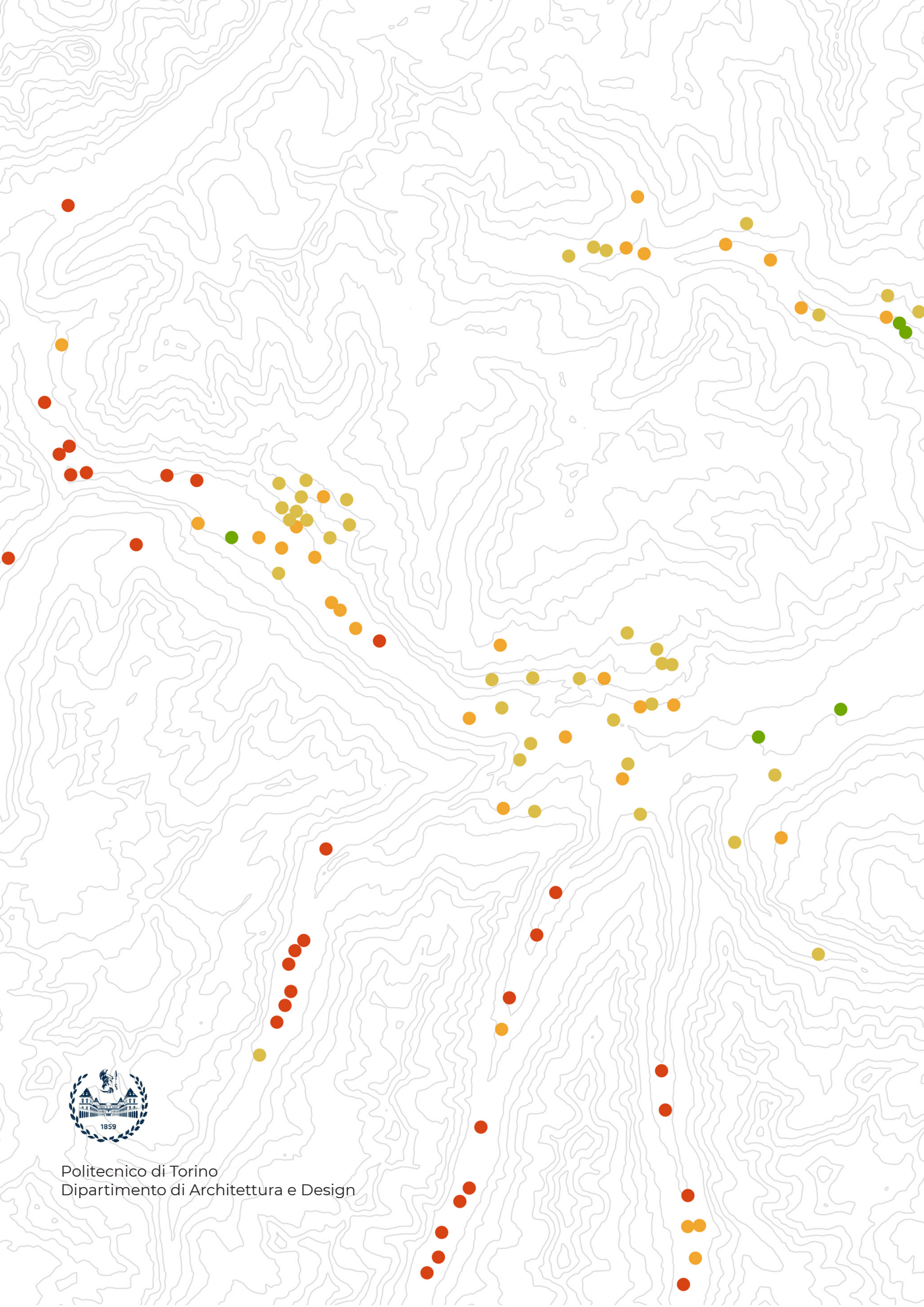
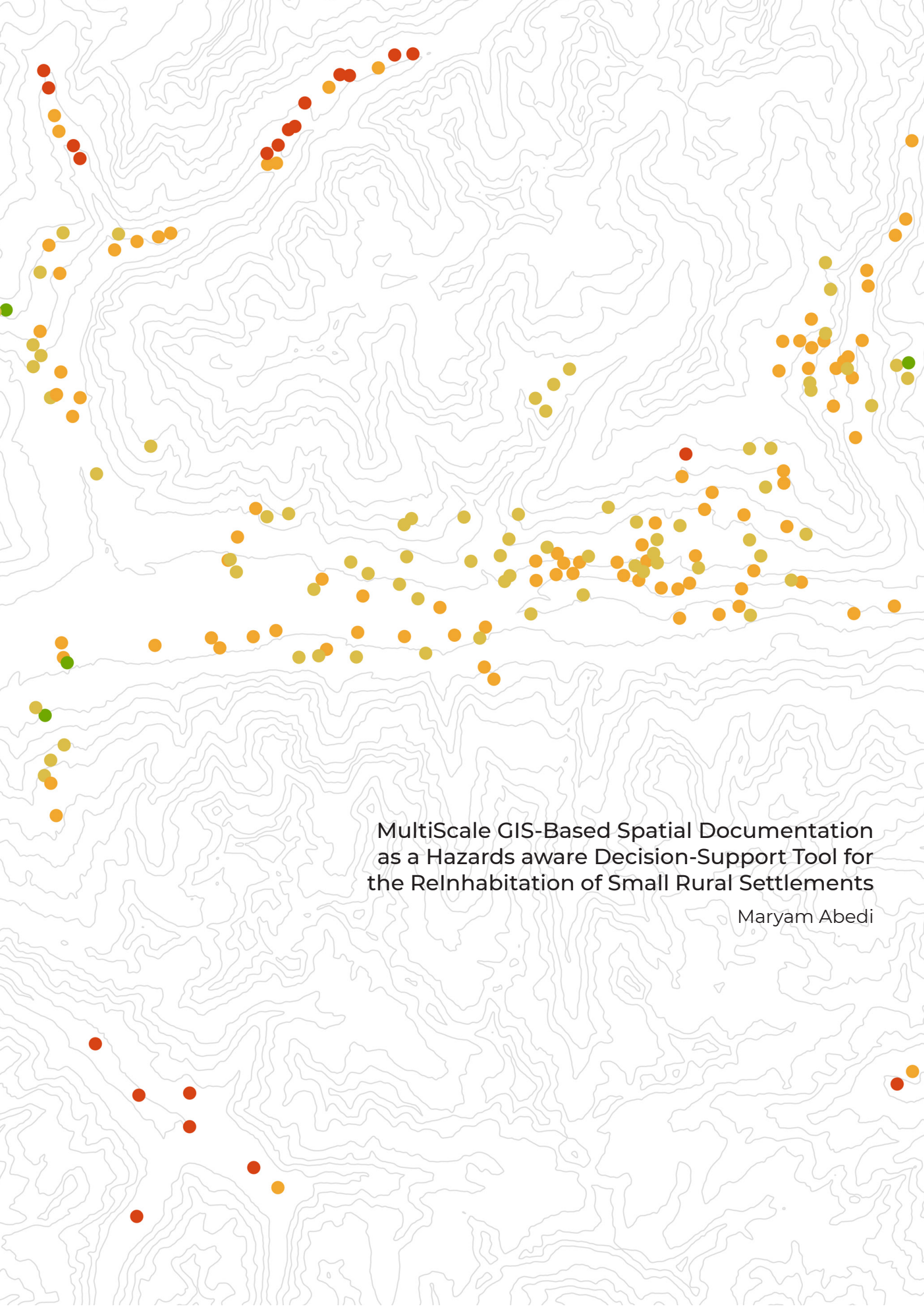




Politecnico di Torino
Dipartimento di Architettura e Design



MultiScale GIS-Based Spatial Documentation
as a Hazards aware Decision-Support Tool for
the Relnhabitation of Small Rural Settlements

Maryam Abedi

Master's Degree Thesis

Multiscale GIS-Based Spatial Documentation as
a Hazards-Aware Decision-Support Tool for the
Reinhabitation of Small Mountain Rural Settlements

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Finally, to the mountains and the communities that inspired this thesis, may the attention paid here, however modest, contribute in some small way to the broader effort of keeping these places alive in memory and in practice.

Abstract

Small Mountain Rural Settlements (SMRS) across the Italian Alps are experiencing a slow and compounding process of demographic decline, physical abandonment, and escalating environmental hazard exposure. Rooted in long-term structural forces including depopulation, service withdrawal, and infrastructural fragility, this crisis is particularly acute in the mountain regions of Northwestern Italy, where settlements classified as Minor Historical Centers (MHCs) carry significant cultural, architectural, and landscape heritage value yet remain marginal within mainstream conservation and planning frameworks. Despite renewed policy interest at both national and European levels, expressed through instruments such as the National Strategy for Inner Areas (SNAI), the National Recovery and Resilience Plan (PNRR), and the EU Long-Term Vision for Rural Areas, reinhabitation initiatives remain largely disconnected from systematic spatial evidence, producing outcomes that are episodic, project-based, and rarely embedded in long-term, data-driven governance strategies.

This thesis develops and tests a multiscale GIS-based spatial documentation framework designed to evaluate reinhabitation feasibility across four nested scales of analysis: national settlement inventory and operational boundary definition, regional hazard exposure mapping, territorial geomorphological and infrastructural analysis, and building-level hazard intersection. The framework operationalizes the concept of Small Mountain Rural Settlements through progressive geographic filtering, integrating heterogeneous datasets from national statistical archives, regional geoportals, remote sensing services, and institutional hazard inventories within a unified analytical workflow. A composite Hazard Constraint Score is introduced to bridge geomorphological documentation and building-level feasibility assessment, combining internal hazard exposure with access corridor vulnerability. To bridge the gap between complex spatial data and practical governance, the resulting multiscale outputs are operationalized within an interactive WebGIS decision-support platform designed for non-specialist stakeholders.

The framework is applied to three case studies in Piedmont and Valle d'Aosta, namely Ollomont, Macugnaga, and Elva, selected to represent complementary and structurally distinct conditions of demographic fragility, compound hazard exposure, and policy intervention. Findings demonstrate that SMRS represent a profoundly heterogeneous population of settlements whose reinhabitation challenges cannot be addressed through uniform policy instruments. Ollomont presents near-total compound hazard convergence across its building stock alongside acute demographic fragility. Macugnaga exhibits a spatially concentrated triple-hazard vulnerability node within

Abstract

an otherwise moderately constrained settlement supported by a seasonal tourism economy. Elva, by contrast, faces minimal hazard exposure but a near-total collapse of its permanent resident population, with fewer than 0.25 permanent residents per structure across its six dispersed hamlets.

To address the structural data gap identified at the building scale, the thesis proposes the Building Vulnerability and Heritage Index (BVHI), a standardized attribute extension to existing building footprint layers encoding physical condition, hazard damage history, heritage and cultural value, renovation cost estimates, and legal ownership status within a single composite layer. The BVHI is designed to transform the current hazard count output into a full reinhabitation feasibility score per structure, constituting an operational decision-support tool at a resolution that no existing Italian planning instrument currently achieves.

Key findings also reveal critical data harmonization deficits across Italian regional geoportals, a systematic misalignment between heritage certification frameworks and the most peripheral and administratively fragile settlements, and the near-total absence of building-scale physical condition data from existing reinhabitation policy instruments. The entire framework is executable using open-source GIS software and publicly available institutional datasets, complemented by a replicable WebGIS architecture. It is designed to be transparent, scalable across other Italian mountain regions and, with appropriate adaptation, to comparable alpine and rural contexts in the broader European context.

Keywords

Minor Historical Centers, Small Mountain Rural Settlements, GIS-based spatial documentation, multiscale analysis, hazard-aware planning, reinhabitation feasibility, demographic decline, inner areas, landslide hazard, avalanche hazard, flood hazard, building vulnerability, decision-support tools, Italian Alps, rural regeneration, territorial fragility, Piedmont, Valle d'Aosta.

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LIST OF ABBREVIATIONS

AA	Aree di attenzione (Attention Zones)
ANPCI	Associazione Nazionale Piccoli Comuni Di Italia (National Association of Italian Small Municipalities)
ARPA	Agenzia Regionale per la Protezione Ambientale (Regional Agency for Environmental Protection)
BDTRE	Base Dati Territoriale di Riferimento degli Enti (Core Territorial Reference Database of Public Authorities)
BVHI	Building Vulnerability and Heritage Index
CAP	Common Agricultural Policy
CLPV	Carte della Localizzazione Probabile delle Valanghe (Map of Probable Avalanche Localization)
CRS	Coordinate Reference System
DEGURBA	Degree of Urbanization
DEM / DTM	Digital Elevation Model / Digital Terrain Model
DRR	Disaster Risk Reduction
EAWS	European Avalanche Warning Services
EC	European Commission
EEA	European Environment Agency
EU	European Union
EUSALP	EU Strategy for the Alpine Region
GeoDB	geodatabase
GIS	Geographical Information Systems
HCS	Hazard Constraint Score
HPH	High Probability Hazard
HUL	Historic Urban Landscape
ICCD	Istituto Centrale per il Catalogo e la Documentazione (Central Institute for Cataloging and Documentation)
INSPIRE	Infrastructure for Spatial Information in the European Community
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Italian Institute for Environmental Protection and Research)
ISTAT	Istituto Nazionale di Statistica (Italian National Institute of Statistics)
kPa	kilopascals
LAU	Local Administrative Unit
LCC	Land Cover Class
LPH	Low Probability Hazard
MASE	Ministero dell'Ambiente e della Sicurezza Energetica (Ministry of Environment and Energy Security)
MHC / MHCs	Minor Historical Center(s)
MPH	Medium Probability Hazard
OECD	Organization for Economic Co-operation and Development

LIST OF ABBREVIATIONS

PAI	Piano per l'Assetto Idrogeologico (Hydrogeological Plan)
PNRR	Piano Nazionale Ripresa e Resilienza (National Recovery and Resilience Plan)
PRGC	Piano Regolatore Generale Comunale (Municipal General Urban Plan)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SIVA	Sistema Informativo Valanghe (Avalanche Information System)
SLR	Systematic Literature Review
SMRS	Small Mountain Rural Settlements
SNAI	Strategia Nazionale per le Aree Interne (National Strategy for Inner Areas)
SRS	Small Rural Settlements
SS	Small Settlements
UNCEM	Unione Nazionale Comuni Comunità Enti Montani (National Union of Mountain Municipalities and Communities)
UNESCO	United Nations Educational, Scientific and Cultural Organization
WFS	Web Feature Service
WMS	Web Map Service

1

Introduction

1.1 Background and Problem Statement

Rural and alpine territories across Italy and the broader European context are experiencing long-term processes of **demographic decline, service reduction, and infrastructural fragility**. At the core of this vulnerability are small villages, scattered hamlets, and **Minor Historical Centers (MHCs)** (Macchi Jánica & Palumbo, 2019). Conceptually, MHCs are defined as small-scale settlements that possess cultural, architectural, and landscape heritage values, yet are often affected by partial or total abandonment (De Rossi et al., 2015; ISTAT, 2020a; Postiglione et al., 2009). Despite their recognized heritage significance and renewed potential contribution to territorial regeneration, particularly in the post-COVID-19 period (Barbera & De Rossi, 2021; Frixia & Mirabile, 2024), these settlements often remain marginal within mainstream conservation and planning frameworks. Reversing this marginality requires a conceptual shift: rather than viewing them as isolated monuments, they are best understood as layered cultural landscapes, in line with the Historic Urban Landscape (HUL) approach (UNESCO, 2016).

