges. The specific degree of these pressures depends on the project's size and location, underlining the importance of comprehensive environmental assessments to gauge and mitigate negative impacts accurately.

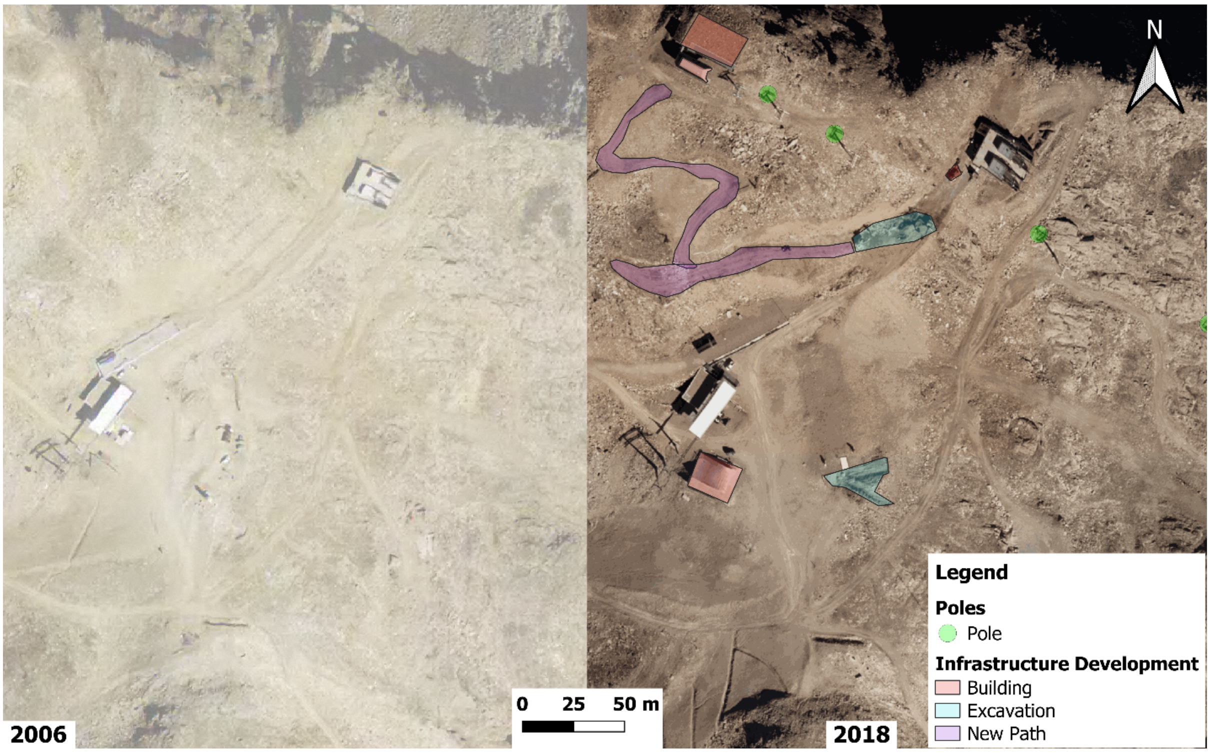


Figure 4-14: Infrastructural development changes from 2006 to 2018 at Cimalegna (Source: author contribution)

As shown in figure 4-14, in 2006, the area shows relatively few developments. There are a couple of isolated buildings with a network of dirt roads and paths. The terrain is largely barren, typical of an undeveloped landscape. On the right side, labeled 2018, the area has undergone significant changes. The purple areas indicate new paths or roads that have been constructed, providing improved access to the buildings and to new areas. The buildings are outlined in brown, and one can see that new structures have been added. There is also a marked area for excavation, suggesting construction activity, and the presence of poles for power lines or telecommunications, denoted by the green circles. This side-by-side comparison serves to illustrate the extent of human intervention and infrastructure development over a 12-year period. The new paths indicate increased traffic and accessibility, while the excavation area suggests economic development, such as the establishment of a new facility. The poles are a clear sign of infrastructure development, potentially improving utilities for the existing buildings.

An analysis of the infrastructural evolution within the Cimalegna region over the period spanning from 2006 to 2018 reveals a distribution of development across three primary categories. Construction of buildings accounts for 25% of the total area of development, reflecting a significant addition to the existing structural landscape. Excavated regions, indicative of developmental groundwork, comprise roughly 21.56% of the modifications. Furthermore, the most pronounced change is evident in the formation of pathways, which represent 53.44% of the altered area, underscoring a strategic expansion in access routes within the specified area.

6) Energy Consumption Pressures

The pressure from increased energy demand is twofold: it leads to higher emissions from energy production and puts pressure on water bodies through increased abstraction for ski industry as shown in figure 4-12. This drives changes in the demand and supply of resources, like water and energy.

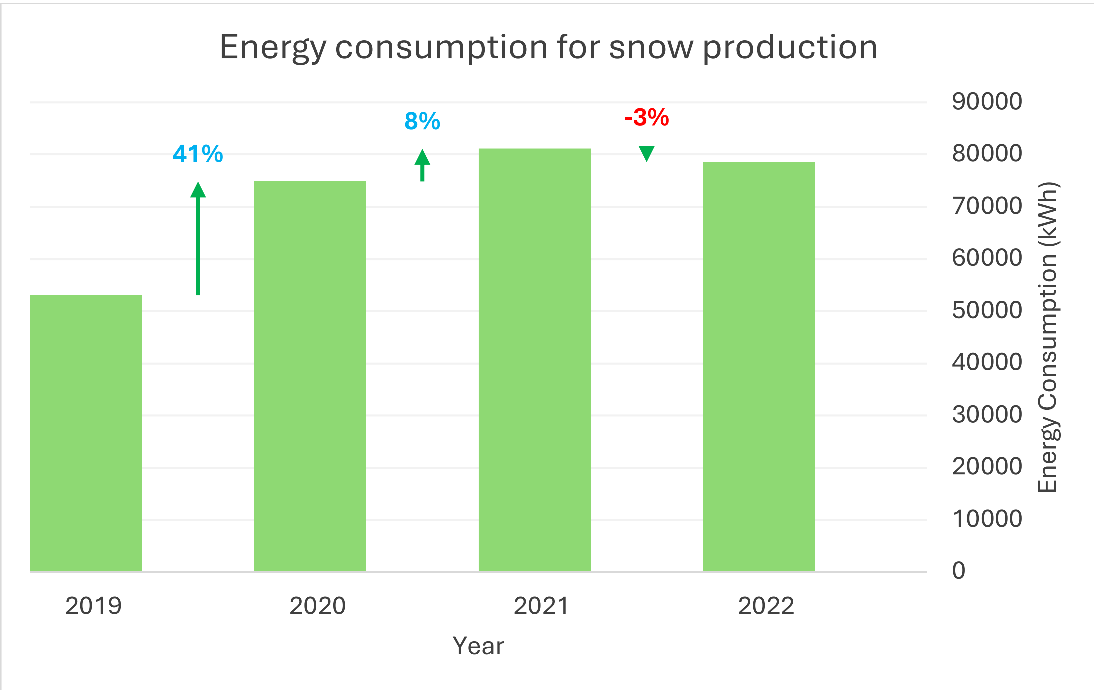


Figure 4-15: Energy consumption for production of artificial snow (Source: Monterosa 2000, AWGP)

Figure 4-15 shows the energy consumption for snow production from 2019 through 2022, detailing significant fluctuations over the four-year span. Starting in 2019, establishes a baseline for energy usage, which then escalates sharply by 41% in 2020, indicating a substantial increase in the energy required for producing snow. This surge might suggest a heightened demand for artificial snow or an expansion in snow production operations. The next year's rise continues, but it is less than the year before; there has been around 8% growth relative to the subsequent year which may represent a more stable demand or slightly less efficient manufacturing methods. In 2022 the trend declines, but only by around 3%; this may implicate improvements in snow making technologies, less snow making or favorable weather which requires fewer artificial snow. In the snow production industry, the latest year's information has pointed to a fluctuating energy landscape with a positive decline that can eventually be credited to environmentally friendly ways of production and operational changes.

7) Transportation-Related Pressures

Transportation exerts environmental pressure primarily through both air and noise pollution which degrades environmental quality. The expansion of transportation networks also puts pressure on land use and can lead to habitat disruption and fragmentation, directly affecting the connectivity and viability of ecosystems. These pressures do not have equal distribution either in time or in space, according to the data from municipal government (interview with Roberto Veggi, Mayor of Alagna Valsesia).

Seasonal tourism in Alagna Valsesia results in varying degrees of pressure during winter and summer. Data shows a significant difference: in winter, the municipal government of Alagna Valsesia notes an influx of 2,000 vehicles into the hamlet, with only 10% attributed to locals. The vehicular flow fluctuates in the shoulder seasons, with 1,000 to 1,500 cars arriving depending on snow conditions that attract winter sports enthusiasts. In contrast, during the peak summer period, particularly on weekends and the mid-August holiday, the area sees up to 1,000 cars. In terms of spatial impact, winter sees vehicles predominantly clustered along the main roads and parking areas adjacent to the Sesia river within the Alagna hamlet. Conversely, in summer, vehicles are more dispersed throughout the municipal area.

*4.3.2.3 Environmental States Resulting from Identified Pressures*

1) States Arising from Precipitation and Temperature Variations

The more frequent extreme weather events linked to precipitation exert substantial pressure leading to states such as increased debris flow, the prevalence of floods, and the exposure of land previously protected by vegetation or ice. These states reflect significant hydrological and geomorphological changes in the environment. As shown in figure 4-16, rivers, especially those with strong torrents, have the power to significantly shape and influence the valleys they flow through. In this context, the torrential river has exerted pressure on the valley bottom through various fluvial processes. One such process involves debris flows, which are mixtures of water, mud, and other materials. These flows tend to deposit their contents at the edges of the river, creating accumulations of sediment and other debris. Moreover, large floods from the river due to higher precipitation have inundated much of the valley bottom, leading to a landscape marked by multiple river channels, termed a "multi-channel landscape."

Given these dynamic and sometimes unpredictable river behaviors, the local population faced challenges. The threats of floods and debris flows posed risks to infrastructure, property, and resources situated close to the river. To minimize these risks, the community took a strategic approach to settlement. They decided to develop their villages on higher terraces away from the immediate vicinity of the torrent. By positioning their homes and infrastructure on these elevated areas, they provided a safer buffer against the river's potential threats.


Figure 4-16: River torrents pressurizing the valley bottoms due to fluctuated precipitation (Image source: Cristina Viani)

Rising temperatures cause states characterized by the melting of ice and snow cover, leading to slope instability and an increased risk of avalanches. The state of ecosystems that rely on cold temperatures is thus destabilized, with these areas becoming increasingly vulnerable to the associated geomorphological changes. In regions with snow and ice-covered terrains, increased melting due to temperature variations is causing destabilization of slopes. As the protective and stabilizing layer of snow and ice diminishes, the underlying slopes are left vulnerable. As shown in figure 4-17, The natural rock channels within these slopes serve as pathways for melted water, snow runoff, and sediment transport, including rock blocks. This flow can modify the slope's angle, potentially making it more unstable.