Although their cultural and architectural value is widely acknowledged, MHCs and historical hamlets lack a universally standardized definition and dedicated spatial datasets within Italian statistical frameworks. From a legal and institutional perspective, the defining metric for these vulnerable contexts is typically set at a demographic threshold of fewer than 5,000 residents. This parameter is historically rooted in legislative proposals such as Bill No. 1942 and heritage conservation frameworks dating back to the 1964 Venice Charter, and is currently the operational baseline utilized by advocacy organizations like the National Association of Italian Small Municipalities (ANPCI) (Associazione Nazionale Piccoli Comuni Di Italia, n.d.). However, this 5,000-resident threshold is often too broad, frequently encompassing semi-urbanized areas rather than genuinely rural contexts. Because qualitative concepts like 'historical center' or 'hamlet' do not have a rigid operational meaning in standard municipal census data, this thesis utilizes specific data-driven proxies. It employs the spatial footprints of **Small Settlements (SS)**, defined as residential settlements with a population of fewer than 1,000 inhabitants, and **Small Rural Settlements (SRS)**, which are SS located in rural areas according to the Degree of Urbanization (DEGURBA) classification (Eurostat, 2011), to successfully identify and analyze these heritage contexts.

SS, SRS and SMRS Definition

Building upon this operational framework, this thesis specifically narrows its focus to **Small Mountain Rural Settlements (SMRS)**, reflecting the geographic reality of the Italian Mountain regions. In these high-altitude contexts, demographic decline is further intensified by severe **environmental constraints**, including landslides, avalanches, and climate-related changes

1.1 Background and Problem Statement

that increase exposure and maintenance costs (Delmonaco et al., 2023; Membretti et al., 2025). Furthermore, many of these SMRS fall within Italy's so-called "Aree Interne" (Inner Areas), defined as territories characterized by limited accessibility to essential services, such as healthcare, education, and mobility infrastructure, and often associated with economic marginality (Lucatelli, 2015). This complete translation, from the broad, qualitative classification of heritage villages to the rigid, operational boundaries of SS, SRS, and SMRS required for the analysis, is illustrated conceptually in Figure 1.

The limited demographic scale, fragmented ownership structures, and weak administrative capacity of MHCs obstruct their effective integration into standard policy instruments (Fratesi et al., 2026). While a range of regeneration initiatives has been implemented over recent decades, outcomes have frequently been uneven or modest, rarely producing long-term structural change (De Rossi, 2019; European Commission, 2021a; ISTAT, 2020b; OECD, 2020; UNESCO, 2016). At the regional scale, networks such as the Borghi Alpini initiative (UNCCEM, 2026), spearheaded by the Piedmont chapter of the National Union of Mountain Municipalities and Communities (UNCCEM) (Unione Nazionale Comuni Comunità Enti Montani, 2019), highlight how revitalizing the architectural heritage of these valleys can foster economic resilience, protect local autonomy, and attract new enterprises. Yet, despite such localized efforts to stimulate contemporary recovery, many interventions remain episodic, project-based, or weakly embedded in long-term, data-driven governance strategies. Consequently, broad regional strategies frequently overlook the highly idiosyncratic nature of these territories. Because each mountain hamlet possesses a unique historical development and localized vulnerability profile, macro-level planning must be counterbalanced by a **multiscale** approach capable of adapting to the granular, site-specific realities of the local scale.

Parallel to these challenges, national and European policy frameworks, including the Italian National Strategy for Inner Areas (SNAI) (La Strategia nazionale per le aree interne, 2021), the National Recovery and Resilience Plan (PNRR) (Piano Nazionale Ripresa e Resilienza, 2024), and the European Union (EU) Long-Term Vision for Rural Areas (European Commission, 2021a), clearly promote the **revitalization** of marginal territories and historical settlements. However, there is often a clear disconnection between policy ambitions and practical implementation (Cotella & Vitale Brovarone, 2024; European Commission, 2021b; Ministero della Cultura, 2021; Presidenza del Consiglio dei Ministri, 2021). A critical review of current practices reveals that documentation initiatives, hazard assessments, demographic analyses, and funding programs

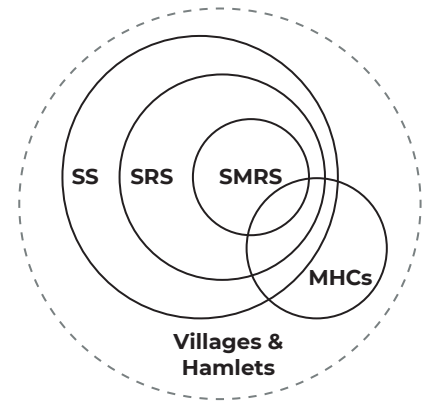


Figure 1. Translation of qualitative heritage concepts into operational spatial boundaries for GIS analysis. (Source: Author's elaboration)

Policy frameworks

1.1 Background and Problem Statement

tend to be developed in parallel rather than in coordination, relying on heterogeneous datasets and incompatible spatial or semantic frameworks. This fragmentation makes it difficult for local administrations and planners to assess reinhabitation potential in a systematic, hazard-aware, and evidence-based way. Emerging geospatial datasets, such as Copernicus Italia land monitoring (Copernicus Italia, 2014.) and ground-motion services, national and regional geoportals, hazard inventories, and statistical archives, offer opportunities to understand rural and alpine territories with high spatial and thematic resolution. Yet, these resources are rarely integrated into unified workflows. Consequently, there remains a lack of operational decision-support tools capable of connecting environmental hazards, accessibility, and building stock conditions to systematically assess the feasibility of reinhabitation.

1.2 Objectives and Questions

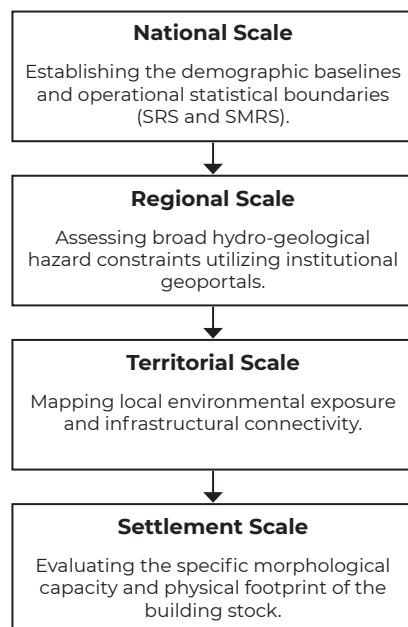


Figure 2. Methodological progression of the spatial analysis framework, moving from national operational boundaries to settlement-level physical constraints.
(Source: Author's elaboration)

Directly addressing the lack of operational decision-support tools capable of connecting environmental hazards, accessibility, and building stock conditions to systematically assess reinhabitation feasibility, **the main objective of this thesis is to investigate whether and how hazard-aware, data-driven spatial documentation, integrating multiscale geospatial datasets and spatial analysis tailored to the specific scale and morphology of MHCs, can be structured into a functional decision-support tool.**

By addressing this aim, this thesis intends to assist planners in the identification of viable, safe, and strategic pathways for the potential reinhabitation of SMRS and historical centers in alpine areas. Furthermore, the thesis aims to critically assess the limitations of existing policies and planning frameworks, examining why, in certain contexts, reinhabitation strategies may not be feasible or effective.

To achieve this objective, the thesis develops and tests a Geographical Information Systems (GIS)-based multiscale documentation framework. Because the feasibility of rural reinhabitation cannot be evaluated through a single spatial lens, the analysis integrates heterogeneous datasets across a descending hierarchy of operational boundaries. This methodological progression, moving from macroscopic

1.2 Objectives and Questions

national policy down to microscopic physical constraints at the settlement level, is illustrated in Figure 2.

Ultimately, this structured approach aims to bridge the persistent gap between high-level policy ambitions and local implementation challenges. By providing a scalable and replicable model, the resulting framework attempts to empower planners to move beyond episodic interventions toward sustainable and evidence-based regeneration strategies. In doing so, it ensures that the architectural preservation of these territories is inextricably linked to their long-term environmental safety and demographic survival.

To bridge the persistent gap between broad regeneration policies and the complex realities of local environmental constraints, the primary question guiding this study asks:

How can hazard-aware, data-driven spatial documentation, integrating multiscale geospatial datasets and MHC-inspired documentation methods, support the evaluation of conditions under which viable, safe, and strategic pathways for reinhabitation of small villages and historical centers can be identified?

Main Question

This question is articulated through the following sub-questions, which are designed to unpack the specific spatial, environmental, and strategic dimensions of the thesis:

Thematic Questions

Data and Multiscale Documentation

Which multiscale spatial datasets, such as national geoportals, remote sensing data, and regional hazard maps, are most relevant for documenting settlement structure, accessibility, infrastructure, and environmental hazard in rural and alpine contexts?

Integration Across Scales

How can different spatial scales (National, Regional, Territorial, and Settlement) be integrated within a unified GIS-based documentation workflow to assess reinhabitation potential?

Hazard and Climate Exposure

How do environmental hazards (landslides, avalanches, floods) spatially correlate with demographic decline, service accessibility, and infrastructural fragility in selected case studies?

1.2 Objectives and Questions

Which hazard indicators most strongly constrain reinhabitation potential and settlement morphology?

Reinhabitation and Planning Practices

To what extent do existing rural regeneration and reinhabitation strategies employ spatial, data-driven, or GIS-supported methods, particularly in relation to hazard, accessibility, and policy frameworks?

How can micro-scale morphological and building-use attributes be combined with environmental hazard constraints within a multicriteria spatial matrix to prioritize structural suitability for adaptive reuse?

Policy Effectiveness and Data Gaps

After the identification and analysis of case studies, which datasets, indicators, or forms of spatial information are currently missing or insufficient to support reinhabitation decisions, and how do these gaps affect the effectiveness of existing policies and planning frameworks?

1.3 Scope and Limitations

Spatial Scope

This thesis focuses on rural and alpine contexts in Northwestern Italy, specifically within the Piedmont and Valle d'Aosta regions. The empirical analysis is conducted through a set of selected case studies, Ollomont, Elva, and Macugnaga, which represent complementary conditions of demographic fragility, hazard exposure, and policy intervention.

Methodologically, the selection of these sites followed an inductive, bottom-up logic. The geographic focus was established based on localized site familiarity, logistical feasibility, and integration with ongoing departmental research initiatives. Rather than arbitrarily selecting sites from a national statistical database, these locations were chosen precisely because their known, on-the-ground complexities dictated the parameters required for the broader multiscale spatial documentation framework.

Specifically, the case studies were selected to illustrate these varied spatial constraints and complementary conditions:

1.3 Scope and Limitations

Ollomont (Valle d'Aosta):

Selected based on extensive prior architectural and morphological investigations, this site allows for the analysis of specific anthropogenic risks (abandoned mines) alongside severe hydrogeological hazards (Unité des Communes valdôtaines Grand-Combin, 2024). It represents a state of acute demographic fragility, maintaining a residual population of approximately 70 inhabitants rather than total abandonment (ISTAT, 2024).

Elva (Piedmont):

Included due to its active involvement in national funding strategies (PNRR), offering a crucial lens into current policy interventions and regeneration attempts in isolated mountain contexts while representing a contrasting condition of marginalization and abandonment (Bongioanni, 2025).

Macugnaga (Piedmont):

Selected to represent seasonal economic contraction and demographic vulnerability. Geographically situated in close proximity to the Belvedere Glacier, it highlights high-altitude environmental vulnerability, particularly regarding glacial dynamics and associated debris flow hazards. (ISTAT, 2024).

By anchoring the thesis in these pre-identified local realities, the study subsequently scaled upwards. The specific physical and environmental constraints observed at the settlement scale directly informed the operational boundaries applied at the territorial, regional, and national scales. However, translating these specific, complex locations into measurable spatial data introduced several methodological limitations. The primary limitation is the lack of official spatial data specifically delineating MHCs within Italian statistical frameworks. The primary national data source, National Institute of Statistics (ISTAT) (Istituto nazionale di statistica, 2021), classifies territories strictly by administrative units, such as Comuni and Frazioni, lacking morphological categories for hamlets or historical centers. Consequently, to establish a reproducible method capable of quantitatively isolating a marginalized alpine village within ISTAT framework, this thesis utilizes SS, SRS, and SMRS as operational boundaries. These proxies function as the necessary spatial footprints to extract data regarding settlement morphology and environmental constraints.

The use of SS, SRS, and SMRS in this thesis does not imply a full definitional equivalence with MHCs. They are adopted as an operational spatial proxy that allows the qualitative

Case Studies

Operational Boundaries

1.3 Scope and Limitations

and heritage-based concept of MHCs to be translated into measurable GIS units. This translation inevitably involves a degree of approximation: some SMRS may not correspond to historically significant centers, while some MHCs may fall outside the demographic, rural, or mountain criteria used to define SMRS. For this reason, the SMRS category is treated as a preliminary spatial filter rather than as a final heritage classification. Its validity is subsequently refined through case study analysis, local heritage references, and the intersection with hazard, accessibility, and settlement-structure indicators.

Data Accessibility

Beyond these terminological overlaps, severe structural limitations exist regarding spatial data accessibility and harmonization in Italy. While extensive national and regional datasets such as ISTAT, Geoportale Piemonte, and Geoportale della Regione Autonoma Valle d'Aosta exist, they are notoriously difficult to navigate. Regional Geoportals lack standardization, meaning the organization, cataloging, and access protocols vary drastically from one region to another. Furthermore, data availability is highly fragmented, while some datasets are fully downloadable as vector shapefiles, other layers are restricted to online visualization via Web Map Service (WMS) or Web Feature Service (WFS) protocols, lacking direct vector downloading options for local geoprocessing. Even when web services can be integrated into a GIS, the lack of uniform data schemas complicates cross-regional spatial analysis. To overcome this local fragmentation and ensure cross-regional comparability, this thesis sometimes relies on standardized European geospatial datasets, such as Copernicus and the European Environment Agency (EEA), which are downloaded and clipped to the local study areas.

Finally, two further limitations must be acknowledged. First, hazard assessments within this thesis rely primarily on existing institutional inventories and remote-sensing indicators rather than newly conducted, site-specific geotechnical engineering studies. Second, the thesis does not aim to provide a comprehensive socio-economic redevelopment plan, but rather to support spatial prioritization and strategic evaluation through data-driven documentation.

Accordingly, the concept of reinhabitation is treated as a conditional and context-dependent process, acknowledging that in certain cases, severe environmental hazards or structural constraints may limit or entirely prevent viable re-settlement. Therefore, the resulting framework should be viewed as an essential spatial diagnostic tool, a critical preliminary filter that ensures future socio-economic investments and detailed engineering interventions are directed toward the most viable and resilient territories.

1.4 Scientific and Practical Contribution

This thesis contributes to the fields of geomatics, and rural and heritage studies through four main dimensions:

Methodological:

Advances the use of GIS and spatial documentation as a connective infrastructure capable of integrating heterogeneous datasets, including heritage documentation, environmental hazards, demographic statistics, and accessibility indicators, across multiple spatial scales. Specifically, it operationalizes a descending spatial framework that translates national statistical proxies into localized, building-level morphological assessments. Furthermore, this connective infrastructure establishes the structural foundation for a centralized geodatabase (GeoDB), serving as a unified repository designed to systematically aggregate, store, and describe the multi-dimensional indicators characterizing these MHCs.

Empirical:

Produces structured, case-based spatial datasets for selected MHCs within the Northwestern Italian Alps, demonstrating how existing, often fragmented open data (such as ISTAT, regional geoportals, and Copernicus services) can be reassembled into coherent documentation frameworks. By applying an inductive logic to diverse stages of abandonment, the thesis provides actionable spatial baselines for rural settlements that frequently remain invisible in standard statistical mapping.

Analytical:

Foregrounds the role of environmental hazard and climate-related constraints in shaping reinhabitation potential, moving beyond purely architectural or socio-cultural interpretations of abandonment. It evaluates how severe hydrogeological and anthropogenic vulnerabilities limit, delay, or dictate the terms of resettlement, challenging overly romanticized narratives of village revival.

Policy-oriented:

Aligns the proposed approach with Italian and European strategies for inner areas and rural regeneration, offering a replicable decision-support tool that can guide evidence-based spatial planning within programs such as SNAI, the PNRR, and the EU Long-Term Vision for Rural Areas. It effectively bridges the persistent gap between macro-

1.4 Scientific and Practical Contribution

level funding ambitions and the micro-scale realities of hazard exposure and infrastructure deficit.

By bridging spatial documentation, hazard analysis, and planning practice, this thesis positions data-driven GIS methodologies as a critical instrument for assessing the feasibility, risks, and spatial conditions of reinhabitation processes. Ultimately, it shifts the discourse of rural regeneration from a purely theoretical heritage conservation debate toward a quantitative, hazard-integrated, and spatially aware governance strategy.

1.5 Structure of the Thesis

This thesis is structured as follows. Chapter 2 presents a Systematic Literature Review (SLR), examining existing research on rural depopulation, heritage conservation, reinhabitation strategies, and data-driven spatial approaches. Chapter 3 introduces the conceptual framework of MHCs and explores current reinhabitation policies and practices. Chapter 4 focuses on environmental hazards and constraints, analyzing hydrogeological hazards and climate-related factors affecting rural and alpine settlements. Chapter 5 outlines the methodological framework, detailing the GIS-based and multiscale spatial documentation approach developed and applied in this thesis. Chapter 6 presents the application of this methodology to the selected case studies, visualizing and interpreting the spatial data. Finally, Chapter 7 discusses the broader implications of the findings, addresses the thesis questions, and outlines potential avenues for future planning practices.

2 **Systematic Literature Review**

This chapter presents a SLR aimed at synthesizing research on MHCs, rural and alpine settlements, hazard and climate analysis, and GIS-based documentation and planning approaches. To capture both the academic theory and operational reality of these territories, the review bridges traditional peer-reviewed literature with institutional gray literature, contemporary case studies, and foundational thesis references.

2.1 Objectives of the Review

Rural and alpine villages across Europe, particularly in Italy, are experiencing simultaneous demographic decline, service contraction, and increasing exposure to climate-related hazards such as landslides and flooding. These combined pressures affect both the viability of local communities and the conservation of historical centers and cultural landscapes.

At the same time, the growing availability of multi-source geospatial and remote sensing datasets, such as Copernicus (European Commission, n.d.), national geoportals, and regional hazard inventories increasingly enables detailed analysis across national, regional, territorial, and settlement scales.

Against this backdrop, this SLR is conducted to serve three main aims:

1. To build a coherent understanding of the research domain at the intersection of GIS-based spatial documentation, rural and alpine settlement systems, hazard and climate-analysis, reinhabitation strategies, and policy frameworks.
2. To synthesize a highly fragmented, cross-disciplinary body of literature that currently spans spatial planning, environmental engineering, heritage documentation, and rural development.
3. To establish the conceptual and methodological foundation for a hazard-aware, multiscale GIS decision-support tool. Acknowledging that qualitative concepts like MHCs lack rigid operational definitions in census data, this review also substantiates the necessity of using SRS and SMRS as data-driven spatial proxies to support reinhabitation strategies.

These objectives are operationalized through three review questions:

SLR Questions

SLRQ1. GIS & Documentation:

How are GIS and multiscale spatial documentation methods applied to small villages, historic centers, and rural or alpine settlements?

SLRQ2. Hazard & Climate Change:

What hazard and climate datasets, indicators, and assessment methods are used to analyze rural and alpine areas?

2.1 Objectives of the Review

SLRQ3. Reinhabitation Strategies:

Which policy, planning, or data-driven strategies support reinhabitation, revitalization, or adaptive reuse in rural and alpine contexts?

2.2 Familiarization with the Topic

Before designing the review protocol, an in-depth reading of established multiscale heritage documentation frameworks was conducted. This familiarization provided a conceptual and methodological baseline by clarifying multiscale documentation workflows across four primary operational levels (National → Regional → Territorial → Settlement), introducing approaches relevant to heritage documentation, and describing relationships between spatial datasets and planning tools. This step refined the vocabulary and cross-domain connections that subsequently informed the search terms, screening logic, and inclusion criteria.

2.3 Rationale for Using a SLR

A systematic approach was selected to overcome structural misalignments in the current state-of-the-art. Because the survival of these territories depends on intersecting factors, from environmental safety to architectural heritage, integrating these domains requires a structured, transparent, and reproducible review protocol, guided by the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses framework (PRISMA) (Page et al., 2021).

To establish this structure, the literature was categorized into five thematic pillars:

- (1) GIS-based multiscale documentation,**
- (2) hazard and climate exposure,**
- (3) rural and alpine contexts,**
- (4) reinhabitation strategies, and**
- (5) policy frameworks.**

2.3 Rationale for Using a SLR

By tracking search procedures, inclusion criteria, and thematic coding across these defined pillars, the SLR maps the critical gaps between existing documentation practices and the operational needs of rural regeneration policies.

2.4 Search Strategy

2.4.1 Sources and Process

The search process was designed to bridge the gap between academic theory, institutional data, and operational policy. Crucially, the selection process actively prioritized open-access literature and open-source spatial datasets. Because some stakeholders might lack the financial resources to access proprietary data or paywalled academic journals, it was essential that the derived indicators and spatial proxies remained freely accessible to local administrations and territorial stakeholders. This review aligns with the principles of open-data access as a foundational requirement for equitable rural revitalization planning.

The identification of relevant sources followed a structured, multi-tiered approach designed to ensure cross-disciplinary depth across the primary layers of the territory. As categorized in Table 1, the review balanced high-level academic databases with web searches, forward and backward snowballing, and targeted gray literature. This collaborative structural classification is designed to ensure that macro-scale strategic drivers are directly paired with localized, quantitative statistical and environmental datasets.

Operationally, these distinct source streams were implemented through a continuous feedback loop where qualitative insights and technical indicators directly cross-referenced one another. High-level database queries in Scopus established the broader methodological benchmarks for spatial documentation, which were subsequently tested against real-world alpine contexts extracted via targeted web searches. Concurrently, backward and forward snowballing tracking from foundational regional ontologies ensured that localized settlement definitions remained tethered to active institutional frameworks. This comprehensive synthesis prevents the review from drifting into purely theoretical configurations, ensuring that every selected academic reference is firmly anchored by the operational realities, datasets, and strategic horizons of contemporary national and European rural policies.

2.4 Search Strategy

2.4.1 Sources and Process

Source category	Specific repositories	Main contribution
Academic databases	Scopus	State-of-the-art in GIS & heritage studies.
Snowballing	Backward/forward citation tracing	Multiscale methodologies & MHC semantics & ontologies.
Web search	Google Scholar, General Web search, ResearchGate	Supplementary studies, contemporary hospitality models
Gray literature	EU Rural Vision, Alpine Convention, SNAI, PNRR, ISTAT, ISPRA, Copernicus	Strategic objectives for rural regeneration & policy drivers, Quantitative indicators for demography, & risk.

Table 1. Multidisciplinary Source Categorization.
(Source: Author's elaboration)

2.4.2 Search Terms and Parameters

Search strings in Scopus were strictly calibrated to balance geographic depth with policy precision, isolating the specific morphological and legislative constraints of the European Alpine context. Crucially, these strings were designed to mirror a “revitalization lifecycle”, moving from the baseline documentation of the physical architectural shell and its environmental constraints, upward to the strategic governance and planning frameworks required to ensure long-term habitability.

To establish the formal state-of-the-art in spatial modeling, multi-criteria decision support, and heritage documentation, systematic keyword queries were executed exclusively within the Scopus database. These Scopus search strings were organized around the initial three specific target domains of the revitalization lifecycle: (i) GIS-based multiscale documentation, (ii) hazard and climate exposure, and (iii) reinhabitation and rural revitalization. As detailed in Table 2, these operations successfully isolated the geomorphological and regulatory realities of the target regions, yielding explicit document sets for subsequent eligibility screening.

Italian localization terms (borghi, aree interne, centri storici minori) were integrated to ensure absolute compatibility with

2.4 Search Strategy

2.4.2 Search Terms and Parameters

national regulatory and funding frameworks like SNAI and the PNRR. The temporal scope was restricted to 2000–present to align with the active technological evolution of modern GIS and major European territorial cohesion frameworks.

Domains	Scopus strings	N
(i) GIS-based multiscale documentation (Baseline)	TITLE-ABS ("rural village" OR "small village" OR "historic cent*" OR "minor historical cent*") AND (GIS OR "multiscale" OR "spatial documentation") AND ("Alpine")	23
(ii) Hazard & climate exposure (Baseline)	TITLE-ABS ("alpine" OR "mountain area" OR "inner area" OR "borghi") AND ("hazard" OR "risk" OR "avalanche" OR "landslide" OR "debris flow" OR "flood") AND ("GIS" OR "spatial modeling" OR "remote sensing") AND ("historic settlement" OR "MHC" OR "small village")	8
(iii) Reinhabitation & rural revitalization (Strategic)	TITLE-ABS ("reinhabitation" OR "repopulation" OR "adaptive reuse") AND (GIS OR "spatial planning" OR "data-driven") AND ("borghi" OR "MHC" OR "abandoned village" OR "historic settlement")	6

Table 2. Scopus search strings and document yields for the (iii) primary domains.
(Source: Author's elaboration)

2.5 Screening, Inclusion, and Exclusion Criteria

An adapted two-stage screening workflow was applied to filter the corpus for geographical relevance, spatial data availability, and thematic focus. To maintain strict methodological coherence, several categories of literature were deliberately omitted from the review. Studies were excluded if they focused primarily on megacities or macro-scale metropolitan systems, or if they were rooted in purely theoretical rural sociology lacking explicit spatial mapping or GIS components. Furthermore, the review bypassed global or extra-European contexts that do not share the distinct geomorphological or legislative frameworks characteristic of the Italian Alpine regions. Finally, tourism-marketing analyses were excluded when they were completely detached from the structural habitability or local environmental hazard patterns of the settlements.

2.5 Screening, Inclusion, and Exclusion Criteria

Conversely, studies were retained for final analysis if they contributed rigorous methodological or empirical data to at least one of the five thematic pillars. Ultimately, this rigorous screening funnel narrowed the initial multi-source identification pool down to a final consolidated corpus of 82 references, achieving a strategic equilibrium between high-impact academic research and institutional policy data. Furthermore, gray literature stemming from local community knowledge repositories, such as local newspaper archives, public community questionnaires, and non-academic civic forums, was intentionally excluded from the final corpus. While valuable for localized sociological contexts, these sources fall outside the structural scope of this review.

2.6 Justification of Methodological Strategies

To ensure the methodological transparency and reproducibility of the review, several deliberate structural choices were implemented. The exclusive reliance on Scopus for the primary systematic queries ensured a baseline of peer-reviewed quality, while parallel searches across institutional portals captured the gray literature essential for applied territorial planning. This dual-source approach was governed by strict disciplinary boundaries; deliberately excluding works that lacked explicit spatial, rural, or hazard relevance maintained methodological coherence and prevented the review from drifting into purely sociological or historical domains. Furthermore, the search terminology was strategically calibrated to align with active institutional frameworks. Keywords were drawn directly from established MHC vocabularies (Coletta, 2006; Rolli, 2008), standard hazard classifications (Istituto Superiore per la Protezione (ISPRA), n.d., regional geoportals, Copernicus), and official EU and Italian policy documentation. Finally, the integration of backward and forward citation tracing proved essential for capturing highly specific multiscale and alpine hazard modeling methodologies, which are frequently embedded in specialized technical reports and not consistently indexed within broad academic databases. By anchoring the methodology in these explicit, reproducible parameters, the resulting literature corpus transcends a simple bibliographic summary. Instead, it functions as a verified data repository that directly informs the spatial proxies and indicators developed in subsequent chapters. Ultimately, these structural constraints can guarantee that the proposed GIS workflow remains both academically rigorous and directly applicable to the real-world administrative needs of Alpine municipalities.

2.7 Visualization of the Review Process

The review process and its outcomes are synthesized through two complementary visual tools. First, an adapted PRISMA flow diagram shown in Figure 3, which provides a transparent account of the identification, screening, eligibility, and inclusion stages. This diagram illustrates the rigorous methodological progression from an initial broad search pool across four source categories down to the final corpus of 82 references.



Figure 3. Adapted PRISMA flow diagram detailing the identification, screening, and inclusion phases of the SLR. (Source: Author’s elaboration)

For complete transparency and methodological reproducibility, the comprehensive database of the evaluated literature is provided in **Appendix 1**. This Appendix details the full reference corpus, including the source category, methodological status, and specific relevance scores assigned to each document across the five thematic pillars. To operationalize this matrix, a multi-tiered scoring system was applied to evaluate the

2.7 Visualization of the Review Process

depth of each study's contribution to the respective domains. Documents were assessed on a numerical scale of 0 to 4: 0 indicates keywords are absent; 1 denotes an incidental mention where objectives are not integrated; 2 represents a conceptual factor lacking specific variables or data application; 3 represents substantial relevance as a significant methodology component; and 4 designates a core focus driving the study's analytical framework. By filtering the corpus through this quantitative threshold, the most critical methodological frameworks were explicitly isolated from general thematic discussions.

Building upon this scoring system, the second visual tool is a thematic coding matrix detailed in Table 3 that organizes the selected references across the five analytical pillars defined in the review protocol. Specifically, this matrix highlights the distribution of high-value references (those scoring a 3 or 4), demonstrating where the literature provides robust, actionable data versus where it remains superficial. This visual categorization allows for a rapid cross-comparison between heterogeneous sources, highlighting the density of existing research within certain domains while simultaneously exposing critical gaps in interdisciplinary, multiscale documentation.