A consequential pressure from these changes is the risk of snow avalanches and debris flows. When combined with sediments and rocks, the force and speed of these avalanches increase significantly. These rapid and powerful movements pose a direct threat to infrastructures below, such as roads, buildings, and bridges. As such, areas prone to these geohazards need strategic planning and protective measures to mitigate potential damage.


Figure 4-17: Snow avalanches and debris flow caused by temperature variations (Image source: Cristina Viani)

2) States Related to Glaciers

The retreat and shrinkage of glaciers due to climatic pressures result in states that include moraine formation, development of torrents, and an increase in moraine slope angles. On numerous occasions, the stability of these rocks is weakened in the moraines which can cause new lakes to be formed and alter the basic functioning of local ecosystems by modifying their physio-chemical and hydrological bases.

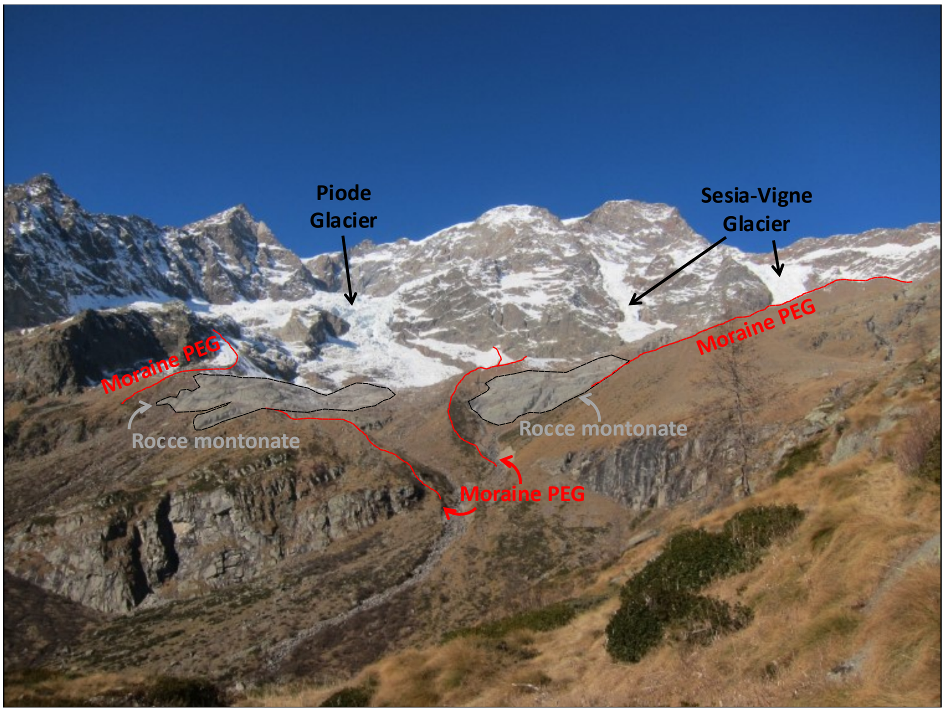


Figure 4-18: glacial shrinkage and formation of moraines (Image source: Cristina Viani)

The Piode and Sesia Vigne glaciers underwent significant fluctuations during and after the Little Ice Age (LIA). Because of these fluctuations, moraines were established. Moraines are essentially an accumulation of dirt and rocks that have been pushed along by a moving glacier, as shown in figure 4-18. After the retreat of these glaciers prompted by the LIA, the landscapes began showing substantial changes. One result was a steepening of the moraine slopes, and this increase was caused by the absent stabilizing mass of the glaciers. New torrents and powerful streams of water emerged in the study area. The formation of new torrents and streams of water continued to shape the area through an increase in erosion, the carving of paths, and the wearing away of the surface. A key result of this increased erosion was the exposure of 'roches moutonnées' - smoothed rock formations that have been sculpted by the passing glaciers.

Furthermore, figure 4-19 shows that in the past, glacial processes played a pivotal role in shaping our landscape, leading to the formation of lakes by acting as natural dams within valleys. Over time, however, the influence of running water, or fluvial erosion, has significantly altered these lake environments. This erosion has caused incisions, effectively cutting into the lake's threshold, which can change its size, depth, or even lead to its drainage. As a result, the landscape surrounding the lake evolves, showcasing a blend of ancient glacial imprints and the more recent effects of flowing water.

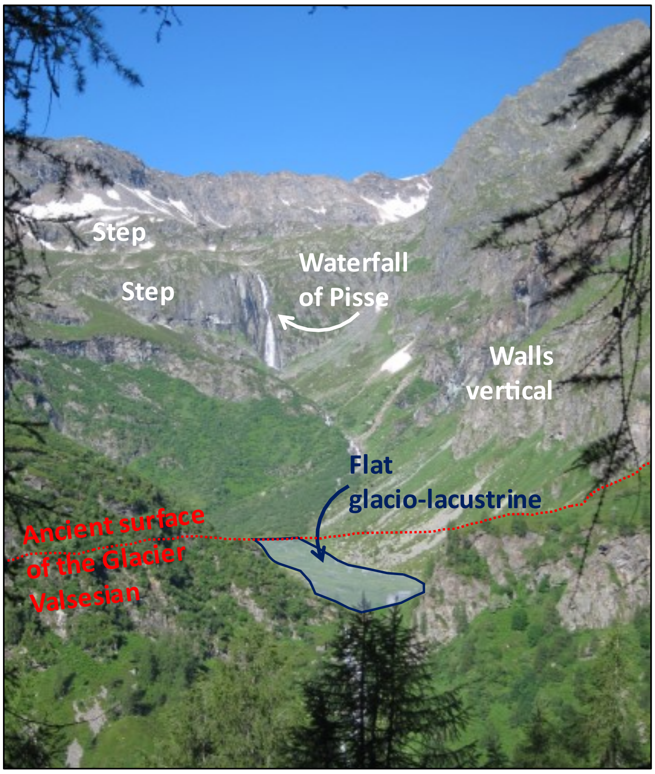


Figure 4-19: Ancient formation of lakes due to glacial processes (Image source: Cristina Viani)

3) States Influenced by River and Torrent Dynamics

The pressures from altered fluvial processes lead to states that manifest as changes in river flow, debris flow incidents, and frequent floods. Additionally, temporary regimes are altered, which might include the seasonal flow patterns of rivers and streams, influencing the overall state of aquatic and adjacent terrestrial ecosystems. As evident from figure 4-20, following the end of the glaciation period, rivers have become the primary agents driving fluvial processes in the region. These rivers transport glacial sediments, which are materials previously trapped or shaped by glaciers, and move them towards areas at lower altitudes.

Furthermore, the valleys, which were once sculpted and influenced by glaciers, are now undergoing "retrogressive erosion." This type of erosion means that the erosion works backward or uphill, reshaping the land progressively. As a result, what was once a glacial valley typically U-shaped due to the slow grinding of glaciers is being transformed into a fluvial valley, which tends to have a more V-shaped profile because of the cutting action of flowing water.

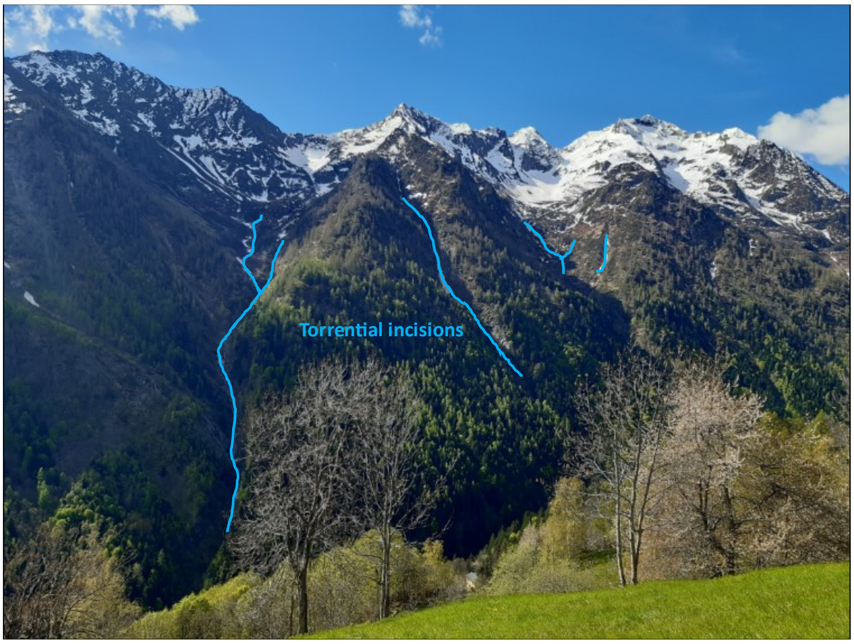


Figure 4-20: Torrential incisions due to fluvial processes (Image source: Cristina Viani)

4) States Arising from Tourism & Recreation

The exploitation of natural resources and water stress caused by tourism activities, particularly in sensitive mountain regions, change the state of these environments by diminishing water tables, altering natural flow regimes, and increasing the burden on local landscape.

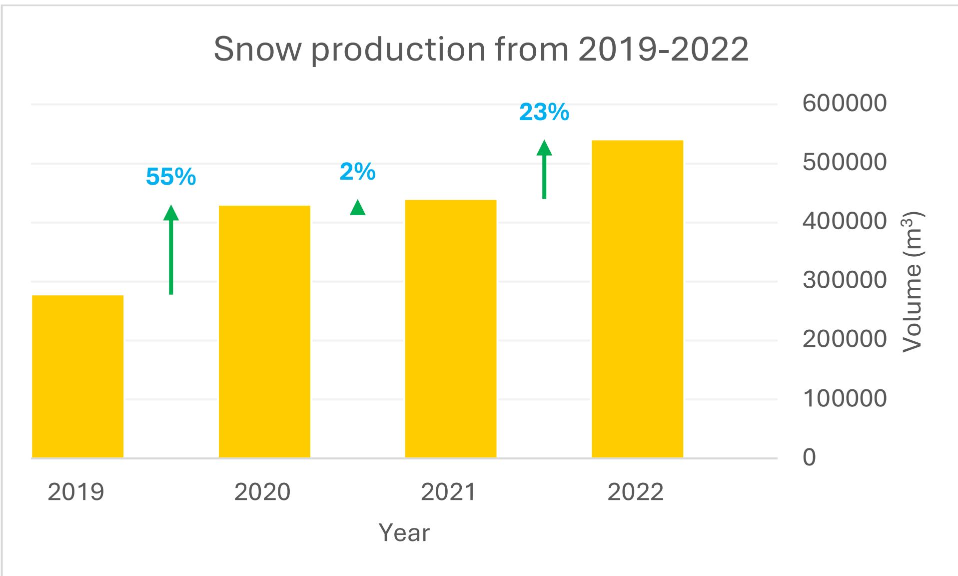


Figure 4-21: Artificial snow production in Alagna Valsesia (Source: Monterosa 2000, AWGP)

As figure 4-21 shows, snow production from 2019 to 2022 highlights the clear upward trend in the production of artificial snow. The year 2019 sets the baseline for the volume, which experiences a sharp increase of 55% in 2020, indicating a significant rise in snow production, potentially due to increased demand or an expansion in snow-making capabilities. The following year, 2021, sees a stabilization in production levels with a marginal increase of 2%, suggesting that the previous year's growth had met the demand or that operational capacities had reached a temporary level. However, in 2022, snow production ramps up again, this time by 23%, pointing to a further escalation in demand. This overall upward trajectory might be attributed to factors such as changing climate conditions, which reduce natural snowfall, and a boost in the popularity of winter sports that rely on artificial snow. The escalating snow production from 2019 to 2022 likely places a significant strain on water resources, considering the substantial volumes of water required for artificial snow. This increase in production underscores the potential for overexploitation of natural resources, as the process not only consumes substantial amounts of water but also demands considerable energy, which can lead to broader environmental impacts.