Thematic pillars	References with 3 = substantial relevance OR 4 = core contribution values in relation to pillars.	Count
(1) GIS-based multiscale documentation	S2, S3, S4, S5, S6, S7, S9, S10, S12, S15, S17, S18, S19, W2, W17, W18, W19, W21, W22, SN3, SN10	21
(2) hazard and climate exposure	S2, S3, S5, S6, S7, S8, S10, S11, S17, S18, W1, W6, W7, W8, W10, W16, W20, W22, W23, SN2, SN4, SN5, SN8, SN11, SN13, SN14, G1, G2, G3, G4, G5, G7, G8, G9, G10, G11, G12, G13, G14, G18, G20	41
(3) rural and alpine contexts	S1, S2, S3, S4, S5, S7, S8, S9, S11, S13, S14, S15, S16, S18, S19, S20, S21, W1, W3, W4, W5, W13, W14, W15, W20, W21, W22, W23, SN1, SN2, SN4, SN5, SN6, SN7, SN8, SN9, SN11, SN13, SN14, G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, G11, G12, G13, G14, G15, G16, G17, G20, G21, G22	59
(4) reinhabitation strategies	S1, S4, S5, S9, S12, S14, S15, S16, S19, S20, S21, W7, W10, W11, W20, W21, W22, W23, W24, SN2, SN4, SN8, SN9, SN11, SN13, SN14, SN15, G20	28
(5) policy frameworks	S1, S11, S12, S13, S16, S19, W9, W12, W21, W22, W23, SN3, SN12, G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, G11, G12, G13, G14, G15, G16, G17, G18, G19, G21, G22	34

Table 3. Thematic coding matrix categorizing the final corpus of 82 references across the five primary analytical pillars.
(Source: Author's elaboration)

2.7 Visualization of the Review Process

To structurally synthesize the matrix data, Figure 4 quantifies the level of interdisciplinary integration by tracking exactly how many of the five analytical pillars each reference addresses with high significance (scoring a 3 or 4). While individual references that score highly in only one or two pillars represent deeply specialized domain contributions, the aggregate distribution reveals a clear lack of cross-disciplinary breadth across the broader state-of-the-art.

Legend

- Repeated 1 time
- Repeated 2 times
- Repeated 3 times
- Repeated 4 times
- Repeated 5 times

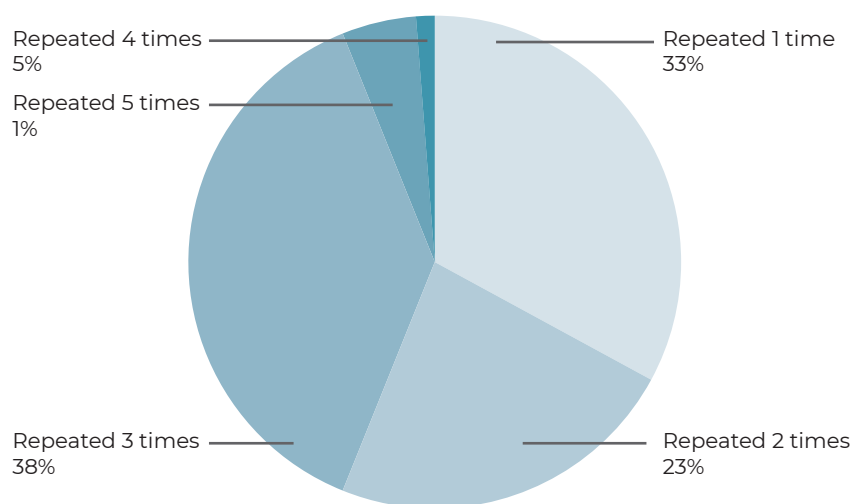


Figure 4. Distribution of High-Relevance Scores Across (5) Thematic Pillars.
(Source: Author's elaboration)

A substantial majority of the evaluated works remain restricted to narrow thematic focus areas: 33% (27 references) address only a single pillar, frequently isolating cultural heritage elements without environmental context, while 23% (19 references) bridge two pillars. Although a strong middle-tier cluster of 38% (31 references) achieves integration across three distinct analytical dimensions, a critical decision-support gap re-emerges at higher levels of scale synthesis.

Only a minimal fraction of the final corpus demonstrates comprehensive, multi-layered systemic depth, with a mere 5% (4 references) bridging four pillars, and only 1% (1 reference) managing to successfully intersect all five operational domains. This descriptive breakdown confirms that existing research is heavily compartmentalized within technical silos, leaving an underdeveloped methodological foundation for the holistic variable sets required to construct a comprehensive Analysis for sustainable mountain reinhabitation in rural and Alpine territories of Italy.

2.8 Thematic Insights and Gaps

The coding process reveals several structural patterns within the literature, highlighting a critical lack of interdisciplinary depth. Only a limited fraction of current research achieves high-level integration across the spatial, environmental, and strategic pillars.

1. Fragmented Documentation Practices The literature includes a wide range of documentation systems operating at different institutional levels. National datasets (ISTAT, ISPRA) provide extensive territorial coverage, while specialized approaches focus on architectural semantics. However, these contributions evolve in distinct disciplinary silos. Current research frequently treats historical settlements as static architectural shells, resulting in physical documentation that frequently remains hazard-blind. Furthermore, the literature reveals a persistent struggle to operationally define heritage settlements in statistical terms, reinforcing the necessity of using SRS and SMRS proxies.

2. Parallel Assessment Approaches A substantial body of research addresses environmental hazards and climate exposure using tools like Copernicus and Agenzia Regionale per la Protezione Ambientale (ARPA) inventories. Concurrently, heritage studies focus on historical, architectural, or morphological dimensions. These assessments are typically developed in parallel, treating environmental hazard and heritage value as separate disciplines rather than intersecting vulnerabilities.

3. Policy-Oriented but Tool-Limited Frameworks European and national policies explicitly promote the revitalization of marginal territories. The literature offers extensive qualitative governance analyses of these frameworks. However, there is a clear disconnection between these macro-level policy ambitions and practical implementation; the field severely lacks operational, data-driven tools capable of linking funding objectives to spatial documentation, project selection, or long-term hazard monitoring.

These thematic patterns reveal a structural misalignment. On this basis, three interrelated research gaps are clearly identified:

Gap 1. Hazard-aware documentation is missing: Almost no studies integrate micro-scale architectural documentation with macro-scale hazard datasets.

Gap 2. Multiscale integration is rare: Territorial, settlement,

Structural patterns

Gaps

2.8 Thematic Insights and Gaps

and building scales are typically treated separately.

Gap 3. Decision-support tools are limited: Existing GIS frameworks fail to explicitly support hazard-informed rural planning or prioritize viable reinhabitation scenarios.

These three interrelated gaps directly inform the methodological structure developed in Chapter 5. The framework explicitly attempts to address each: integrating micro-scale architectural documentation with regional hazard datasets, maintaining coherence across multiple spatial scales within a unified GIS workflow, and producing operational decision-support outputs directly usable by planners and local administrators.

Looking at the chronological evolution of this literature, a clear trajectory emerges: while early studies relied heavily on analog and interpretive mapping, recent research has decisively shifted toward semantic, digital, and open-data infrastructures. However, despite this digital evolution and the broad coverage of spatial scales, ranging from local architectural surveys to national statistical inventories, the primary limitation persists. Very few existing frameworks successfully integrate these multi-source datasets (hazard, heritage, and demography) into a single interoperable GIS environment for reinhabitation planning.

Ultimately, the SLR confirms that the current field is interdisciplinary but fragmented; rich in thematic studies but weak in integrated spatial methods; and adequately aware of policy ambitions but disconnected from operational GIS tools. By addressing these structural misalignments, this thesis aims to develop a hazard-aware, multiscale GIS documentation workflow that bridges physical heritage preservation with environmental hazard assessment, providing a replicable WebGIS decision-support platform for rural and alpine governance.

The next chapter builds directly on these insights to explicitly define MHCs, review current reinhabitation policies, and position the methodology within national and European planning frameworks.

3 Framing MHCs and Reinhabitation

This chapter establishes the conceptual framework of MHCs by examining their structural vulnerabilities at the intersection of demographic decline and environmental fragility. It critically reviews current reinhabitation models and multiscalar policy frameworks, ranging from local adaptive reuse strategies to high-level European and national agendas, to highlight the vital need for interoperable spatial documentation that can bridge the persistent gap between abstract governance and operational planning.

3.1 Framing MHCs and Structural Vulnerability

The small historic settlements of Italy, traditionally referred to as borghi and in recent spatial research as MHCs, represent a unique class of cultural heritage positioned at the critical intersection of environmental fragility and demographic decline. The unique morphologies and peripheral locations of these settlements make them both highly valuable in terms of cultural potential and structurally vulnerable.

Recent policy attention, observed in analyses of national regeneration (De Luca, 2023) and the EU Long-Term Vision for Rural Areas (European Commission, 2021a), signals renewed institutional interest in re-activating these marginalized places. Yet, as highlighted by Alpine Convention reports (Permanent Secretariat of the Alpine Convention, 2007- 2023) and Italian demographic analyses compiled by ISTAT (ISTAT, 2020a), structural challenges persist: declining population density, shrinking essential services, and the severe intensification of climate-related hazards.

Across the 82 references analyzed in the SLR, a consistent pattern emerges: the absence of interoperable documentation, the partial integration of hazard data, and limited cross-scale alignment between national, regional, and local strategies. Within this framework, MHCs must be understood not merely as static architectural artifacts, but as living socio-environmental systems. Their sustainable reinhabitation depends fundamentally on coupling cultural documentation with environmental, infrastructural, and demographic data.

3.2 Defining MHCs and Documentation Needs

MHCs are small historic settlements, often overlapping with what are colloquially referred to in Italy as borghi, that combine cultural and architectural heritage with severe socio-environmental fragility. MHCs are characterized by several intersecting conditions. First, despite significant demographic decline, these settlements retain a high degree of material, architectural, and spatial coherence. Second, they suffer from declining functionality, experiencing shrinking local economies, reduced public services, and partial or total abandonment. Finally, because they are frequently situated in peripheral, alpine, or inner areas, they face acute infrastructural, environmental, and accessibility challenges (Colucci et al., 2021; Rolli, 2008). Because qualitative concepts like MHCs lack rigid operational boundaries

3.2 Defining MHCs and Documentation Needs

in census data, identifying their physical footprints necessitates the use of spatial proxies. This intersection of vulnerabilities can be categorized across three territorial classifications:

Borghi: Traditionally celebrated as tourist destinations or heritage sites, borghi frequently overlap with MHCs, though the term itself is qualitative and does not formally capture population or functional decline (Sau, 2018).

Inner Areas: MHCs often fall within the boundaries of SNAI, which targets peripheral municipalities suffering from critical service gaps, structural depopulation, and connectivity issues (De Rossi, 2019).

Alpine Settlements: Alpine MHCs face compounding environmental pressures, navigating extreme topography, landslides, debris flows, hydrogeological instability, and climate-sensitive hazards (Action Group 6, 2023; Permanent Secretariat of the Alpine Convention, 2015).

Existing national catalogs, such as ISTAT settlement datasets, the Istituto Centrale per il Catalogo e la Documentazione (ICCD) heritage inventories, and regional geoportals, document isolated elements of MHCs but rarely capture the settlement system as an integrated whole. Rolli (2008) observed that minor centers fall awkwardly between the institutional categories of “monument” and “city,” causing persistent under-representation in Italy’s formal heritage policies. To address this, Colucci (2022) proposes an ontology-based framework capable of linking semantic descriptors (materials, architectural typologies, historical phases) with multiscale GIS representations. This approach aligns with broader European efforts toward data harmonization under INSPIRE and CityGML standards, but remains one of the few implementations tailored specifically to historic villages.

The urgent need for interoperable documentation is reinforced by several other foundational works:

The Publicarchitecture@Polimi research group (2009) documented abandonment via qualitative mapping but lacked systematic database harmonization.

ISPRA “Ghost Cities” inventory (Delmonaco et al., 2023) mapped abandoned settlements extensively but without semantic architectural detail.

ISTAT’s Inner Areas analyses (ISTAT, 2020; 2022) stressed the necessity for spatially enabled documentation to support rural planning.

Italian terms and classifications

Documentation projects

3.2 Defining MHCs and Documentation Needs

Together, these works confirm the central diagnosis of the literature: the fragmentation of data remains the primary weakness in MHC governance.

3.3 Reinhabitation Models and Dynamics

The demographic, economic, and spatial trajectories of Italy's inner and mountain areas are extensively documented by ISTAT and the SNAI program. Studies across the literature converge on similar patterns of structural fragility (Rocchelli & Berizzi, 2019), detailing long-term depopulation trajectories in rural municipalities (De Rubertis, 2019) and analyzing how cohesion policy instruments operate in marginal territories (Cotella & Vitale Brovarone, 2024).

While the literature outlines these depopulation dynamics, achieving successful revitalization requires operational models. Reinhabitation involves adaptive, incremental interventions designed to restore functional vitality to MHCs. While acknowledging that these models do not represent an exhaustive inventory, the literature distinguishes several primary strategies:

Adaptive Reuse

Adaptive reuse transforms abandoned or under-utilized heritage buildings for contemporary purposes while preserving their core cultural value. Key applications of this strategy include the recovery of housing stock for residents or new settlers (Amodio, 2022; De Luca, 2023), and the creation of community facilities and creative hubs to stimulate localized socio-economic activity (Salvatore et al., 2020). Crucially, sustainable adaptive reuse in MHCs requires multiscale spatial knowledge, linking building-scale interventions with overarching environmental constraints such as slope stabilization and flood adaptation (Pirlone, 2016).

Albergo Diffuso

The Albergo Diffuso (distributed hotel) model represents a heavily tourism-driven strategy for revitalization. It distributes hospitality functions across existing, vacant residential structures within the village, effectively

3.3 Reinhabitation Models and Dynamics

minimizing new construction and preserving the traditional urban fabric (Morena et al., 2017; Vallone & Veglio, 2014). While effective at generating short-term economic benefits and promoting local identity, this model does not inherently address long-term demographic sustainability. Furthermore, without GIS-based assessment, such models remain hazard-blind, risking the promotion of tourism in environmentally vulnerable sectors.

Bottom-up vs. Top-down Approaches

Revitalization strategies generally operate through two distinct governance vectors. Bottom-up, community-driven approaches emphasize incremental revitalization, local knowledge, and social cohesion (Salvatore et al., 2020). Conversely, top-down, policy-led initiatives, such as the PNRR “Borghi” programs or SNAI interventions, focus heavily on macro-scale infrastructure, financial incentives, and rigid regulatory frameworks (De Luca, 2023; Prezioso, 2018). The literature converges on the necessity of hybrid approaches: combining local community involvement with structured national policy support.

These works argue collectively that successful reinhabitation requires incremental, place-based strategies supported by community participation and spatial knowledge. Yet, this domain currently lacks the multiscale GIS tools necessary to realize these goals.

3.4 Policy Context

The revitalization of MHCs aligns with a multi-scalar matrix of policy frameworks that dictate strategic funding and development across European and Italian territories. Moving beyond static architectural conservation, contemporary governance now positions these settlements as critical nodes for sustainable development and demographic resilience. These policies cascade directly from high-level EU directives down to targeted national interventions, establishing the financial and regulatory parameters required to support long-term reinhabitation.