5) States Due to Infrastructure Development

Changes in land use and land cover due to the infrastructural development led to the change in state in the form of artificial (man-made) ground.

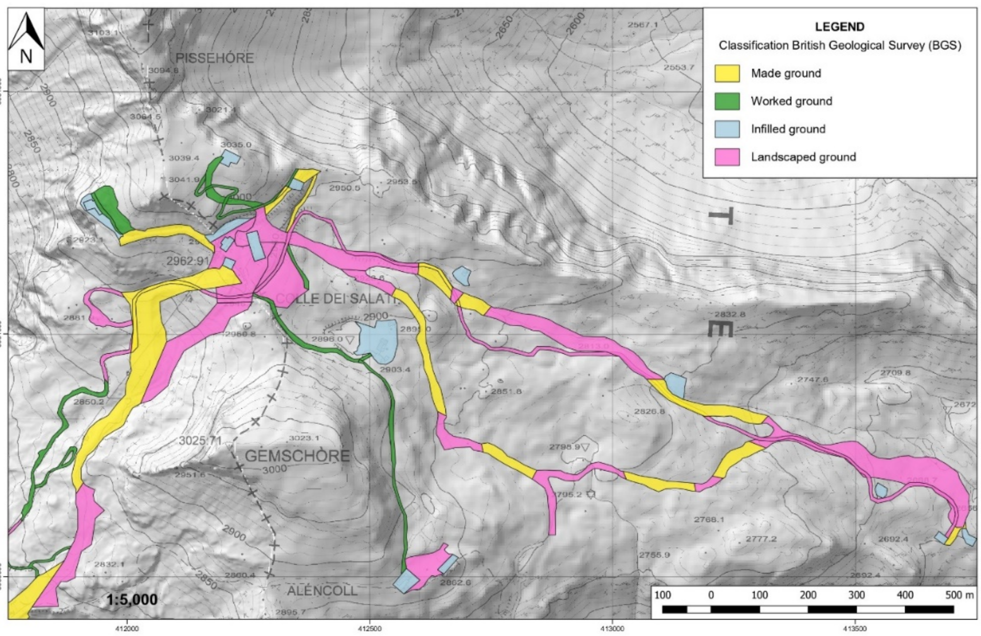


Figure 4-22: QGIS map of anthropic forms classified according to the BGS criteria (modified from Tognetto, 2019).

The topographical analysis as shown in figure 4-22, based on the British Geological Survey classifications, reveals significant human-induced alterations in the landscape. The map, characterized by contour lines depicting terrain elevation, shows extensive areas marked as 'Made ground' (in yellow), indicating substantial additions to the original landform for construction and development purposes. 'Worked ground' areas (in green) suggest regions that have undergone excavation and terrain leveling for preparatory groundwork for infrastructure. 'Infilled ground' (in blue) highlights depressions that have been filled, which denote land reclamation efforts. Lastly, 'Landscaped ground' (in pink) points to deliberate terrain sculpting for aesthetic and recreational (skiing) land use enhancements. The map underscores a pronounced transformation in the topography and usage of the land over the observed period, demonstrating the extent of human impact and the reshaping of the natural landscape to suit various anthropogenic needs.

6) States Triggered by Energy Consumption

The pressure from increased energy demand as shown in figure 4-15 and water abstraction as shown in figure 4-12; contributes to states of high-end consumption patterns, reflected in reduced water quality and quantity. Altered hydrological regimes of streams and rivers denote a state where traditional ecosystem functions and services are compromised.

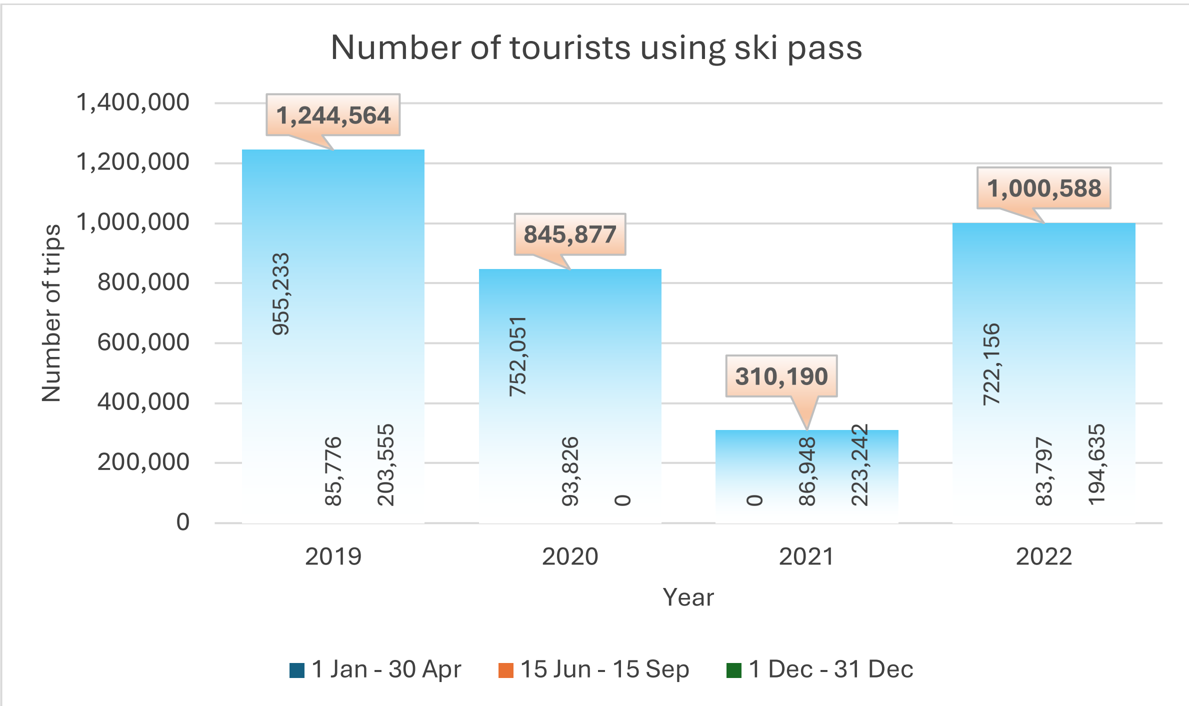


Figure 4-23: Passage of tourists (Source: Monterosa 2000, AWGP)

As shown in figure 4-23, In 2019, the first period (January 1st - April 30th) saw the highest usage with 955,233 ski pass users, indicating a busy winter season. The summer period (June 15th - September 15th) had a lower usage with 85,776, which is expected given that this is typically the off-season for ski activities. The end-of-year period (December 1st - 31st) recorded 203,555 users, suggesting some winter activity, likely tied to the holiday season. For 2020, there was a decrease in the number of users during the first period to 752,051, possibly due to the impact of the COVID-19 pandemic. Summer usage saw a slight increase from the previous year to 93,826, which could be due to ski resorts offering summer activities or tourists purchasing passes in anticipation of future seasons. Notably, there were zero ski pass users recorded in the December period of 2020, likely reflecting the significant restrictions and closures of ski resorts during the pandemic. In 2021, the first period shows no ski pass users, which points to extended closures and disruptions due to the pandemic. The summer period had a small increase in users to 86,948, and the December period showed a rebound in activity with 223,242 users, indicating a return of some winter tourism. The year 2022 continues this recovery trend with 722,156 users in the first period and 83,797 in the summer. The end-of-year number, while lower than the start of the year, is at 194,635, showing continued interest in winter activities, although not at the pre-pandemic level.

Overall, the data indicates significant fluctuations likely due to seasonal trends and the impacts of the COVID-19 pandemic, with a general pattern of recovery in 2021 and 2022. The zero values in certain periods highlight the extreme effects of the pandemic on tourism and the ski industry, with a gradual return to activity as conditions improve. These figures suggest robust tourist activity, likely translating into significant energy and water usage for snow production and maintenance of ski facilities. The marked peaks in ski pass usage during these periods are indicative of a seasonal surge in resource consumption, as ski resorts operate at full capacity to cater to the entry of tourists, which in turn could lead to a considerable socio-economic and environmental effects.

7) States from Transportation Activities

Environmental pollution from transportation pressures, notably through emissions and habitat fragmentation, lead to a decreased state of environmental quality. The introduction of pollutants can alter the state of both air and water quality, which can disrupt the equilibrium of biological communities and the physical structure of habitats.

#### *4.3.2.4 Environmental Impacts Resulting from Identified States*

1) Impacts from Precipitation and Temperature Variations

The states of increased debris flow and floods lead to the loss of land, property, and resources, disrupting human settlements and natural habitats. Exposed land as a state can result in freezing and thaw cycles that further degrade the land's stability and fertility. The state of melting ice and snow cover has profound impacts on local ecosystems, including increased slope angles, which may lead to an increase in the occurrence and severity of avalanches. Additionally, the damage to utilities and communication infrastructure can have far-reaching effects on human communities and economic activities.

As shown in figure 4-24, in the Otro valley, rising temperatures have led to significant melting of ice and snow cover. The melting of ice is not an isolated incident, but rather a continuous process that has had numerous implications for the stability of the landscape in the valley. Due to the melting of the snow and ice, the slopes that were supported by the frozen masses have lost their stability. This can result in various forms of instability. Instability resulting in avalanches is one of the forms that continues to present a significant imminent danger. An avalanche refers to the abrupt, sudden slippage of snow down a mountain slope.

Moreover, the river has undergone a significant transformation into a more formidable rapid as a result of the thawing ice and snow from both slopes of the valley, leading to an increased velocity of water through the valley bottom. Currently, there is a significant occurrence of retrogressive erosion in the valley bottom. Erosion has, in some cases, initiated at higher elevations along the valley sides and is actively downcutting as it progresses through the valley. Occasionally, certain valley sides exhibited an almost vertical inclination. Therefore, there is a risk of landslides occurring in the valley side.

The alterations in the environment within the Otro valley are crucial, particularly in relation to the human-made infrastructures. As a consequence of the slope becoming steeper and the increased probability of avalanches, there is a growing risk of infrastructure, such as roads, buildings, and bridges, being damaged or even obliterated by the changing environment. This demonstrates that the temperature has implications not only for environmental changes in the geological aspects but also for the well-being of individuals.