3.4 Policy Context

EU Rural Agenda

The Long-Term Vision for Rural Areas outlines a strategic objective to build stronger, connected, resilient, and prosperous rural territories by 2040. It heavily prioritizes demographic renewal, digital connectivity, and the green transition (European Commission, 2021a, 2021b; McEldowney, 2021). Supported by tools such as the Rural Pact and Smart Villages, this agenda provides the overarching conceptual baseline for Italy's localized strategies, heavily aligning with the Common Agricultural Policy (CAP) (European Commission, 2026).

Italian National Frameworks

At the national level, regeneration relies on a matrix of intersecting programs. The National Adaptation Communication (Government of Italy, 2023) integrates climate adaptation and disaster risk reduction, while ISTAT datasets (ISTAT, 2020a, 2020b) provide the quantitative baselines necessary to measure demographic decline and service gaps.

Concurrently, the PNRR “Borghi” programs promote immediate cultural regeneration, while territorial cohesion frameworks emphasize transport, accessible services, and socio-spatial equity as non-negotiable prerequisites for reinhabitation (Amodio, 2022; Bacci et al., 2020; Prezioso, 2018).

Alpine Convention and Mountain Policies

The Alpine Convention provides trans-national governance specifically tailored to Alpine sustainability. Policy priorities within this framework have evolved significantly over the past two decades: shifting from a sectoral focus on transport and tourism (2007–2013), toward urgent demographic change and risk governance (2015–2020), and currently focusing on Alpine towns as drivers of sustainable regional networks (Action Group 6, 2023). Within the Ministero dell'Ambiente e della Sicurezza Energetica (MASE) institutional framework, datasets produced by ISPRA and ISTAT continually highlight the compounding threats of residential mobility patterns and climate-driven hazards in these fragile high-altitude environments (Delmonaco et al., 2023; ISTAT, 2022).

Despite this abundance of policy, the literature reveals profound implementation barriers. PNRR interventions often remain

3.4 Policy Context

symbolic rather than structural (De Luca, 2023). Prezioso (2018) highlights the glaring lack of Territorial Impact Assessments for cohesive policies, while Covino (2017) and Battisti (2017) detail the political dimensions of marginality without offering spatial solutions.

3.5 Cross-Framework Insights

An analysis of these distinct policy domains reveals several unified thematic trajectories. First, all frameworks anchor policy in “place-based cohesion,” relying on localized spatial data to inform rural regeneration. Second, resilience has evolved into a primary territorial strategy, where climate adaptation, hazard management, and demographic revitalization are treated as interdependent operational pillars. Third, depopulation is universally recognized as the central underlying vulnerability driving settlement decay. Fourth, Infrastructure for Spatial Information in the European Community (INSPIRE), MASE, and ISTAT datasets increasingly provide the vital geospatial backbone required for modern GIS governance. Finally, there is a recognized shift in cultural integration; marginalized villages are no longer viewed merely as declining settlements, but as vital heritage assets (Rolli, 2008; Veith, 2011) that require data-driven monitoring to survive.

However, as established in the SLR, these high-level policy ambitions collide with severe operational limitations. Despite the abundance of trans-national funding mechanisms, such as the PNRR and the EU Rural Vision, and the availability of highly sophisticated, isolated datasets (e.g., Copernicus remote sensing and ISTAT demographic indicators), a critical structural bottleneck persists. Heritage, demographic, and environmental data continue to be collected using incompatible schemas, preventing integrated spatial analysis. While theoretical models like Colucci's (2022) ontology attempt to resolve this data fragmentation, existing institutional inventories remain stubbornly siloed. Consequently, small municipalities frequently fall short of the technical or financial resources required to bridge these domains. Although national and European policies explicitly recognize the value of MHCs, operational constraints persist; addressing this gap, the subsequent chapters of this thesis develop the interoperable GIS workflows needed to translate baseline spatial documentation into targeted project selection and long-term hazard monitoring.

3.6 Linking Research and Policy Agendas

The reinhabitation of MHCs sits firmly at the intersection of territorial cohesion, climate adaptation, hazard resilience, and heritage valorization. Multiscale GIS documentation offers the precise technical bridge required to operationalize these high-level policy objectives into ground-level planning. The specific frameworks analyzed here, ranging from the trans-national EU Rural Vision down to Italy's targeted PNRR, were deliberately selected because they represent the primary, active funding and regulatory mechanisms currently driving Alpine and rural regeneration. Other localized or purely socio-economic frameworks were excluded if they lacked explicit spatial mandates or failed to directly address the infrastructural and demographic realities of marginalized mountain contexts. To bridge conceptual policy targets with empirical data, Table 4 outlines the alignment of prominent frameworks with their corresponding spatial parameters. Consequently, this matrix is not intended as an exhaustive inventory of all territorial policies, nor does it preemptively list the exact localized files utilized in the subsequent case studies. Instead, it functions as a theoretical guide illustrating which categories of spatial indicators these policies demand to transition abstract governance goals into measurable, operational GIS outputs.

Policy Framework	Core Policy Goal	Required Spatial Indicators	Operational GIS Output
EU Rural Vision 2040 / CAP	Demographic renewal & cohesion of rural territories.	Rural-urban classification proxies & demographic variation rates.	Macro-scale mapping of functional rural shrinking areas to establish demographic baselines.
National Strategy for Inner Areas (SNAI)	Guarantee equitable access to essential services (Health, Education, Mobility).	Accessibility models, travel-time indices, and service catchment radii.	Identification of infrastructural deficits and prioritization of SMRS for service hub integration.
PNRR "Borghi" Measures	Structural recovery & cultural regeneration of historic buildings.	Settlement footprints, volumetric analysis, & residential vacancy proxies.	Morphological assessment to determine physical capacity for adaptive reuse.
EU Climate Adaptation & MASE Plan	Disaster Risk Reduction (DRR) & hydrogeological resilience.	Hazard inventories & remote-sensing environmental constraints.	Exclusion mapping to identify zones where environmental hazard renders reinhabitation unviable.
Alpine Convention & EUSALP	Trans-national environmental protection & sustainable mountain economies.	Topographic constraints, slope analysis, & altitude baselines.	Vulnerability indices tailored specifically to the geomorphology of high-altitude settlements.

Table 4. Operational Alignment of Policy Frameworks with Spatial Indicator Categories.
(Source: Author's elaboration)

3.6 Linking Research and Policy Agendas

As illustrated in Table 4, the shift from policy ambition to spatial execution relies heavily on specific categories of geospatial data. However, identifying these requirements is only the first step. In practice, planners must navigate a highly fragmented digital landscape to acquire these layers, often cross-referencing European satellite observations with rigid national census blocks and localized environmental hazard inventories. The operational challenge, therefore, lies not just in identifying the correct spatial indicators, but in constructing an interoperable GIS environment capable of synthesizing these disparate sources into a unified analytical model.

3.7 Strategic Alignment and Next Steps

This disconnect between policy ambition and technical execution reinforces the core rationale of this thesis. To move beyond symbolic interventions and deeply fragmented data silos, rural regeneration requires a comprehensive, data-driven methodology. By developing a multiscale, hazard-aware GIS workflow, operationalized through a WebGIS decision-support platform, this thesis aims to build the necessary technical bridge between macro-level policy objectives and the ground-level realities of Alpine villages.

However, before any spatial documentation or socio-economic policy can be successfully applied to these marginalized territories, the physical survivability of the settlements must be established. Because the actual realization of any reinhabitation strategy relies fundamentally on environmental safety, the following chapter shifts focus entirely to the specific hydrogeological hazards, landscape processes, and climate-related constraints that physically dictate the future of these territories.

4 Hazard and Environmental Constraints

This chapter evaluates the physical environment as an active, structural constraint on the survival and potential reinhabitation of marginalized alpine settlements. By analyzing the primary hydrogeological and cryospheric hazards, specifically floods, landslides, and avalanches, alongside the compounding effects of climate change and landscape abandonment, the chapter establishes the critical environmental parameters required to operationalize a multi-scale, hazard-aware spatial diagnostic tool.

4.1 Geomorphological Dynamics and Spatial Constraints

When evaluating the demographic abandonment, or the conditional reinhabitation of MHCs across rural and alpine territories, the physical environment must be understood as an active, structural constraint. These settlements do not exist as static coordinates on a map, but are embedded within dynamic geomorphological systems that respond continuously to shifts in land management, vegetation succession, and climatic forcing.

Within this alpine context, environmental exposure is predominantly driven by acute, episodic, or catastrophic events, which act upon slope systems that have been progressively destabilized over decades by the cumulative effects of agrarian neglect and altered drainage patterns (Meusburger & Alewell, 2008). High-intensity precipitation events and gravity operate as immediate triggers upon these unmaintained slope structures, transforming long-term structural decay into sudden, destructive mass movements.

For territorial planners and regional stakeholders, geomorphological processes establish the absolute threshold of physical viability. Hazard exposure cannot be interpreted as an accidental, external disruption, but must be recognized as an intrinsic territorial attribute that governs the structural preservation of vernacular architecture, dictates the safety of local accessibility corridors, and defines the spatial boundaries of safe re-settlement zones.

Hazard layer selection logic

This chapter transitions away from heavy, site-specific geotechnical engineering modeling to establish a macroscopic, planning-oriented analysis of regional hazard inventories and climate change vectors. Rather than treating environmental constraints through a generalized, non-differentiated lens, this thesis adopts an inductive logic rooted in the specific physical realities of the selected case studies, which are Ollomont, Elva, and Macugnaga.

By evaluating the predominant hydrogeological and cryospheric hazards actively impacting these three distinct alpine contexts, this chapter establishes the specific parameters of the multiscale GIS documentation framework. It is explicitly acknowledged that while numerous other environmental forces, such as wind-throw events or seismic vulnerabilities, influence mountain territories, the scope of this thesis is strictly bounded to landslide, flood, and avalanche hazards, as they represent the primary geomorphological constraints dictating alpine settlement survival. Consequently, these three core hazards are systematically structured across descending regional, territorial, and settlement tiers to filter spatial data precision according to the specific geographic scope of each planning phase.

4.2 The Abandonment Paradox

The geomorphological response of mountain slopes to human abandonment is non-linear, multi-directional, and highly dependent on regional topography, historical engineering interventions, and temporal phases. In academic discourse, landscape abandonment is frequently treated through a simplified, one-dimensional lens, assuming a uniform trajectory of degradation. Real-world landscape processes, however, reveal a complex split, demonstrating that the cessation of human maintenance can produce completely contradictory geomorphological states depending on the specific geographic context. In high-angle alpine environments historically modified by human hands, such as the terraced slopes surrounding many Italian MHCs, abandonment operates as an immediate trigger for slope instability. Built over generations to make steep profiles cultivable, dry-stone retaining wall networks are hybrid heritage-infrastructure assets that fulfill a critical hydrogeological stabilization function. When properly maintained, these systems regulate the downslope movement of water, promote infiltration, and minimize surface soil displacement.

The abandonment of these terraced landscapes actively increases hydrogeological hazard levels (Agnoletti et al., 2019). The lack of routine stone-wall maintenance leads to vegetation overgrowth, the clogging of traditional agricultural drainage channels, and the concentration of uncontrolled surface runoff (Raso et al., 2019). Under intense rainfall conditions, hydrostatic pressure builds up behind the unmaintained structures, leading to the cascading structural collapse of the engineered slopes, which transforms traditional agricultural assets into active triggers for shallow landslides and rapid debris flows that threaten the built fabric of the villages below. In contrast, a completely different ecological and geomorphological trajectory is documented in abandoned agricultural sectors in Portugal (Nunes et al., 2010). At these locations, the long-term absence of human intervention allowed natural vegetation to spontaneously recover, driving an extensive rewilding process across the unmaintained slopes. Over a transitional threshold of approximately one decade, the progressive establishment of dense scrub and forest cover significantly reduced soil erodibility and slowed surface water runoff, resulting in lower erosion and landslide rates than during the active agricultural phase. This contrast in results is detailed in Figure 5.

This divergence proves that landscape abandonment is not a one-dimensional phenomenon. The structural degradation of high-angle artificial terracing exacerbates vulnerabilities, while natural rewilding on non-engineered profiles can actively mitigate geomorphological hazards over time. Consequently, it is methodologically imperative that planners do not rely on generalized, regional-scale generalizations. Instead, the

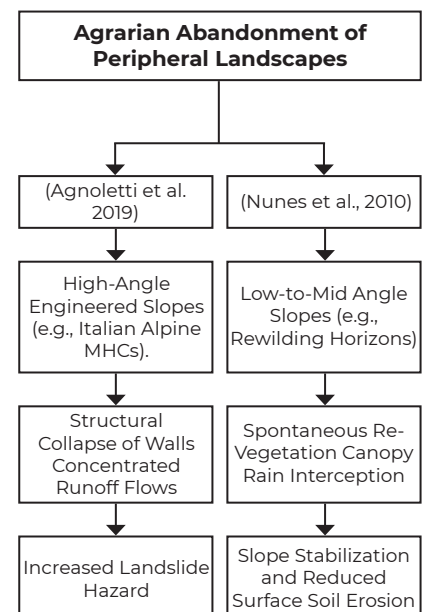


Figure 5. Land abandonment paradox in rural areas.
(Source: Author's elaboration)

4.2 The Abandonment Paradox

conditional feasibility of reinhabitation must be evaluated by executing site-specific hazard assessments for each unique territory, mapping the precise interaction between local slope morphology, historical engineering structures, and contemporary land cover patterns. Crucially, planners must consider transitional risks: reinhabitation activities like clearing brush or building roads can temporarily destabilize slopes that had reached a natural equilibrium through rewilding.

4.3 Analyzed Hazard Typologies

To construct an operational decision-support tool, the multiscale GIS framework prioritizes the three primary hydrogeological and cryospheric hazards that structurally constrain alpine reinhabitation, utilizing specific institutional classification matrices to measure and standardize physical danger across the Italian territory.

4.3.1 Flood Hazard Classification

Hydraulic hazards refer strictly to the physical probability and magnitude of potentially destructive water events, distinct from flood risk, which evaluates the socio-economic exposure of the impacted areas.(Laidlaw & Percival, 2024; Wang et al., 2022).

To accurately model these physical threats within mountain catchments, it is necessary to distinguish between the specific mechanisms of water accumulation:

Flood Hazard Typology

Fluvial (Riverine) Flooding: The flooding of typically dry areas caused by the increased water level of an established river overflowing onto surrounding banks and shores.

Pluvial Flooding: Flooding that occurs when an extreme rainfall event causes inundation independent of an overflowing water body.

Flash Flooding: A rapid, extreme, and potentially life-threatening flow of high water into a typically dry area, which can begin shortly after an intense causative event.

4.3 Analyzed Hazard Typologies

4.3.1 Flood Hazard Classification

Compound Flooding: An extreme event caused by a combination of hydrological and meteorological processes that overwhelm natural drainage systems.

To standardize the mapping of these hydraulic hazards across the territory in compliance with the Flood Directive 2007/60/EC and its national transposition via Legislative Decree 49/2010, the ISPRA IdroGEO platform delineates flood hazard (Pericolosità da alluvione) into three primary spatial dataset layers.

Based on the official ISPRA 2020 mosaic of flood-prone areas, these three probability scenarios are measured using calculated hydrologic return periods (T), covering the following extents of the national territory, High Probability Hazard (HPH), Medium Probability Hazard (MPH), and Low Probability Hazard (LPH), which are detailed in Table 5.