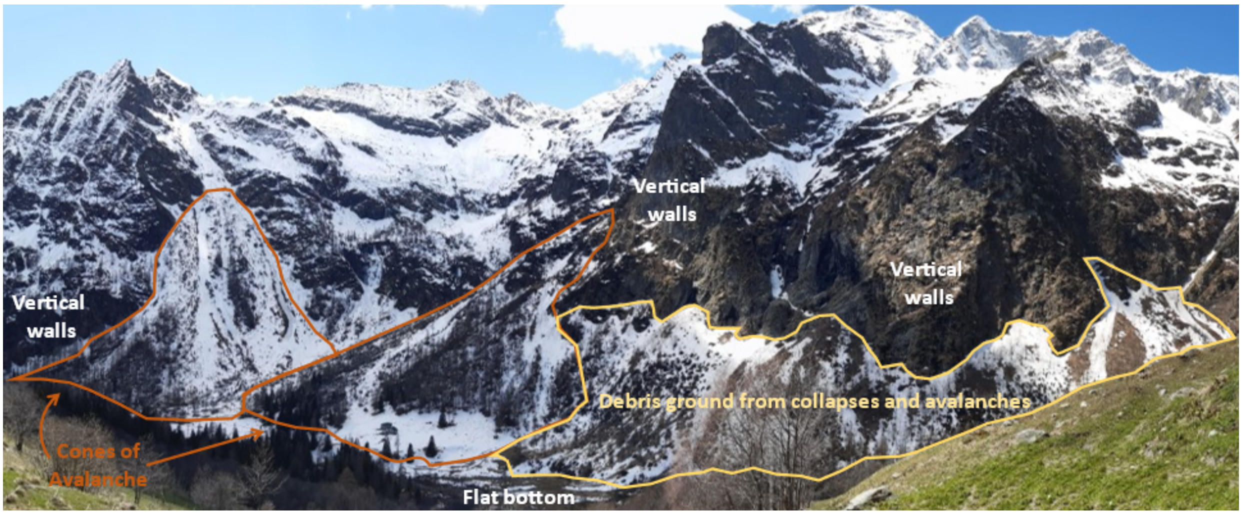


Figure 4-24: Impacts of temperature and pressure variations in Otro Valley (Image source: Cristina Viani)

2) Impacts from Glaciers

The presence of phenomena such as moraine formation and the development of torrents can lead to landscape changes that have significant implications. Rockfalls and landslides exemplify the two most fitting ways in which this biome experiences alteration. The retreat of glaciers can lead to catastrophic events through the formation of lakes. These lakes are commonly recognized as Glacial Lake Outburst Floods (GLOF) and pose a substantial threat to the environment. These events result in extensive flooding, erosion, and alterations to sedimentation patterns downstream. Corno Bianco is situated in the elevated Alpine Mountain range, known for its remarkable height. The Corno Bianco area is currently experiencing substantial changes. Figure 4-25 provides a clear outline of those changes. An important change to highlight is the shrinking of glaciers. It is quite evident that beneath the rock faces of Corno Bianco, the stability of once solid rock has been compromised due to the receding glaciers and the subsequent decrease in pressure, they exert leading to unstable state.

The glaciers historically played a vital role in buttressing or supporting these slopes. With their retreat, the once-held slopes are now more prone to movement and disintegration. This increased instability has led to the manifestation of landslides, where large volumes of rock, soil, and debris move swiftly downslope, affecting areas in their path.

Moreover, an intensified mode of erosion has been observed, erosion being defined as the gradual deterioration of the land surface caused by natural phenomena such as water and wind. The areas most affected are concentrated on the lower flatlands, specifically in the Corno

Bianco region. The topographical change is far from benign; it gives rise to multiple complications for ecosystems and any human settlements or infrastructures present in the vicinity.

The landscape of Corno Bianco is undergoing reshaping due to climatic fluctuations, resulting in the retreat of glaciers and a series of geomorphic changes. These changes will have a significant impact on both the natural and human environment on a larger scale.

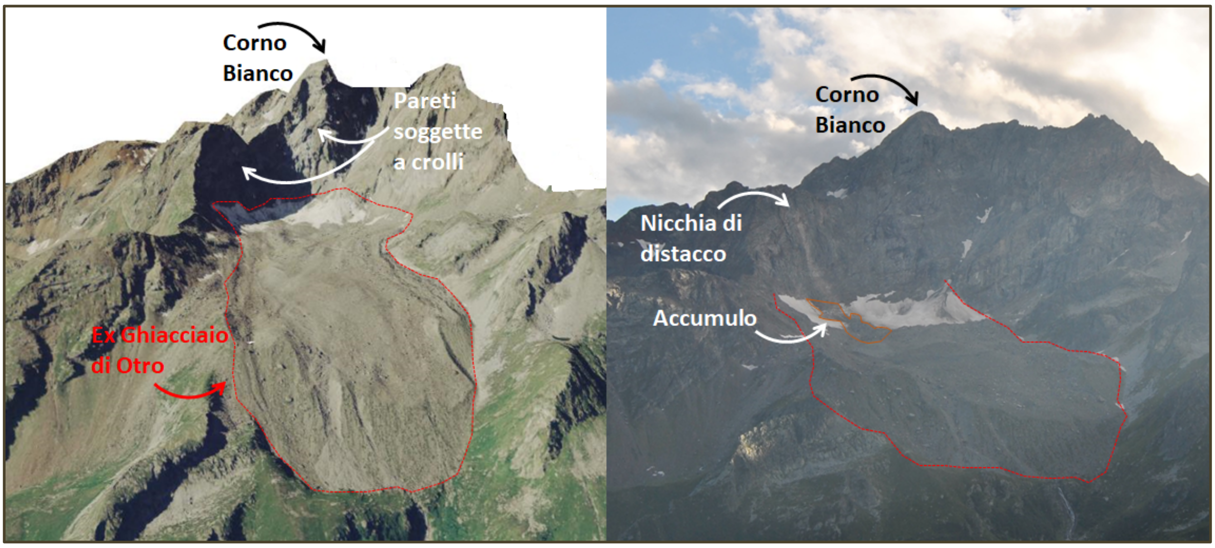


Figure 4-25: Impacts caused by the landslides and erosion (Image source: Cristina Viani)

3) Impacts from River and Torrent Dynamics

The alteration of the river flow can have an impact on the land and lead to the deposition of organic material. The deposition of organic material creates possibilities for the development of distinctive geological landscapes and increased productivity.

Figure 4-26: Impacts from river and torrents dynamics (Image source: Marco Giardino)

Figure 4-26 illustrates the intensification of the river as it passes through an urban area, implying an increased susceptibility to flooding and erosion. The presence of buildings and infrastructure, such as roads, indicates the continuous encroachment of human activity into river floodplains. The tangible outcome of such action is the loss of land, property, and resources. The occurrence of this unforeseen danger is attributed to the continuous flow of water, which can lead to erosion of the riverbanks. Consequently, the house that is built on these banks becomes even more vulnerable and incapable of supporting the adjacent property. The structure is put at risk and there is potential for the building to collapse. Additionally, the water supply becomes unreliable as the natural process of depositing organic material on the bank is disrupted. The boulders within the riverbed, shaped and smoothed by the persistent force of the flowing water, create natural barriers that alter the flow of the river, contributing to the instability.

Above the edge of the river, human habitation and modifications to the landscape are visible. There is a stone wall as a protective barrier. Buildings are nestled close to the river, highlighting the delicate balance between utilizing the beauty and resources of such an environment while risking the impacts of erosion and potential flooding. The lush grass vegetation along the banks suggests a rich, moist habitat, possibly subject to changes in sediment and organic material deposition caused by the variable flow of the river. Therefore, showing the dynamic interplay between natural watercourses and human settlement, underlining the importance of sustainable environmental management.

4) Impacts from Tourism & Recreation

The exploitation of natural resources and ensuing water stress impact soil ecosystems through erosion and degradation, leading to increased pollution from runoff and potentially a loss of geodiversity. Such impacts may also bring about changes in the natural landscape and loss of ecosystem services, which include water filtration and habitat provision.

Within the context of tourism and recreation, the impacts on Alagna are unequally experienced across different locations and times, according to the data from municipality of Alagna Valsesia. The resident population of Alagna, normally 700, increases significantly throughout the year due to tourist influx. During the winter peak season, the number increases with an additional 5,000 tourists staying as residents and 2,000 daily visitors from nearby regions. This concentration of activity, particularly in the Alagna hamlet, leads to a spike in pollution levels (based on the increased amount of garbage as stated by the municipal waste collection service), as it is the focal point for both tourist and local activities. In contrast, during the summer months, the tourists, alongside the local visitors, disperse across the entire municipal region. Their movement along trails, even reaching into the high mountain areas, contributes to and exacerbates soil erosion, also contributing to the dispersed littering which poses maintenance challenges.

5) Impacts from Infrastructure Development

The indicated modifications to the terrain as highlighted in figure 4-22 have had a multifaceted impact on the area. The creation of made ground and the processes leading to worked ground demonstrate a significant human footprint, possibly altering natural drainage patterns, affecting local ecosystems, and changing the visual landscape. Such alterations can increase the risk of erosion or flooding if not managed correctly. Infilled ground suggests areas that were previously unusable have been filled, which can lead to the displacement of wildlife habitats and the introduction of non-native soil materials. Meanwhile, the landscaped ground reflects a deliberate shaping of the land for aesthetic and functional purposes, which, while potentially enhancing recreational value and human enjoyment, also indicates a departure from the natural state of the environment.

Infrastructural development within the test area of the Cimalegna high plain caused changes in natural landscape due to the pressures highlighted in figure 4-14. Furthermore, the impact on geodiversity is testified by the loss of geodiversity of the alpine landscape, significant changes in landforms and superficial deposits have been recognized within the area, for example, 'roches moutonnées' moraine ridge block streams, pro talus ramparts, pavement stones, and rock glaciers. These transformations, driven by the needs of development, embody the complex interplay between progress and conservation, leaving permanent marks upon the landscape and its future potential.

6) Impacts from Energy Consumption

The impacts of the state of high energy consumption and altered hydrology include local economic stress due to unsustainable resource depletion. The loss of hydro-geodiversity reflects a diminishing of the natural variability of hydrological systems, which are critical for maintaining geo-ecological balance.

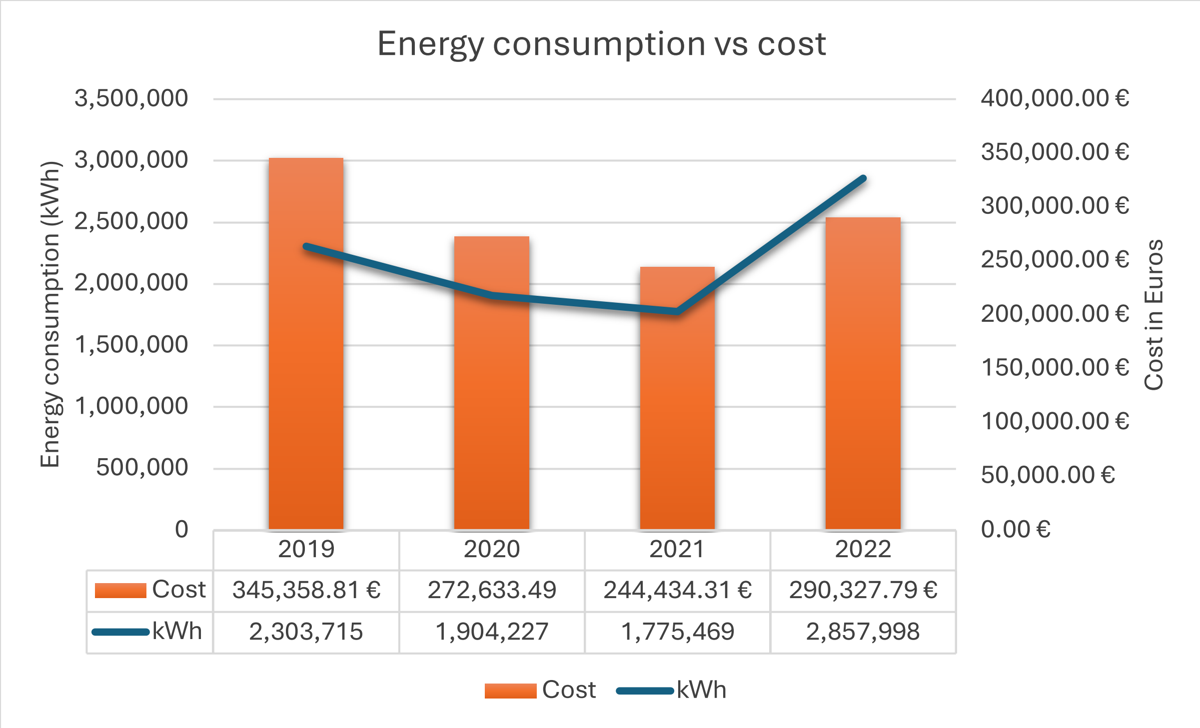


Figure 4-27: Energy consumption versus cost per kWh (Source: Monterosa 2000, AWGP)

Figure 4-27 provides a comparative analysis of energy consumption in kilowatt-hours (kWh) and its corresponding cost in euros over a span from 2019 to 2022. In 2019, there was a substantial consumption of energy amounting to approximately 2,303,715 kWh, incurring the highest cost observed over the four years at around €345,358.81. The following year, 2020, saw a reduction in both energy usage, with consumption decreasing to about 1,904,227 kWh, and costs, which went down to roughly €272,633.49. Interestingly, in 2021, even as energy consumption dipped slightly to an estimated 1,775,469 kWh, the cost associated with this consumption rose to about €244,434.31, suggesting an increase in the unit cost of energy. The year 2022 marks a significant rebound in energy consumption, soaring to approximately 2,857,998 kWh, which is the highest consumption level on the chart, paired with a corresponding cost increase to nearly €290,327.79. The graph indicates that while energy consumption initially decreased from 2019 to 2021, the cost did not strictly correlate with consumption, hinting at the influence of fluctuating energy prices or changes in the efficiency of energy use. The sharp increase in both energy use and cost in 2022 could reflect heightened operational activity, such as more extensive snow production, or factors like rising energy prices or shifts towards more expensive energy sources.

The rising energy consumption for the tourism industry, particularly evident in 2022, imposes a significant financial burden on the local economy. Such an increase in expenditure can strain the budgets of local businesses and authorities responsible for tourism activity. Moreover, the high energy requirements for snowmaking can affect hydro-geodiversity, as it may lead to the depletion of local water resources as the area mainly relies on the water usage for artificial snow production and hydroelectricity, and which can alter the natural hydrological cycles, potentially impacting local ecosystems and geodiversity.

7) Impacts from Transportation

On a global scale the state of the decreased environmental quality due to transportation results in an increase of extreme events. On the local scale this leads to further imbalance in the natural occurrence in the weather patterns such as, temperature and precipitation. Also, at the local scale these can affect ecosystems and human activities relying on stability of these patterns. For example, increased intensity of rain and snow precipitation can limit the slope and river network stability. Thus, limiting the accessibility and transportation in the area.

In the most recent event landslide occurred on 5$^{th}$ March 2024, in the Valsesia region, a situation of critical importance has emerged due to the enforced closure of roads leading to the localities of Alagna, Rima, and Carcoforo, as shown in figure 4-28. This directive affects approximately 1,500 inhabitants along with over 600 visitors. The renowned ski resort had initially implemented limited time slots to facilitate the movement of tourists and residents, a measure that was operational over the preceding weekend. However, the aggravation of a landslide on Provincial Road 299 in the vicinity of Piode necessitated the revocation of these travel windows due to the heightened risk conditions. Consequently, the communities of Campertogno, Mollia, and Rassa find themselves in a state of isolation. Presently, only vehicles pertaining to emergency services and those carrying essential supplies are permitted passage. Notably, supply trucks, under escort, managed to reach the accommodation in Alagna after a disruption spanning two days.


Figure 4-28: Provincial Road 299 blocked due to landslide (Source: RAI TGR)

### 4.3.3 Geosystem services and DPSIR

The DPSIR framework presented in figure 4-29 illustrates a range of environmental states and impacts caused by various natural drivers and pressures that lead to significant impacts on geosystem services. Debris flow, slope instabilities, avalanches, and moraine dynamics, along with associated processes like the development of torrents and new lake formations, represent states that emerge due to climatic and physical changes. These states induce several impacts: loss of land and property, loss of resources, freeze and thaw cycles, increased slope angles, damage to utilities and communication, and Glacial Lake Outburst Floods (GLOF). Each of these effects can be mapped to disruptions in regulating services (such as climate regulation, flood regulation and terrestrial processes), provisioning services (like food and drink, fuel, and industrial minerals), cultural services (including cultural, spiritual and historic meanings, and geotourism and leisure), and supporting services (such as land and water as a platform for human activity and storage), and knowledge services (such as earth history). For example, floods as a state have an adverse effect in the form of flood regulation causing disruption in delivery of regulating services (highlighted in yellow). Additionally, floods as a state tend to have impacts in the form of loss of land and property causing disruption to the supporting services (highlighted in purple), also impacting the resources undermining the provisioning services (highlighted in green). Therefore, it underscores the complex interplay between the environmental states and impacts and the cascading effects they have on the various categories of geosystem services, highlighting the interconnectedness and fragility of these systems.

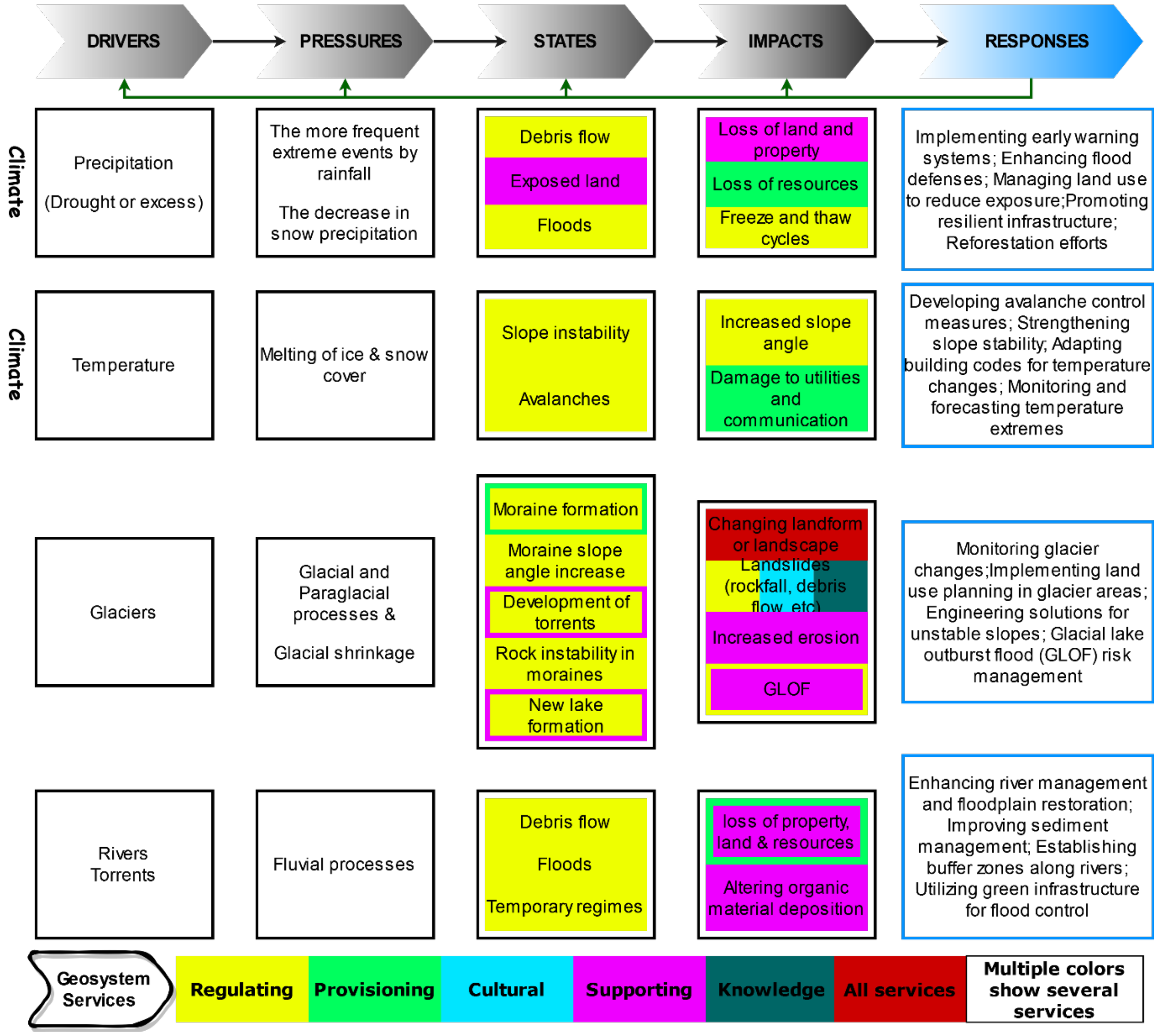


Figure 4-29: DPSIR framework natural components highlighting various impacts on geosystem services

Similarly, the results delineated in the DPSIR framework depicted in the figure 4-30 emphasize the intricate linkages between environmental states and impacts that arise from specific drivers and pressures related to human activities, leading to a profound influence on geosystem services.