Hazard Level	Code	Description	Characteristics
High Probability Hazard	HPH	Frequent floods; short return period between 20 and 50 years.	These cover 5.4% of the national territory equal to 16,224 km ² .
Medium Probability Hazard	MPH	Infrequent floods; moderate return period between 100 and 200 years.	These cover 10% of the national territory equal to 30,196 km ² .
Low Probability Hazard	LPH*	Rare or extreme flood events; captures the absolute geographical limit of potential danger.	These cover 14% of the national territory equal to 42,376 km ² .

* While these scenarios provide a vital baseline for institutional compliance, it must be emphasized that in small alpine headwater catchments, intense convective rainfall events trigger flash floods and torrential surges that behave with extreme volatility relative to standard basin-wide calculations. These macro-scale frameworks can underestimate local torrent behavior, meaning that peripheral sectors classified under LPH scenarios may still face significant exposure to episodic torrential dynamics. Table 5. ISPRA Flood categorization and terminology. (Source: Author's elaboration)

4.3.2 Landslide Hazard Classification

Landslides constitute the most frequent, immediate geomorphological hazard impacting marginalized alpine centers. Slope movements are differentiated by their failure kinematics (falls, topples, slides, spreads, and flows) and the geotechnical properties of the involved materials, such as rock, clay, debris, and gravel. Based on the updated Varnes classification (Hungr et al., 2014), the framework acknowledges the difference between deep-seated clay/ silt rotational slides (traditionally termed slumps) in cohesive deposits, shallow gravel/sand/debris slides occurring in loose colluvial veneers over stronger substrates, and extremely rapid, flow-like debris avalanches that initiate on steep slopes without channel

Landslide Hazard Typology

4.3 Analyzed Hazard Typologies

4.3.2 Landslide Hazard Classification

confinement.

The degree of strength loss during the primary failure stage determines the post-failure velocity and overall destructiveness of these events. However, for mapping the landslide hazard, this thesis relies on the available data, which sometimes does distinguish between the aforementioned types.

In the context of Italian planning, these diverse slope processes are monitored and regulated through the Piani di Assetto Idrogeologico (PAI), compiled by the competent River Basin District Authorities and consolidated nationally by ISPRA.

The PAI framework measures and maps landslide hazard (Pericolosità da frana) by evaluating both active slope movement inventories and territorial susceptibility indices, accounting for post-failure activity states such as re-activated, dormant, or relict features. The institutional standard establishes a strict five-tier ordinal scale to categorize the level of danger across the territory, Very High Hazard (P4) , High Hazard (P3), Medium Hazard (P2), Moderate Hazard (P1), and Attention Zones (AA), which are detailed in Table 6.

Hazard Level	Code	Description	Key Implications & Characteristics
Very High Hazard	P4	Active, rapid, or large-scale slope movements with an immediate probability of occurrence.	Imposes absolute building bans. Includes extremely rapid phenomena where spontaneous evacuation is impossible.
High Hazard	P3	Moderately active or highly susceptible slope sectors.	Geomorphological processes directly threaten structural stability.
Medium Hazard	P2	Areas characterized by potential instability, or ancient, dormant, or relict landslide perimeters.	Requires site-specific geotechnical validation.
Moderate Hazard	P1	Stable slope sectors with low geomorphological susceptibility under standard triggers.	Minimal immediate risk under normal conditions.
Attention Zones	AA	Boundary sectors that do not exhibit active failures but are structurally/ topographically connected to unstable catchments.	Requires long-term monitoring to ensure stability.

Table 6. ISPRA landslide categorization and terminology.
(Source: Author’s elaboration)

4.3 Analyzed Hazard Typologies

4.3.3 Avalanche Hazard Classification

In high-altitude alpine catchments, snow avalanches represent a dominant cryospheric hazard constraint that dictates the seasonal accessibility and physical survivability of mountain settlements. An avalanche is defined as a mass of snow, often mixed with ice, soil, pebbles, and other material, that moves rapidly down a slope, standardly exceeding a length and width of 50 meters (EAWS Glossary, 2026). Mechanically, avalanches are categorized by their release type and liquid water content, distinguishing between loose snow avalanches, which originate from a single point in cohesionless snow, and slab avalanches, which occur when a cohesive snow layer detaches along a distinct fracture line over a failure plane (Maggioni & Massari, 2019).

Furthermore, avalanches are classified by their wetness into dry-snow avalanches, driven by mechanical instability within cold snowpacks, and wet-snow avalanches, which are triggered by liquid water infiltration that destroys capillary cohesion between snow grains (EAWS Glossary, 2026). The release mechanism is heavily influenced by mountain terrain parameters, snowpack stratigraphy, and immediate meteorological triggers, where terrain gradients between 30 degrees and 45 degrees represent the critical slope threshold for slab detachment (LAB SNOW, 2026). Conventional avalanche forecasting and hazard evaluation require a multiscale analysis of these terrain parameters, assessing how local slope morphology interacts with structural weaknesses within the snow accumulation profile (Maria et al., 2024).

Avalanche Hazard Typology

To operationalize these cryospheric processes within territorial planning, this thesis had to synthesize spatial data from two separate regional mapping agencies, as the administrative criteria, classification categories, and underlying regulatory philosophies differ significantly between the Autonomous Region of Valle d'Aosta and the Region of Piedmont. Because avalanches cross borders but spatial planning frameworks do not, these institutional discrepancies alter how land exposure is calculated and managed at the regional level.

Aosta Valley:

Because over 60% of its territory sits above an elevation of 2,000 meters, the Valle d'Aosta region executes an exhaustive, territory-wide avalanche hazard evaluation (Permanent Secretariat of the Alpine Convention, 2019). The regional database of this region is divided into distinct, localized spatial vector layers, "ambiti_valanghe", "valanghe_paline", "valanghe_paravalanghe", and "valanghe_valanghe". The ambiti_valanghe vector layer delineates the absolute spatial boundaries of the analyzed avalanche catchments, which are tied directly to the strict,

4.3 Analyzed Hazard Typologies

4.3.3 Avalanche Hazard Classification

legally binding regulatory zoning tiers (V1, V2, V3) calibrated by calculated impact pressures and statistical frequencies. Under Valle d'Aosta legislation, V1 zones outline high hazard sectors characterized by severe expected events, such as those with a return period of $T \leq 100$ years and an impact pressure equal to or exceeding 30 kilopascals (kPa), imposing absolute building bans. V2 Zones represent Medium hazard sectors with a 100-year return period and impact pressures between 5 kPa and 30 kPa, requiring structural reinforcement, and V3 Zones dictate low hazard zones under 5 kPa. All classifications of this layer are further explained in Table 7 (Aosta Valley Geoportal, 2026).

Hazard Level	Code	Italian Legend	Key Implications & Characteristics
High Hazard Zone	V1	Area ad alto rischio.	Subject to strict administrative building bans due to high destructive potential or frequent historical recurrence.
Active Avalanche Core Path	Va	Zona esposta a fenomeni valanghivi	Delineated physical tracks, release zones, or runout corridors actively exposed to documented avalanche phenomena.
Medium Hazard Zone	V2	Area a medio rischio	Medium exposure areas where building modifications require specific structural reinforcement or seasonal safety and evacuation protocols.
Probable Avalanche Sector	Vb	Zona di probabile localizzazione dei fenomeni valanghivi	Susceptibility perimeters capturing the statistical or topographic likelihood of avalanche interaction, extending outside immediate historical footprints.
Low Hazard Zone	V3	Area a basso rischio	Low-exposure peripheral boundaries where standard territorial safety monitoring is maintained without restrictive structural prohibitions.
Mitigated / Reclaimed Zone	Vs	Valanghe o settori di valanga che, per la presenza di opere di difesa attiva considerate efficienti, sono allo stato attuale da ritenersi bonificate	Mitigated / Reclaimed Zone: Active avalanche paths or sectors that are officially classified as stabilized or reclaimed due to the verified installation of functional defense assets (opere di difesa attiva) such as snow bridges, nets, or retention structures.
Non Applicable Area	Np	Ambito non presente	Non Applicable Area: Zones falling completely outside the mapped or analyzed boundaries of the regional avalanche inventory catchments.

Table 7. Aosta Valley Avalanche categorization and terminology. (Ambiti Valanghe). (Source: Author's elaboration)

4.3 Analyzed Hazard Typologies

4.3.3 Avalanche Hazard Classification

While the macro-scale `ambiti_valanghe` dataset outlines the legally binding planning boundaries across the landscape, the `valanghe_valanghe` layer functions as the granular regional historical avalanche inventory repository, tracking specific mapped events and localized structural perimeters. The data is classified with many attributes, the typology differentiates the geometry of the entry, where a code of C represents the continuous maximum overall historical footprint of a known path corridor, while S indicates a single seasonal event captured outside traditional historical limits. The “categoria” attribute serves as an institutional data validation tracking index rather than a physical danger alert. This field measures the completeness of the supporting archival documentation, where a status of green implies a fully verified, photogrammetrically confirmed perimeter with complete data sheets, yellow marks paths with verified occurrences but incomplete secondary records, and orange represents legacy entries with high geometric uncertainty.

Lastly, the layers `valanghe_paravalanghe` (avalanche defense structures and snow bridges) and `valanghe_paline` (snow monitoring stations and palines) are not addressed in this thesis.

Piedmont:

In contrast to the continuous, regulatory territory-wide zoning of Valle d'Aosta, the Region of Piedmont operates its spatial planning and cryospheric tracking through the Sistema Informativo Valanghe (SIVA) overseen by Arpa Piemonte. The repository consists of a highly diversified set of vector layers that segment avalanche data into separate historical, photogrammetric, territorial, and structural management files. The core of this system revolves around the Carte della Localizzazione Probabile delle Valanghe (CLPV), an empirical mapping framework that isolates the maximum historical perimeters of documented sites. Rather than enforcing generalized predictive safety boundaries across all slopes, the Arpa Piemonte architecture leverages these discrete spatial layers to track known events relative to anthropized sectors or local municipal master plans (Piano Regolatore Generale Comunale (PRGC)). By organizing the dataset into targeted components such as historical information, structural defenses, and municipal planning integrations, the SIVA framework establishes an empirical database optimized for localized spatial planning (Arpa Piemonte, 2025).

Table 8 catalogs the vector files of Arpa Piemonte's official SIVA data structure, leaving fields empty where explicit layer definitions are unlisted on the Arpa portal.

4.3 Analyzed Hazard Typologies

4.3.3 Avalanche Hazard Classification

Layer	Arpa SIVA Layer	Definition and Mapped Feature
PIE_infostoriche	Historical information (Informazioni Storiche)	Mapped perimeters or tracking points derived from verified historical records, archival documents, and past event logs.
PIE_modterr	Territorial Modifications (Modifiche Territoriali)	-
PIE_operedifesa	Avalanche Mitigation/ Structural Defenses (Opere di Difesa)	Active and passive avalanche defense assets, protective retaining infrastructure, and structural slope installations.
PIE_valfoto	Aerial Photogrammetry Avalanches (Valanghe da Foto interpretazione)	Avalanche perimeters and boundaries delineated through multitemporal aerial photogrammetry and remote-sensing photointerpretation.
PIE_valmin	Minimum-Scale Mapped Avalanches (Valanghe Minime)	Mapped extents of minor or minimum-scale observed avalanche events that do not reach the threshold of macro historical sites.
PIE_valminprgc	Municipal Master Plan Minor Avalanche Zones (Valanghe Minime PRGC)	Spatial overlay of minor avalanche features intersecting local municipal master plan (PRGC) regulatory boundaries.
PIE_valprgc	Municipal Master Plan Mapped Avalanches (Valanghe PRGC)	Main historical avalanche perimeters mapped or referenced directly within the urban planning zones of the municipal master plans (PRGC).
PIE_valterreno	Avalanches Mapped via Ground Survey (Valanghe da Rilievo a Terreno)	Avalanche footprints, release vectors, and runout zones mapped and verified directly via physical field surveys and ground telemetry.
PIE_zoneper	Delineated Boundary Zones (Zone Perimtrate)	Delineated boundary zones outlining high-susceptibility avalanche perimeters used to evaluate local terrain hazards.
PIE_zoneprgc	Municipal Master Plan Delineated Hazard Zones (Zone Perimtrate PRGC)	Perimetrated avalanche hazard areas integrated directly into the municipal master plan (PRGC) administrative land-use layers.

Table 8. Piedmont Avalanche categorization and terminology. (Source: Author's elaboration)

4.4 Climate Change Dimensions as Hazard Multipliers

Climate change operates as a profound hazard multiplier across high-altitude territories by fundamentally altering the spatial boundaries, intensity, and frequency of primary alpine risks. Mountain settlements were historically established in specific topographic zones deemed secure over centuries of observation and traditional environmental knowledge. However, contemporary climate variability introduces unprecedented environmental pressures that destabilize these historically safe areas, transforming once-secure locales into high-risk zones. Rather than introducing entirely novel geomorphological phenomena, climate change accelerates and de-synchronizes existing environmental dynamics, pushing natural processes past historical thresholds. Under current climate scenarios, small high-altitude settlements face an escalated exposure to a triad of critical hydro-meteorological and gravitational hazards, floods, landslides, and avalanches, for which historical structural placements and traditional defenses are entirely unprepared (Intergovernmental Panel on Climate Change (IPCC), 2023).

Shifting Baselines of Torrential Flooding

The primary meteorological driver of altered hazard profiles in alpine catchments is the transformation of precipitation delivery. While total annual precipitation metrics in regions like Northwestern Italy have remained relatively stable over long historical timelines, the internal structure of these regimes has shifted toward highly concentrated, intense convective rainfall events. This sudden volumetric delivery of water over brief intervals triggers catastrophic flash floods and torrential surges within mountain catchments. Because these extreme rainfall events occur with higher velocity and volume than historical baselines, the resulting surface runoff easily overflows traditional channels. Consequently, torrential floods are now breaching the boundaries of historical safe zones, routing high-velocity water and debris directly into the core of old settlements that were topographically insulated from historical flood events (Intergovernmental Panel on Climate Change (IPCC), 2023).

Acceleration of Landslide Activity

Concurrently, rising average alpine temperatures are driving an unprecedented reduction in seasonal snowpack duration and depth, fundamentally altering the stability of mountain slopes. The progressive upward migration of the freezing level, combined with a higher ratio of liquid rain to solid snowfall during winter and early spring months, leads to rapid soil saturation during periods when the ground was historically protected by a frozen cryospheric buffer. This altered hydrological cycle accelerates slope instability. The combination of intense, localized rainfall events and unstable, water-logged soil profiles

4.4 Climate Change Dimensions as Hazard Multipliers

triggers deeper and more frequent landslide and debris flow activations (Intergovernmental Panel on Climate Change (IPCC), 2023). Slope failures are now occurring along channels and inclines that had remained dormant for generations, directly threatening historical settlements constructed at the bases of these seemingly stable slopes.