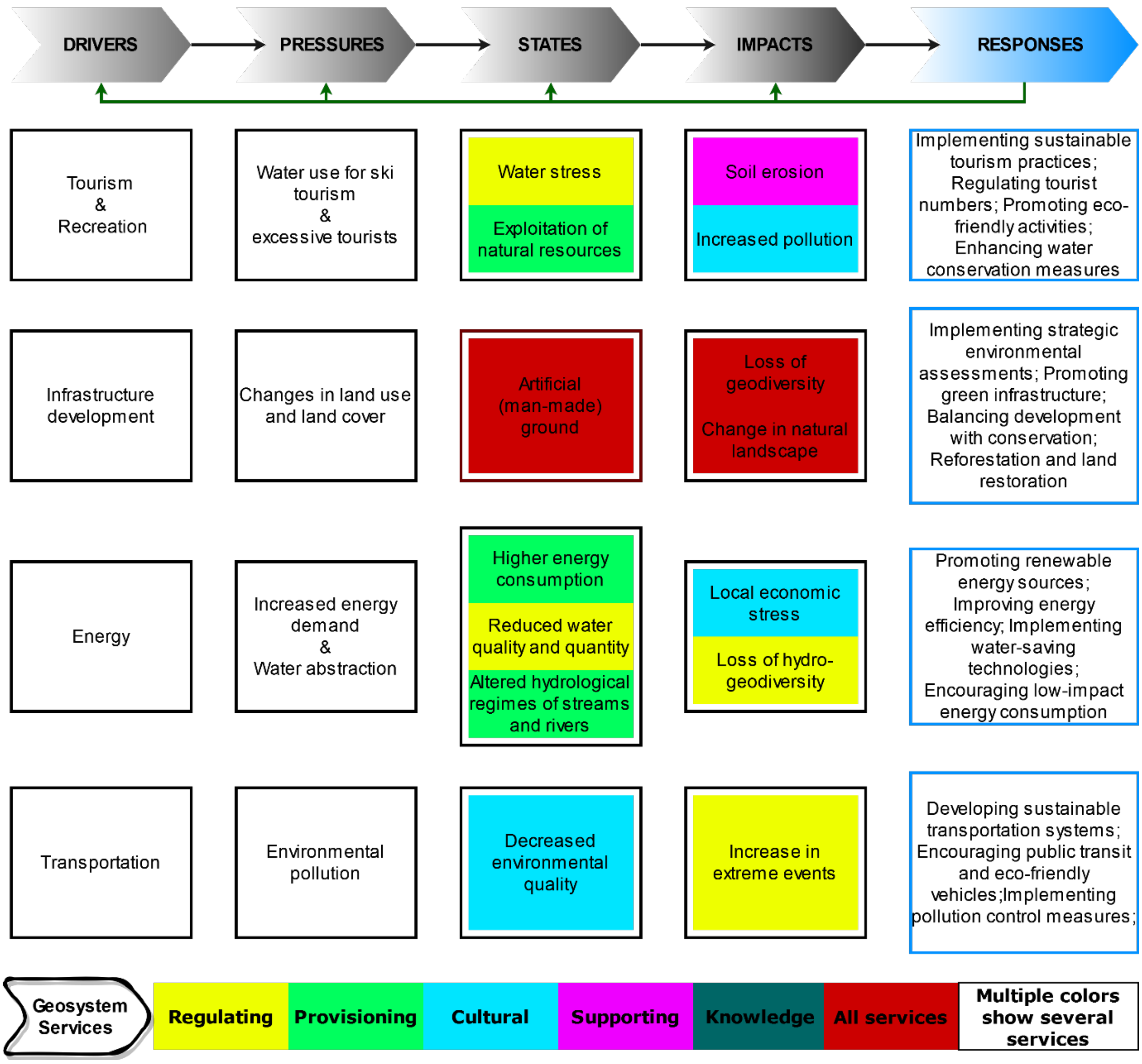


Figure 4-30: DSPIR framework human components highlighting the impacts on geosystem services

States such as water stress, exploitation of natural resources, artificial man-made ground, higher energy consumption, reduced water quality and quantity, altered hydrological regimes, and decreased environmental quality manifest due to shifts in climate patterns and human activities. These states catalyze a series of impacts including soil erosion, increased pollution, loss of geodiversity, changes in the natural landscape, economic stresses, loss of hydro-geodiversity, and a rise in extreme environmental events. These impacts translate into significant disruptions across a spectrum of geosystem services. For example, artificial man-made ground as a state has an effect on the provision of overall geosystem services (highlighted in red), and also reflects the impacts as human alteration of natural landscapes, and loss of geodiversity which affects the overall geosystem services.

Therefore, this framework highlights the multifaceted and interdependent nature of geosystem services, revealing how environmental changes caused by human activities can precipitate a cascade of effects across a wide range of geosystem services. It underscores the need for integrated environmental management strategies to mitigate these impacts and preserve the integrity and sustainability of geosystem services.

#### 4.3.4 Responses

In case of the responses, we analyzed each driver causing pressure to environment and presented suggestions for considering and avoiding possible problems related to natural or human activities. In the wake of the shift in rainfall patterns as result of climate change, DPSIR framework brings a holistic approach towards its mitigation and adaptation which is very crucial in addressing the increased flooding and drought risk due to climate change. The suggestive responses are listed in table 4-2.

##### *4.3.4.1 Responses to climate change*

First and foremost, a very important response would be the creation of definitions, concepts, and clarifications in meteorology in order for us to have an early warning system. The early warning system would therefore help to provide alarms for hazards and extreme weather events by using advanced meteorological data and forecasting models. All scientific literature agreed on the importance of the early warning systems on reducing disaster risk. The next response towards the water quantity issues would be the improvement in flood defenses. This may include structural solutions such as levees and flood walls for the benefit of rural development areas. Meanwhile, it will also involve nature-based solutions like the restoration of the natural floodplains and wetlands. This is important to control and divert floodwaters and also to reduce the risk of flooding due to heavy rain and less snowfall (as highlighted in figure 4-16).

Additionally, sustainable land use management may be implemented as another response to reduce exposure to extreme weather events (as depicted in figure 4-8b). This should be addressed in the context of rural planning to limit development in areas with high susceptibility to extreme weather events and promote agricultural practices that preserve natural buffers, which can significantly reduce the severity of debris flows and land exposure. Also, resilient infrastructure may be used as another measure. This means communities should design roads, utilities, and buildings to withstand heavy rainfalls, freeze-thaw cycles, and other extreme weather events. These alterations will contribute to a decrease in the level of potential danger a community might face, the ability of a community to sustain important services and the increase in speed at which a community could recover. This makes the region more resilient to change. Further, the forestation is vital in the curbing of soil erosion and flash floods and reduce runoff by more water being absorbed by the soil which will also increase the retention capacity of the soil, which could be useful in the phenomena of changing precipitation patterns (as evident in figure 4-8c). These strategies, which include technological innovation, infrastructural resilience, sustainable land use management and ecological restoration, must be seen as multidimensional required responses to the climate change challenge.

To effectively manage the challenges of temperature change, a holistic approach needs to be adopted. One major response to temperature change is developing avalanche control measures (e.g. in response to temperature variations as shown in figure 4-17) in mountainous regions where the land area is characterized by steep slopes such as Vail. This involves measures such as snowpack monitoring to determine snowpack's stability, controlled explosions, building of barriers and that help reduce the risks that are associated with avalanche hazard due to warming temperatures. Another response is strengthening slope stability, which is a range of engineering solutions which includes constructing of retaining walls, terracing and embankment control and improved drainage in the slopes that will help prevent landslide and slope failure in cases where ice and snow melting has taken place making the soils weak (as revealed in figure 4-24). The above range of measures are vital in ensuring that the integrity of the landscape is maintained while protecting communities that live in areas that are prone to landslides or possibly mass slope failure.

Another important aspect is adapting building codes to accommodate temperature fluctuation. This would require updating the construction standards for the infrastructure to endure the ever-changing climatic conditions. This would encompass requirements for thermal insulation, ventilation, and the use of materials that can adapt to the freeze-thaw behavior of the climate to help ensure the resilience and safety of the building with the ever-changing temperature. Furthermore, monitoring and forecasting temperature extremes are crucial for planning and executing timely mitigation actions to minimize the impacts. By using advanced meteorological technologies and prediction models we can have a better understanding on the temperature trends and provide appropriate actions to cope with the extreme temperature impacts. The collaborative responses to temperature impacts to ecosystems are implementing avalanche control measures, applying better methods to the slope to make it more stable, modifying building codes because of temperature swings, and evaluating temperature extremes affecting the built environment (impacts). Consequently, by combining tech, engineering strategies, legislation adaptation, and advanced state-of-the art and forecasting agents would effectively address the host of risks temperature change pose and make the area less vulnerable to the above-mentioned temperature-specific environmental risks.

*4.3.4.2 Responses to glacier dynamics*

A multi-pronged approach is necessary to respond to the challenges posed by glacier changes. Monitoring glacier changes is the primary response. This involves using remote sensing and ground observations to track glacier dynamics, a necessary step in understanding and predicting how glaciers will change further and to understand the effect those changes will have on the surrounding environment.

An additional response to deal with the issue of the glacial crisis would be to carry out land use planning. This is a broad scale policy requiring strict land use regulations. This would essentially prevent high risk development in glacier-affected areas. In this case, land planning would involve reducing moraine instability risks and reducing GLOF (glacial lake outburst flood) risks (as illustrated in figure 4-10). In addition to this, it would enable us to manage human resources, control human activities and manage the risks associated with glacially influenced landscapes through sustainable practices. One important part of this concept is to find engineering solutions against unstable slopes. Such as Stabilization of the morainic slopes that are most likely to be unstable through the different kind of engineering constructions, like rock bolts, retaining walls, drainage systems, is the best way to avoid the risks of landslides and fragility due to the glacier dynamics and the melting (e.g. as a response to the moraine formation due to glacier dynamics as shown in figure 4-18). The other important responses are directed against the risks of the GLOFs by supervision of glacial lakes, building of safety dams in the most vulnerable areas and establishment of an evacuation plan for the local residents.

It is essential to have these precautions in order to avoid disastrous events when water is suddenly released from glacial lakes, which happens more frequently with the influence of climate change. The strategies of monitoring glacier dynamics, implementing land use planning, engineering for unstable slopes, and GLOF risk management are comprehensive in mitigating the environmental and societal challenges that arise from glacier dynamics. Consequently, the strategies for all these responses are scientific monitoring, regulatory frameworks, engineering interventions, and risk management practices with complexity and evolution of glacier risks in a changing climate.

#### *4.3.4.3 Responses to rivers and torrents*

A comprehensive set of responses are necessary to deal with the problem of rivers and torrents in the context of climate change. The restoration of rivers and floodplain would form a vital part of this strategy. This would involve restoring natural river courses, enhancing the riparian zone, and maintaining the vegetation naturally found on the slopes. Such measures are essential in order to promote natural flood mitigation, as the rivers spread, slow down due to abundant water and are able to flood out over large, vegetated areas as opposed to causing flood risk and the impact of flooding to increase. A second vital response is to improve sediment management. Effectively curbing sediment involves implementing a series of sediment retention techniques which includes checking dams, sediment traps and a series of vegetation strategies to maximize the ability of a river to hold a given sediment load. This is important in reducing debris flow (as shown in figure 4-11) impacts during flood events, maintaining good river health, and preventing vast sedimentation increases which can increase flood risks (e.g. as response to the states arising from river and torrent dynamics as highlighted in figure 4-20). In addition to channelizing rivers, the establishment of buffer zones running along them is important for several reasons. In this buffering zone, natural vegetation is established to absorb the excess water, reduce erosion, and provide habitats. This buffer can make the drainage system, both the natural and artificial one, even more responsive to the changes taking place in the river. The drain can accept excessive water and become less prone to erosion. The buffer zone enhances the natural environment, the ecological system of the riverine systems and acts as a natural barrier that would be able to reduce the flood impact to the adjacent land and surrounding community (e.g. as a response to the impacts caused by river and torrents dynamics as presented in figure 4-26). The third method to accomplish this goal is implementing green infrastructure, such as rain gardens, green roofs, permeable pavements, and sustainable urban drainage systems. These can help to decrease runoff, lower flood impacts, and make mountain areas able to handle extreme weather events. In conclusion, by utilizing green infrastructure, establishing buffer zones, improving sediment management, enhancing river management and floodplain restoration, the combination of these responses, it allows a comprehensive approach to managing the challenges of river and torrent flooding. By combining geo-ecological restoration, sustainable management practices and innovative infrastructure, it allows for the dynamic and complex nature of river systems to be managed effectively in light of climate change.