Intensification and Unpredictability of Avalanches

The same cryospheric degeneration and temperature volatility are destabilizing high-altitude snowpacks, altering the already difficult-to-predict behavior of mountain avalanches. Shifting weather patterns create highly irregular snowpack stratigraphy, characterized by alternating layers of wet snow, ice crusts, and loose fresh snow. As liquid rainfall events penetrate higher elevations even during winter months, they lubricate the basal layers of the snowpack, inducing catastrophic wet snow avalanches. Furthermore, rapid warming episodes trigger unseasonal snow releases. Because these climate-driven instabilities originate at changing altitudinal bands and follow modified trajectories, avalanche runout zones are extending beyond their historical geomorphological limits, encroaching into forested buffers and historical settlement footprints previously classified as entirely safe from winter hazards (Intergovernmental Panel on Climate Change (IPCC), 2023).

4.5 Implications for Hazard-Aware Spatial Documentation

The environmental hazards and climate change dimensions detailed in this chapter demonstrate that the reinhabitation of MHCs cannot be successfully executed through uniform, hazard-blind urban regeneration policies. Because environmental constraints are highly variable across space and time, they must function as the primary diagnostic filters within any proactive spatial planning framework. Rather than applying a single, undifferentiated analysis, this thesis operationalizes these environmental realities through a structured, multiscale GIS mapping framework that adjusts data precision and hazard integration according to the geographic scope of the evaluation.

National Dimension and Baseline Characterization

At the macro-scale, the national territory is evaluated to establish baseline indicators for historical settlements. At this vast

4.5 Implications for Hazard-Aware Spatial Documentation

operational scope, specific hazard layers are purposely excluded from the analysis. Introducing granular hazard mapping at a national scale introduces high data noise and computational inefficiencies that obscure broader territorial patterns. Instead, this tier serves to isolate settlement distributions and macro-level geographic characteristics, establishing the foundational spatial layer before zooming into specific administrative boundaries.

Regional Dimension and Primary Hazard Typologies

At the meso-scale, the thesis introduces regional hazard layers utilizing a standardized typology classification system. For flood and landslide hazards, the framework integrates layers defined by a high to low probability, allowing for a clear differentiation of structural exposure across different catchments. Avalanche hazards are treated as a distinct data typology due to their unique cryospheric mechanics and specific topographic dependencies. This regional tier allows for the rapid identification of highly exposed mountain areas.

Territorial and Settlement Dimensions and High Precision Downscaling

At the micro-scale, the GIS environment zooms directly into targeted mountain areas with significantly heightened geometric and thematic precision. This tier refines the broad regional hazard boundaries by integrating localized geomorphological data and exact settlement footprints. By downscaling the analysis, the territorial tier captures the precise spatial interactions between localized slopes and historic built structures, providing the highly detailed diagnostic view necessary for actual planning interventions.

Crucially, this thesis establishes that environmental hazards interact dynamically with linear transport infrastructure, meaning that a settlement's vulnerability cannot be evaluated solely through direct structural impacts. Instead, territorial diagnostic workflows must systematically intersect environmental hazard perimeters with the regional road network to map accessibility fragility.

In topographically enclosed Alpine valleys, small rural communities often depend on highly vulnerable, single-access linear corridors. When a landslide, flood, or avalanche crosses these critical infrastructural lines, it triggers a state of functional isolation, cutting off access to medical care, education, and supply networks, even if the physical building stock remains completely untouched. Therefore, the spatial documentation model downscales the environmental parameters into

4.4 Climate Change Dimensions as Hazard Multipliers

two distinct metrics: Structural Exposure (direct geometric intersection of built assets with hazard polygons) and Network Accessibility Fragility (topological choke points along primary transport corridors).

Ultimately, framing environmental hazards as a conditional, multiscale planning criterion ensures that the architectural preservation of Italy's historic villages is inextricably linked to long-term geomorphological safety and demographic survival. The following chapter details the exact technical methodology, spatial database configurations, and GIS workflows designed to operationalize this hazard-aware diagnostic framework within a replicable WebGIS decision-support environment.

5 Methodology

This chapter develops the multiscale spatial methodology applied across four analytical levels, from national settlement inventory to building-level hazard intersection. It operationalizes the SMRS definition through progressive geographic filtering, constructs regional hazard exposure layers for flood, landslide, and avalanche processes, and produces territorial and settlement scale cartographic outputs for three specific case studies and their valleys: Ollomont in the Valpelline Corridor, Macugnaga in the Anzasca Valley, and Elva in the Maira Valley. The Hazard Constraint Score is introduced as a composite measure combining internal hazard exposure with access corridor blockage, providing the analytical bridge between the geomorphological documentation of each valley and the building-level reinhabitation feasibility assessment.

5.1 Thesis Design and Multiscale Spatial Framework

This thesis adopts a hazard-aware, data-driven, multiscale spatial methodology structured across four nested levels of analysis. The approach progressively refines spatial resolution, moving from national territorial classification to local-scale settlement-hazard interaction. Particular emphasis is placed on the integration of environmental constraints and accessibility conditions within a unified analytical framework. Table 9 shows the four levels of analysis along with their aim and objectives.

Scale	Aim	Result
National Scale	Identification and spatial distribution of small settlements and their positioning within broader territorial systems.	Defines the settlement universe under investigation.
Regional Scale	Hazard exposure mapping and environmental constraint assessment.	Establishes environmental hazard conditions.
Territorial Scale (Alpine Valley Structures)	Geomorphological, hydrographic, and linear infrastructure network pattern analysis.	Interprets topographic structuring forces and network choke points.
Settlement Scale (Municipal and Local Scale)	Integrated settlement-hazard-infrastructure asset analysis.	Evaluates operational feasibility and spatial constraints for reinhabitation strategies.

Table 9. Methodological Levels of Analysis Matrix.
(Source: Author’s elaboration)

This nested structure ensures coherence across spatial scales, while allowing each level to address a specific objective. The national scale defines the settlement system and its territorial context, while subsequent scales progressively introduce environmental, geomorphological, and operational dimensions. The methodology is grounded in GIS, which enables the integration and spatial analysis of heterogeneous data within a unified framework.

Rather than relying on a single classification system, the thesis adopts a multi-dimensional approach, where different territorial aspects are analyzed through distinct but complementary lenses.

Five main analytical dimensions structure this framework,

5.1 Thesis Design and Multiscale Spatial Framework

starting with the morphological dimension, which identifies settlement structures as spatially defined inhabited clusters. The demographic-functional dimension interprets territorial organization through population density and settlement intensity, while the physical dimension captures environmental constraints related to topography and terrain.

Furthermore, the accessibility dimension reflects proximity to essential services and infrastructural networks, and the socio-cultural dimension highlights historically or culturally recognized settlements.

These dimensions are not merged into a single classification, but are instead maintained as independent analytical layers, whose spatial intersection enables the identification of complex territorial conditions, particularly in marginal and rural contexts.

Three core principles guide this integrated methodological framework, establishing strict parameters for the spatial processing rules. The first principle is scale coherence, which dictates that each analytical dimension is applied at the spatial scale most appropriate to its nature.

The second principle is replicability, requiring that all analytical procedures are based on explicit and reproducible criteria, and the final principle is integrated interpretation, which ensures that settlement patterns are analyzed through the combined reading of multiple territorial dimensions and that these data remain reusable. To establish absolute spatial transparency and ensure the methodological reproducibility of this thesis, a comprehensive directory of the processed cartographic outputs is organized in Table 10.

This technical framework outlines the complete directory of methodological maps, detailing the specific identification code, formal title, localized diagnostic objective, primary source repositories, and target mapping resolution for each visual product.

To ensure geometric alignment and topological consistency across all descending levels of analysis, every spatial layer is re-projected and processed within a uniform reference system, specifically ETRS89 / UTM Zone 32N, which is cataloged as EPSG:32632.

By explicitly mapping out this technical architecture, Table 10 functions as an operational index that links independent, multi source geospatial datasets with the targeted scale interventions developed in subsequent geoprocessing phases.

5.1 Thesis Design and Multiscale Spatial Framework

Code	Name	Aim	Sources	Scale
National Scale				
A1	Map Of Small Settlements (SS), And Territorial Context In Italy	Identify and categorize SS across Italy.	ISTAT Località 2021; Eurostat DEGURBA; EEA Mountain Chains.	1:5,000,000
A2	Map of Small Mountain Rural Settlements (SMRS) And Inner Areas In Italy	Map SMRS and inner areas across Italy to establish vulnerability proxies.	ISTAT Località 2021; SNAI, Agenzia per la Coesione Territoriale.	1:5,000,000
A3	Map of MHCs in Italy Identified Through “Borghi Più Belli D'Italia” Project	Map the “Borghi più belli d'Italia” project to visualize limitations.	ISTAT Località 2021; Borghi più belli d'Italia open layer.	1:5,000,000
Regional Scale				
B1	Flood Hazard Zone Map In Piedmont And Aosta Valley And SMRS Intersection	Map hydraulic hazard zones in study regions, categorizing intersecting SMRS.	ISTAT Località 2021; ISPRA IdroGEO v5.0; EEA Mountain Chains.	1:1,100,000
B2	Landslide Hazard Zone Map In Piedmont And Aosta Valley And SMRS Intersection	Map landslide hazard layers, executing worst-case geometric joins on SMRS.	ISPRA IdroGEO v4.0, ISTAT Località 2021; EEA Mountain Chains.	1:1,100,000
B3	Landslide Hazard Zone Map Zoomed In Aosta Valley And SMRS Intersection	Zoomed geoprocessing visualization for highly exposed sectors within Valle d'Aosta.	SCT Valle d'Aosta, ISPRA IdroGEO.	1:320,000
B4	Avalanche Hazard Zone Map In Piedmont And SMRS Intersection	Map avalanche layers, classifying SMRS by administrative vs physical exposure.	ARPA Piemonte SIVA Database, ISTAT Località 2021.	1:1,100,000
B5	Avalanche Hazard Zone Map Zoomed In Aosta Valley And SMRS Intersection	Zoomed mapping of regulatory hazard bands intersecting SMRS.	Geoportale SCT Valle d'Aosta Catasto Valanghe.	1:320,000

Table 10. Methodological Maps Directory and Technical Architecture. (Source: Author's elaboration)

5.1 Thesis Design and Multiscale Spatial Framework

Code	Name	Aim	Sources	Scale
Territorial Scale				
C1	Hazard And Landcover Map Of The Valpelline Corridor With Flood And Avalanche Overlay	Map flood and avalanche hazard zones and affected land cover.	ISTAT, ISPRA, SCT Valle d'Aosta.	1: 90,000
C2	Landslide Hazard Map Of The Valpelline Corridor	Map landslide hazard zones and affected SMRS.	ISTAT, ISPRA, SCT Valle d'Aosta.	1: 90,000
C3	Slope Analysis Map Of The Valpelline Corridor And SMRS Intersection	Map slope gradient classification and SMRS intersection.	ISTAT, ISPRA, SCT Valle d'Aosta.	1: 90,000
C4	Accessibility Fragility Map Of The Valpelline Corridor And SMRS Intersection	Map road network accessibility fragility and hazard-driven blockage points.	ISTAT, ISPRA, SCT Valle d'Aosta.	1: 90,000
C5	Hazard And Landcover Map Of The Anzasca Valley With Flood And Avalanche Overlay	Map flood and avalanche hazard zones and affected land cover.	ISTAT, ISPRA, ARPA Piemonte.	1:120,000
C6	Landslide Hazard Map Of The Anzasca Valley	Map landslide hazard zones and affected SMRS.	ISTAT, ISPRA, ARPA Piemonte.	1:120,000
C7	Slope Analysis Map Of The Anzasca Valley And SMRS Intersection	Map slope gradient classification and SMRS intersection.	ISTAT, ISPRA, ARPA Piemonte.	1:120,000
C8	Accessibility Fragility Map Of The Anzasca Valley And SMRS Intersection	Map road network accessibility fragility and hazard-driven blockage points.	ISTAT, ISPRA, ARPA Piemonte.	1:120,000

5.1 Thesis Design and Multiscale Spatial Framework

Code	Name	Aim	Sources	Scale
C9	Hazard And Landcover Map Of The Maira Valley With Flood And Avalanche Overlay	Map flood and avalanche hazard zones and affected land cover.	ISTAT, ISPRA, ARPA Piemonte.	1:110,000
C10	Landslide Hazard Map Of The Maira Valley	Map landslide hazard zones and affected SMRS.	ISTAT, ISPRA, ARPA Piemonte.	1:110,000
C11	Slope Analysis Map Of The Maira Valley And SMRS Intersection	Map slope gradient classification and SMRS intersection.	ISTAT, ISPRA, ARPA Piemonte.	1:110,000
C12	Accessibility Fragility Map Of The Maira Valley And SMRS Intersection	Map road network accessibility fragility and hazard-driven blockage points.	ISTAT, ISPRA, ARPA Piemonte.	1:110,000
Settlement Scale				
D1	Settlement Scale Flood And Avalanche Map Of Ollomont Spatial Intersection With Building Footprints	Identify buildings by functional use and spatial intersection with flood and avalanche hazard zones.	SCT Valle d'Aosta, ISPRA IdroGEO.	1:6,000
D2	Settlement Scale Landslide Hazard Map Of Ollomont Spatial Intersection With Slope Flow and Building Footprints	Aspect analysis and buildings intersection with landslide zones.	SCT Valle d'Aosta, ISPRA IdroGEO.	1:6,000
D3	Settlement Scale Debris Flow Hazard Map Of Ollomont Spatial Intersection With Vegetative Cover and Building Footprints	Buildings intersection with approved debris flow hazard zones; vegetative buffer context retained.	SCT Valle d'Aosta, ISPRA IdroGEO.	1:6,000
D4	Settlement Scale Multi-Hazard Exposure Map Of Ollomont Building Footprint Hazard Assessment	Cumulative exposure analysis of buildings and mines to all intersecting hazard zones.	SCT Valle d'Aosta, ISPRA IdroGEO.	1:6,000

Table 10. Methodological Maps Directory and Technical Architecture. (Source: Author's elaboration)

5.1 Thesis Design and Multiscale Spatial Framework

Code	Name	Aim	Sources	Scale
D5	Settlement Scale Flood And Avalanche Map Of Macugnaga Spatial Intersection With Building Footprints	Identify buildings by functional use and map spatial intersection with flood and avalanche hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:5,500
D6	Settlement Scale Landslide Hazard Map Of Macugnaga Spatial Intersection With Slope Flow and Building Footprints	Aspect and slope flow analysis combined with building intersection with landslide hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:5,500
D7	Settlement Scale Multi-Hazard Exposure Map Of Macugnaga Building Footprint Hazard Assessment	Cumulative exposure analysis of buildings and mines to all intersecting hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:5,500
D8	Settlement Scale Flood And Avalanche Map Of Elva Spatial Intersection With Building Footprints	Identify buildings by functional use and map spatial intersection with flood and avalanche hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:6,500
D9	Settlement Scale Landslide Hazard Map Of Elva Spatial Intersection With Slope Flow and Building Footprints	Aspect and slope flow analysis combined with building intersection with landslide hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:6,500
D10	Settlement Scale Multi-Hazard Exposure Map Of Elva Building Footprint Hazard Assessment	Cumulative exposure analysis of buildings to all intersecting hazard zones.	ISTAT, ISPRA, ARPA Piemonte, BDTRE.	1:6,500

5.1 Thesis Design and Multiscale Spatial Framework

A key methodological component of this thesis is the distinction and subsequent integration of environmental and accessibility-based territorial classifications. Mountain areas and Inner Areas, while often spatially overlapping, represent fundamentally different dimensions, specifically geomorphological constraint and service accessibility respectively. Rather than merging them into a single category, they are maintained as separate analytical layers and visualized concurrently to preserve their conceptual independence while enabling comparative interpretation.