*4.3.4.4 Responses to tourism and recreation*

When considering tourism and recreational resources, there are a range of appropriate responses that need to be established particularly for the pressures of water use for ski tourism and the implications of excessive visitors. The most critical point is to establish sustainable tourism through appropriate tourism strategies that entail the concept of developing tourism that will cause a minimal impact on the environment and local communities by integrating all components of the tourism industry through a sustainable management providing a suitable type of tourism. Another crucial measure is to regulate the numbers of visitors (e.g. a response to the tourist entry as displayed in figure 4-13). Authorities can limit the number of visitors to particularly sensitive mountain areas. This can help to control litter, trampling vegetation and the effects of pollution inside the sensitive mountain areas. Controlled visitor numbers can have an upshot in addressing the issue of protecting the geo-ecological balance and attempting to safeguard the future viability of the tourist destination. Similarly, essential is the promotion of eco-friendly activities, it could include persuading the tourist to participate in activities that are less harmful to the environment such as bird watching, hiking, or guided nature walks. Employing, if the idea is promoted successfully, the eco-footprint of the tourism can be dramatically reduced and at the same time, tourists' experiences can also be enhanced, thus which could help to set the foundation for developing a more profound understanding towards the natural environment. A major element is to upgrade the water efficiency measures, especially in areas where tourist activity is high. This involves the adoption of effective water management systems within facilities, encouraging water saving behavior among the tourists and the use of technologies that improve the levels of water consumed in the sector (e.g. a response to the water use for ski tourism as shown in figures 4-12 and 4-21). Such measures will ensure that the tourist sector does not compromise the sustainability of the water resources. The combination of these efforts through the implementation of sustainable tourism practices, regulation of tourist numbers, promoting eco-friendly activities, and the influencing of increased water conservation measures, assist in meeting the challenges to the environment, society, and the living conditions of the region. Combined approaches of strategized exploitation, regulatory approaches, and capacity building promote tourism sustainability and provide support and advantages for local communities.

*4.3.4.5 Responses to infrastructure development*

Developing infrastructure often requires changes in land use and land cover (as shown in figure 4-14) creates challenges that need to be addressed by coordinated responses. One of the main responses is to implement the use of strategic environmental assessments. A strategic environmental assessment is an evaluation of the environmental impacts that arise from implementation of the proposed project. The assessments are carried out before the work on infrastructure begins and outline possible impacts on land, in terms of geodiversity and natural landscape, and focused on reducing such threats to barest minimums to enhance sustainable development. Another major response is promoting green infrastructure. This response includes incorporating natural features into built environments. Some examples would be having green spaces or parks, green roofs, and rain gardens. Green infrastructure helps maintain biodiversity and supports ecosystems. Green infrastructure also improves air and water quality which can help with the balancing of environmental conservation and development.

Sustainable infrastructure growth is determined by balancing development with conservation. This incorporates intending and implementing advancements in a way that limits geo-ecological disturbance and preserves natural landscapes (e.g. a response to changes in states due to infrastructural development as illustrated in figure 4-22). It stresses utilization of land designs to receive an approach targeted at protecting sensitive areas while coping with rural extension and infrastructure demands. A further response is targeted on reforestation and land restoration. In earlier places disrupted by the economic development of infrastructure projects reforestation and land recovery can rebuild the natural habitats, restore geomorphology, revive local flora and fauna, and rehabilitate soil, to achieve a gradual recovery of geodiversity and the balance of the entire region. By implementing strategic environmental assessments, promoting green infrastructure, balancing development, and conservation, and engaging in reforestation and land restoration, these responses become part of a comprehensive strategy to improve the environment and maintain infrastructure development. Proactive planning, integration with ecosystem and restored practices can promote infrastructure development responsibly and harmoniously.

*4.3.4.6 Responses to energy consumption*

Furthermore, to face the problems of rising energy demand (as revealed in figure 4-15), in particular with increased usage of water and abstraction (as shown in figure 4-12), it is important to devise a multi-faceted approach. One strategy is promoting renewable energy. This involves the use of energy sources such as solar power, wind, and hydro power. These natural resources produce less of an impact on the environment than traditional methods involving fossil fuels thus lessening the demand for water as well as reducing amounts of greenhouse gases being released. This in combination with less use of water would create energy consumption that is more sustainable; minimizing the hydro-geodiversity loss. A further paramount response is the improvement of energy efficiency. This includes the acceptance of technology and practices that demote the energy requirement for everyday activities in both the commercial and residential locations. The upgrade to energy efficiency can greatly reduce the patterns of high-end consumption (as depicted in figure 4-23) which in return reduces the total energy demand and energetically attributable environmental impacts such as changed hydrological rivers and streams. The reduction of water quality and quantity that results from energy use can be addressed through the implementation of water-saving technologies, which involve the use of advanced irrigation systems in agriculture and water-efficient appliances at homes and industries. The technology will help reduce water usage, in turn mitigating water stress and helping to maintain the quality of water bodies. Another crucial aspect is to encourage a low-impact energy consumption, in fact, the second initiative should aim at increasing awareness of behaviors that help reducing energy consumption, such as, for example: use public transportation, make an efficient use of heating and cooling systems or recommend the approval of rules aimed to promote less energy consuming lifestyles, and, such behavioral patterns may however reduce economic local stress and preserve hydro-geodiversity. Individually, each of the responses offer ways of dealing with the increases in energy consumption; however, collectively, they provide a schematic policy to combat the environmental and economic issues caused by the increases in energy use. A combination of technological advances, changes to individual actions and the creation of policy initiatives will be necessary to make practices in the field of energy use and water resources sustainable.

*4.3.4.7 Responses to transportation*

A comprehensive approach is essential in addressing the challenges tied to transport and air quality with the focus on creating sustainable transport systems. This implies developing mobility solutions and practices, which includes putting in place infrastructures for environmentally friendly, efficient, and sustainable transport systems. These may result to zero emission or low emission of pollutants, public means of transport that are electric or hybrid in nature, creating walking paths and cycling paths as well as promotion of shared mobility, with the end product being an integrated transport system that would be less polluting and at the same time ensure the mobility of the populations. Another important action is to encourage public transit as well as eco-friendly vehicles. Promoting the use of public transportation systems like buses and trains would greatly help the environment since they have a lower per capita environmental impact compared to private vehicles. Furthermore, people should also be encouraged to use eco-friendly vehicles such as electric cars and bikes, as they produce less emissions. Initiatives can include tax incentives to purchase electric vehicles, installing charging infrastructures and offering subsidies for public transport. Crucial to the minimization of the impact of transportation on the environment is the adherence to pollution control measures. Implementing stricter emission standards, using cleaner fuels, and adopting reduced exhaust emission technologies, can minimize vehicle pollution. Such measures vastly improve air quality and have a significant impact on the reduction of health risks associated with vehicular pollution. These responses build upon one another in a multi-faceted manner such as developing sustainable transportation systems, encouraging the use of public transportation and eco-friendly vehicles, implementing pollution control measures. They combine advances in transportation technology, policy interventions, and urban development to create transportation systems that are sustainable, efficient, and environmentally friendly.

## 4.4 Discussion

This study explored the Alagna Valsesia municipal in the Monte Rosa region of the Western Alps, a geographical marvel and testament to the delicate interplay between geodiversity, geosystem services, and the impacts of global and local changes. The rich tapestry of this mountainous area serves as a microcosm for understanding broader environmental dynamics and the pressing need for sustainable management and conservation practices. Drawing upon the literature, the identification and evaluation of geosites within Alagna Valsesia were underscored by the aim to understand the multifaceted contributions of geodiversity to societal and ecological well-being, echoing the global discourse on the importance of geosystem services (Gray, 2004; Gray et al., 2013). This study's approach of inventorying geosites with plausible justifications like scientific and educational significance aligns with the wider trend in geoconservation. Evaluating a variety of criteria in geosites cataloging on their value and ability to contribute to scientific knowledge as well as educational value of geosites. The use of radar charts (see Figure 4-4) in current study has been gaining popularity in geoscience research because radar charts provide a visual result of an evaluation of a geomorphosite. The application of this method enhances thorough understanding of the individual aspects of Alagna Valsesia geosites and allows greater effective communication as to its value to different groups of stake holders (mountain guides, locals and tourists officers) as demonstrated by Reynard et al. (2016) geomorphosite study.

Furthermore, the geosystem services map produced (see Figure 4-6) from this work seeks to encapsulate the geodiversity aspects underpinning the essential services pivotal to society.

These services, categorized into regulating, supporting, provisioning, cultural, and knowledge services, embody the current geoscience trend to elucidate and map the diverse benefits of geodiversity for ecosystems and societies. This approach aligns with the Millennium Ecosystem Assessment (2005), which advocates for an ecosystem services framework, recognizing the intertwined nature of natural systems and human well-being. The findings, especially the distribution of geosystem services within Alagna Valsesia, underscore a significant emphasis on supporting, cultural, and knowledge services. This emphasis aligns with recent studies, such as that by Tognetto et al. (2021), they investigated the critical role of geosystem services in bolstering the long-term sustainability of geoheritage, cultural heritage, and educational opportunities. Despite the less pronounced representation of regulating and provisioning services in the present study of Alagna Valsesia, their contribution to the overall functioning and maintenance of geo-ecosystems remains indispensable, reinforcing the consensus within geoscience research regarding their value.

The spatial distribution of these geosystem services, as quantified in Table 4-1, further enriches the understanding of their landscape dispersion in Alagna Valsesia. The GIS analysis demonstrates that supporting services predominantly reside within polygonal features, while cultural and knowledge services are more closely associated with linear features. This distinction underscores the variability in how different geosystem services are distributed across the landscape, corelating with the findings of Reynard et al. (2016), who highlight spatial analysis as a crucial tool for grasping the distribution and significance of geomorphological sites and their contributions. In synthesizing the insights from the literature with empirical findings, the present study contributes to the burgeoning body of knowledge on geodiversity and geosystem services within Alagna Valsesia area and underscores the critical need for integrated conservation strategies either by municipal government or by the Sesia Val Grande UNESCO Global Geopark. Such strategies must account for geodiversity's multifaceted role in sustaining both ecosystem functions and human societies. By emphasizing the interconnectedness of natural systems and human well-being, as advocated by the Millennium Ecosystem Assessment (2005), this research underscores the essential nature of geosystem services within the broader context of global change adaptation and sustainable development in mountainous areas like the Monte Rosa region.

Furthermore, utilizing the DPSIR (Drivers, Pressures, State, Impact, Response) framework (see Table 4-2) to analyze Alagna Valsesia has been instrumental in distilling the complex interplay between environmental changes and socioeconomic activities within this distinct geographic locale. This systematic approach, which dissects the environmental narrative into drivers, pressures, state changes, impacts, and responses, resonates with traditional environmental sciences and environmental management principles, reinforcing the framework's significance within environmental studies. This investigation identified multiple drivers of change in Alagna Valsesia, including climatic variations, glacial dynamics, and socioeconomic developments such as tourism and infrastructure expansion. This aligns with the findings by Svarstad et al. (2008), who underscored the intricate interactions between natural and anthropogenic factors contributing to environmental transformations. Furthermore, the local pressures emanating from these drivers, spanning climate change, glacier retreat, river torrents, tourism, and infrastructure developments, aligning with Lewison et al. (2016) and Geneletti and Dawa (2009) findings. These pressures prompt significant state alterations of the local environment, such as geomorphological and hydrological shifts, as evidenced by Callow and Smettem (2007), which subsequently influence human settings and geo-ecological conditions. The impacts of these state changes in Alagna Valsesia, notably the loss of land and property, diminished geodiversity, and altered geo-ecosystems, highlight the severe consequences of environmental shifts in the study area. These findings parallel to those of Turner et al. (2000), who delved into environmental changes' societal and geo-ecological ramifications. Importantly, the focus on the impacts on geosystem services fit together with the discussion by Costanza et al. (2014) concerning the ecosystem services framework, emphasizing the pivotal role ecosystems play in provisioning essential services. By employing the DPSIR framework as outlined, this study embarked on an integrated and comprehensive exploration of the multifaceted challenges faced by the identified components in a mountain region attracting tourism. This work may deepen understanding of Alagna Valsesia's environmental and socioeconomic fabric and illustrates the broader applicability and utility of the DPSIR framework in dissecting and comprehending environmental studies' complex narratives. The DPSIR framework highlights the need for a holistic and thorough strategy to cope with the complex issues stemming from the identified DPSI elements. Recommended actions are offered as measures for mitigation, adaptation, prevention, and management approaches.

In conclusion, the issues the researchers raised demonstrate the complexity and the levels at which drivers of change and their impacts can be addressed and managed through mitigation, adaptation, prevention, and integrated management strategies. Measures like technology innovation, infrastructures resilience, land-based measures, ecosystems restoration and adaptive management encompasses a number of feasibility, planning, design, and implementation options that, in a context of “cascade” governance mechanisms, should be part of a comprehensive strategy to address the drivers of change, in Alagna Valsesia. A proactive, and informed course of collective action towards these measures guarantees a holistic approach which is the effective way to increase resilience to environmental change.

# Chapter 5 Conclusion, limitations, and future implications

## 5.1 Conclusion

To sum up, the multifaceted nature of geodiversity and geosystem services is emphasized within the thesis by bringing together a range of observations from the Monte Rosa area. The scope of the work extends beyond the identification of geosites, using advanced models such as Suzuki and Takagi (2018) to provide a comprehensive evaluation encompassing three dimensions: educational, scientific, and tourism values. By applying this detailed method and supporting the results with radar chart visualization, an in-depth understanding of individual site qualities (geosites) was achieved, and these were each positioned within the wider geological story of Monte Rosa.

Evidence linking pioneering geoscientific works such as those from Brilha (2016) and Gray (2004) demonstrate equivalent principles and novel methodologies. The assessment process, which considers various criteria, leads to a model in line with trends in the wider geoscience community, where tangible and intangible aspects of geoheritage are regarded equally. The results indicate that the intrinsic scientific heritage value of the geosites is not only a valuable attribute, but that the geological sites are valuable regarding their significance in education, tourism, and their cultural merits.

The management implications of the study are considerable; the findings provide impetus for, and guidance on, the decision-making process of geoscientifically-informed geoconservation in particular. The findings represent multidimensional benefits of geosites, which hold significance for strategic decision-making within the geoconservation discipline. Specifically, they raise awareness about the importance of balancing tourism opportunity and conservation requirement to achieve sustainable development of geotourism and preservation of the scientific and educational values intrinsic to these natural assets.

The implications of management are profound in this, with a more sophisticated understanding of the multiple values of geosites guiding strategic decision making in geoconservation. The study stresses the importance of having a balance between tourism and conservation to ensure that the growth of geotourism remains sustainable and does not detract from the scientific and educational value of these sites. In order to do so, it is important to underscore the need for a focused approach to geoconservation, with certain sites receiving priority for protection in view of their scientific significance as well as their conservation status. While all geosites may be valuable, there may be certain drawbacks that would call for more urgent and more stringent conservation measures not found in other sites.

Moreover, it has been of high importance that, throughout this research, the intricacies of the interrelationships between natural processes, human activities and the driving forces were analyzed through employing the DPSIR Framework. The DPSIR framework ensures findings, analysis and thus recommendations are comprehensive; as this framework takes a systematic approach to understanding how various human and natural factors interact with each other, in that, natural environmental processes interact with human activities to create a wide range of pressures that originate from both natural and anthropogenic sources.

Furthermore, drivers are crucial in determining the natural and human-induced shifts impacting the geo-ecosystem. Such drivers act as the causes that can change the environment, affecting Alagna Valsesia. As a result, they also encourage the alterations to have a substantial effect on the conditions that will be observed in relation to environmental changes in the natural resources and geo-ecosystems of Alagna Valsesia.

Significance of each of the following: a) changing river dynamics; b) melting glaciers; c) and evolving patterns of transport and tourism are far reaching and varied. An analysis of these processes reveals the range of impacts that include, for example, loss of land and geodiversity, cultural and recreational opportunities, and links to a far wider range of geosystem services. A consideration of the importance of these services in maintaining geo-ecological equilibrium and support of human well-being reveals many interesting implications of these pressures, emphasizing the need to consider the wider significance of pressures in the area. A fascinating example of the cascade of impacts resulting from the increasing pressures is the implications of changing river dynamics affecting water flow but also the habitats of a wide range of species, ultimately leading to decreased in species diversity. The melting of glaciers triggers various fluvial processes that threaten communities and livelihoods. The evolving tourism could bring benefits or pressures to the region, e.g., tourism could aid economic development and infrastructure improvements but also put added pressure on natural resources and cultural heritage. The confirmation of the multiple problems the region is facing implies the need for complex solutions e.g. recognition from planners and policymakers of short and long-term land use and resource pressures and the importance of maintaining geosystem service provision in the region.

To conclude, this thesis attempts to contribute to the ongoing efforts to address environmental challenges in Alagna Valsesia through a detailed and integrated approach. It focuses on exploring preventative, mitigative, and adaptive strategies, offering a holistic perspective aimed at enhancing resilience to environmental changes. While the suggestions presented are broad and encompass various aspects of environmental management, they are intended as a starting point for further sector-specific research and action. The study acknowledges the complexity of climate change issues in mountain regions and suggests that a multifaceted approach, involving collaboration across different sectors, is essential for effective management and adaptation. Rural planning, geoscientific approach, engineering and infrastructural improvement, and the development of policies relating to energy and transportation, need to be developed to manage this multidimensional problem effectively. It also necessitates collaborative research and development in these fields with the participation of experts from different fields working on climate change and environmental management. The findings and recommendations regarding geo-conservation and especially geo-tourism of this research are expected to be essential input for policymakers, practitioners, and researchers researching the mountain region's sustainable development.

## 5.2 Limitations of the study

The comprehensiveness of the thesis is one of its strengths, but there are some limitations of this thesis. The research, while providing an in-depth analysis of environmental challenges and opportunities in Alagna Valsesia, has a specific focus on certain aspects of the tourism industry. This specialization means that the findings may not be directly transferable to other regions with differing environmental settings, socio-economic conditions, cultural aspects, or to areas where other industries such as farming, commerce, and construction are more predominant.

Another limitation of this thesis is the time the data collected includes contemporary, which means that the results from these data categories do not represent the complete environmental and climate conditions. These results will only cover the short-term factors based on the corresponding years. The thesis will not disclose the gradual changes in geodiversity, which will also affect the environment, humans, and the surrounding community.

Furthermore, the application of the DPSIR framework, while providing a structured approach to understanding environmental dynamics, has its constraints. The model's linear nature may oversimplify complex geo-ecosystem interactions and feedback loops. It tends to present a unidirectional flow from 'Drivers' to 'Responses', which might not accurately reflect the iterative and cyclical nature of environmental changes and human interactions. This could lead to an incomplete understanding of the causality and interdependencies within the system.

## 5.3 Future research implications

There are many exciting areas for future research. One example is to broaden the geographic scale beyond Alagna Valsesia, allowing a comparison between geosite management under different environmental and socio-economic conditions. Long-term monitoring and retrospective analysis would help evaluate the effects of gradual environmental changes, providing a more in-depth understanding of geodiversity dynamics. Furthermore, qualitative methods, such as considering the cultural, historical and community values of geosites, could be integrated in evaluating geosites.

There may be more dynamic ways to represent the complexity of ecosystems rather than using the traditional Driver-Pressure-State-Impact-Response (DPSIR) framework as a stand-alone model. More specifically, incorporating non-linear processes and feedback loops could be considered, as geo-ecosystem and human systems exhibit non-linear dynamics. Furthermore, broadening the models to include socio-economic and political dimensions is essential to effectively tackle the challenges that emerged from the previously discussed action strategies. Besides, insight into stakeholders' motivations, policy frameworks and economic constraints is critical. Many interesting research themes are related to the impacts of global phenomena (e.g., climate change, technology improvement, economic globalization) on local geodiversity/ geo-ecosystems to develop adaptable management. These themes are strongly associated with sociology, economy, and politics.

Secondly, it is vital to research sustainable development models that balance the area's conservation with economic development, especially in geotourism. This includes tourism that minimizes the environmental damage and maximizes the socio-economic benefit for people in the area. Furthermore, investigating the groundbreaking financial mechanism that may underpin the maintenance of geosites is crucial. Moreover, research is important into technology and how remote sensing, GIS and PPGIS, data analytics, and other new technology can underpin the monitoring and management of the geosites, providing pertinent information to top management ranging from identifying high risk to checking the effectiveness of some conservation measures.

Thirdly, it is fundamental to research community engagement, the local community's involvement, and the local people's participation in the management of geosites. The emphasis of future studies should be on exploring the ways in which residents can actively participate in conserving geological resources that hold local, regional and national significance. This approach would guarantee integrating knowledge, needs, and values into the overall management of these areas.

The fourth area worth researching is the development of education and outreach programmes centering on geodiversity and geoconservation. Research should focus on effective education strategies that aim to pass critical messages concerning the importance of the area to the local people and the wider general public.

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