5.2 National Scale

The national scale establishes the foundational spatial framework of the thesis. It defines the operational concept of settlements and situates them within broader territorial conditions, forming the baseline for all subsequent spatial and environmental analyses. At this macroscopic level of analysis, the objective is twofold, aiming first to construct a consistent, data-driven definition of settlements independent of administrative ambiguity, and second, to contextualize these settlements within demographic, environmental, and accessibility conditions.

5.2.1 Settlement Terminology and Administrative Context

In Italy, the definition of settlements is not explicitly embedded within the administrative system. Territorial organization is structured through a hierarchical framework composed of regions, provinces or metropolitan cities, and municipalities, with the latter representing the fundamental administrative unit. As outlined by ISTAT, the municipality, traditionally termed the 'comune', constitutes the lowest level of formal governance and is responsible for local planning, services, and territorial management. However, this administrative structure does not provide a meaningful distinction between different types of settlements based on their spatial, morphological, or demographic characteristics. A municipality may correspond to a large metropolitan area or to a rural village.

Sub-municipal entities such as 'località' and 'frazioni' offer a

5.2 National Scale

5.2.1 Settlement Terminology and Administrative Context

more detailed representation of inhabited places, but they do not have consistent morphological definitions. Similarly, widely used cultural terms such as 'borghi', while common in both academic and daily discourse, are not part of the official statistical framework and do not correspond to clearly defined spatial units. As such, their use remains interpretative and context-dependent, limiting their applicability within a rigorous, data-driven methodology.

As a result, the Italian system lacks a formal classification that links administrative units to the physical and functional characteristics of settlements. In particular, there is no clear or consistent distinction equivalent to terms such as "village" or "hamlet," nor to culturally specific notions such as borghi, within the official territorial structure.

This absence of a formal classification linking administrative units to settlement morphology or size necessitates the adoption of an operational, data-driven definition. In this thesis, the term Small Settlements (SS) is introduced as a methodological construct. This definition does not derive from administrative classifications, but rather from demographic and spatial criteria. Small settlements are here understood as: inhabited places characterized by a limited population size less than 1000 inhabitants, where people reside permanently, excluding non-residential spatial entities such as industrial zones, infrastructure hubs, or airports. This population-based definition allows for the identification of lived spaces, focusing on the actual distribution of resident populations rather than on administrative boundaries. In this sense, SS enables consistent spatial analysis across heterogeneous territorial contexts.

At the same time, the thesis relies on official administrative datasets as a fundamental spatial reference framework. ISTAT constitutes the primary source of territorial and statistical data throughout this study. In particular, the dataset 'Confini delle unità amministrative a fini statistici', provides a standardized representation of administrative boundaries structured into hierarchical levels, including the Località 2021 layer that sets the base for all maps. These datasets confirm that the Italian territorial framework is entirely organized around administrative units, without embedding any classification related to settlement size, density, or morphology. Their use in this thesis therefore serves both as a reliable spatial reference system and as empirical evidence of the absence of a settlement-based classification within official data structures.

Building upon this foundation, the study further refines its focus by introducing the category of "Small Rural Settlements"

5.2 National Scale

5.2.1 Settlement Terminology and Administrative Context

(SRS) and “Small Mountain Rural Settlements” (SMRS). This term identifies a specific subset of SS located within rural and mountainous contexts, characterized not only by small population size but also by geographic isolation, environmental constraints, and limited accessibility.

This definition ensures both conceptual clarity and methodological flexibility, allowing the thesis to operate consistently across scales while maintaining a precise focus on the spatial conditions relevant to rural and alpine areas.

5.2.2 Operational Definition of SS

To ensure consistency and replicability, SS are identified using the ‘Località 2021’ dataset provided by ISTAT. The classification is based on a combination of morphological and demographic criteria within the local database. Specifically, the attributes filtered include ‘TIPO_LOC’, which isolates built-up clusters, ‘POP21’, which restricts the population size, and ‘EDI21’, which verifies the physical presence of residential structures. To filter out single, isolated institutions like hospitals, airports, or standalone country estates, the indicator ensures a minimum cluster size of residential buildings.

Furthermore, the ‘CENTRO_CL’ attribute is evaluated to identify whether a cluster functions as a primary municipal capital or a secondary center, keeping both in the selection because even a primary capital can structurally be an exceptionally small settlement. These attributes are further explained in Table 11 and Figure 6.

Attributes of Localita21 Layer	Description	Analytical Functional Use	Applied SQL / QGIS Filter
TIPO_LOC	Morphological settlement typology.	Selects compact built-up clusters, specifically 1 for Centro abitato and 2 for Nucleo abitato, while excluding production zones and scattered dwellings.	TIPO_LOC IN (1, 2)
POP21	Resident population recorded in the 2021 Census.	Restricts the query to small-scale micro-settlements.	POP21 < 1000

Table 11. SS Structural Filtering Criteria for Localita21 dataset.
(Source: Author’s elaboration)

5.2 National Scale

5.2.2 Operational Definition of SS

Attribute	Description	Analytical Functional Use	Applied SQL / QGIS Filter
EDI21	Total number of physical residential structures.	Enforces a minimum physical structural cluster, filtering out solitary data noise such as hospitals, airports, or isolated estates.	EDI21 ≥ 5
CENTRO_CL	Institutional municipal capital classification.	Identifies administrative centrality, utilizing 0 for secondary centers and 1 for primary capitals, keeping both because even primary centers can remain structurally miniature.	Maintained unconditionally in layer

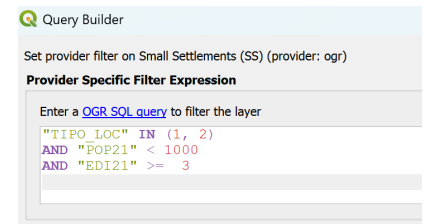


Figure 6. QGIS query for filtering SS. (Source: Author's elaboration)

To fully clarify the structural boundaries of the settlement universe, the morphological implications of the TIPO_LOC variable are organized below in Table 12.

TIPO_LOC Value	Italian Term	Semantic Context and Definition	Methodological Planning Implication
1	Centro abitato	Aggregation of 15 or more contiguous buildings structured with public spaces, streets, and localized service nodes.	Primary morphological core, which forms the structural shell of city centers, towns, or traditional mountain villages.
2	Nucleo abitato	Spatially distinct cluster of 15 or more buildings lacking internal functional service nodes or clear civic fabric.	Small clustered hamlet, representing highly vulnerable outlying settlement systems.
3	Località produttiva	Built-up area dedicated exclusively to commercial, industrial, or logistics infrastructure.	Non-residential node, meaning it is systematically excluded from the reinhabitation database.
4	Case sparse	Dispersed, isolated agricultural or residential dwellings lacking geographic contiguity.	Scattered rural fabric, which is excluded to maintain focus on cohesive settlement centers.

Table 12. Morphological Implications of ISTAT TIPO_LOC Classifications. (Source: Author's elaboration)

5.2 National Scale

5.2.2 Operational Definition of SS

This operational matrix ensures that SS represent coherent inhabited settlement units independent of administrative rank. Within this framework, ghost settlements are formally operationalized as a specific subcategory of SS where all structural and morphological filters are met, but where 'POP21 = 0', representing historically active spaces that are now completely unpopulated, functioning as critical spatial indicators of extreme demographic fragility and territorial contraction.

5.2.3 Rural-Urban Classification

To define rural contexts objectively, this thesis adopts the Degree of Urbanization (DEGURBA) methodology developed by Eurostat and implemented through the Global Human Settlement Layer Settlement Model dataset. This framework provides a harmonized classification system widely used for territorial analysis across Europe. DEGURBA classifies the entire territory along an urban-rural continuum, assigning each Local Administrative Unit, or LAU, to one of three mutually exclusive categories, which are cities (densely populated areas), towns and suburbs (intermediate density areas), and rural areas (thinly populated areas).

This classification is derived from a population grid-based methodology rather than administrative borders. The fundamental spatial unit is a 1 km² population grid, which eliminates spatial distortions caused by uneven municipal boundaries. The DEGURBA framework executes a two-step process, starting with grid-level classification where each 1 km² cell is evaluated based on population density, total size, and contiguity. Cells are grouped into urban centers, which are high-density clusters, urban clusters, which represent intermediate density, and rural grid cells, which encompass all remaining areas. Following the grid-level analysis, the LAU-level classification characterizes each municipality based on the percentage of its population residing within these cells, where Rural Areas are strictly defined as municipalities where more than 50% of the total population lives within rural grid cells (Eurostat, 2011).

To clarify the formal relationship between grid-level demographic data and the resulting municipal typologies, the administrative classification rules mandated by this spatial framework are synthesized in Table 13. This technical matrix provides a direct overview of how localized population grid cell thresholds determine the overarching classification assigned

5.2 National Scale

5.2.3 Rural-Urban Classification

to each Local Administrative Unit, or LAU, across the European Union. By evaluating the precise population concentration values within each spatial grid, the multi-tiered sorting system removes administrative boundary distortion and ensures a harmonized baseline for cross-border comparisons.

Population Grid Cell Matrix (1 km ²)	LAU Municipal Level Classification	Final Territorial Typology
Urban Center: Contiguous cells with density $\geq 1,500$ inh. km ² and total pop. $\geq 50,000$.	$\geq 50\%$ of the municipal population resides within high-density Urban Centers.	Cities (Densely populated areas)
Urban Cluster: Contiguous cells with density ≥ 300 inh.km ² and total pop. $\geq 5,000$.	$< 50\%$ of pop. in rural cells AND $< 50\%$ of pop. in urban centers.	Towns and Suburbs (Intermediate density areas)
Rural Grid Cells: Spatial grid cells situated completely outside mapped urban clusters.	$\geq 50\%$ of the municipal population resides within mapped Rural Grid Cells.	Rural Areas (Thinly populated areas).

Table 13. Eurostat DEGURBA Level 1 Classification Matrix.
(Source: Author's elaboration)

A key strength of the DEGURBA framework is that it provides a standardized and comparable definition of rurality across European territories. Unlike national classifications, it avoids context-specific terminology and instead defines rural areas strictly through population density and spatial configuration.

While the standard DEGURBA classification at the LAU level distinguishes only three categories, cities, towns and suburbs, and rural areas, more detailed grid-based implementations (Level 2) provide a finer subdivision of the rural class, including categories such as villages, dispersed rural areas, and mostly uninhabited zones (Eurostat, 2018). However, these refined classes are not consistently available across all institutional datasets. To resolve the limitation, this thesis spatially intersects DEGURBA grid cell Class 3, representing rural areas, directly with the ISTAT Località vector dataset.

While DEGURBA delineates the macro-regional boundary of rurality, the SS classification extracts the precise, compact structural settlements operating inside those fields. This intersection extracts the final dataset of Small Rural Settlements, or SRS, maintaining compliance with European statistical typologies while preserving high localized precision.

5.2 National Scale

5.2.4 Mountain Areas

Mountain areas in Italy are characterized by a complex and evolving classification framework that reflects both physical and socio-territorial conditions. Early definitions, such as those introduced by Law 991/1952, relied primarily on altitudinal thresholds, identifying mountain municipalities based on elevation criteria. More recent approaches, promoted by UNCEM, have expanded this definition to include additional factors such as orographic complexity, morphological ruggedness, accessibility constraints, demographic vulnerability, and structural service deficits. This reflects a shift from purely physical definitions toward a more multidimensional understanding of mountain territories.

However, despite their conceptual relevance, these municipal-level classifications present significant limitations for spatial analysis, as they typically rely on composite, shifting criteria and are not consistently available in standardized, GIS-ready formats. As a result, their direct application within a reproducible spatial methodology is constrained. For this reason, the present thesis adopts an alternative approach based on the European mountain chain dataset, which provides a physiographic and spatially explicit representation of mountainous regions. This dataset delineates major mountain systems, including the Alps, the Apennines, Balkans / South-East Europe and Western Mediterranean Islands, based on geomorphological continuity rather than administrative boundaries, ensuring a stable, transparent, and reproducible definition of mountain areas (European, 2008).

While this approach does not capture the full socio-economic complexity embedded in institutional classifications such as those proposed by UNCEM, it provides a robust basis for identifying topographically constrained environments, which are central to the analysis of settlement patterns in rural and alpine contexts.

By establishing this stable, geomorphologically defined baseline, the analysis removes the legal or political variation often associated with local mountain classifications. Consequently, any SRS that physically falls within these designated mountain area perimeters is classified as a Small Mountain Rural Settlement, or SMRS.

This spatial intersection combines morphological size, rural density, and topographic constraint into a single operational unit, ensuring that subsequent hazard assessments directly isolate the focus of the thesis, and ensures that the methodology remains reproducible. This baseline layer provides the structural foundation required to transition seamlessly from a national inventory into site-specific hazard diagnostics.

5.2 National Scale

5.2.5 SMRS Operational Definition

The systematic overlay of the morphological, rural, and physiographic layers yields the highly optimized operational layer of Small Mountain Rural Settlements, or SMRS. Within this rigorous geospatial framework, a point asset is classified as an SMRS if and only if it concurrently satisfies the baseline population filters, lies within a designated DEGURBA Class 3 zone, and is physically located inside the continuous geomorphological polygon of the European mountain chain, this definition is shown in Figure 7. To reflect the complex socio-territorial realities of alpine contraction, these SMRS items are structurally split into two independent database categories, which are active inhabited settlements, containing a residual permanent population between 1 and 999 inhabitants, and ghost SMRS, which exhibit a recorded population of zero. This precise categorization ensures that subsequent spatial queries can differentiate between places experiencing severe demographic decline and those that have undergone complete structural abandonment, allowing planners to tailor adaptive regeneration strategies to the unique functional status of each localized cluster. By establishing this, the methodology bypasses the traditional administrative traps that often oversimplify territorial vulnerability, ensuring that the final spatial database isolates genuinely fragile historical contexts rather than broad, non-differentiated municipal sectors.

To establish this foundational settlement layer for the national scale, the comprehensive spatial distribution of small inhabited areas across Italy is mapped and analyzed in Map A1. This geographic visualization overlays the SS points directly against the broader physiographic and demographic characteristics of the country, revealing the macro-scale pattern of these settlements.

By displaying these compact structural footprints relative to the outlines of mountain chains and DEGURBA grid, **Map A1 functions as the baseline environmental index for the entire study.** This cartographic synthesis is particularly crucial for identifying localized MHCs that frequently remain completely invisible in standard municipal-scale mapping, bringing a high thematic resolution to peripheral territories that are traditionally marginalized within mainstream conservation and planning frameworks. Consequently, this multi-layered cartographic representation serves as the primary diagnostic filter used to isolate the initial settlement universe, ensuring that subsequent downscaling operations remain anchored within a verified national framework. By providing this macroscopic spatial perspective, Map A1 contextualizes demographic fragility within the physical boundaries of the Italian landscape, setting up a transparent and reproducible entry point for the downscaled geoprocessing workflows executed in subsequent sections.

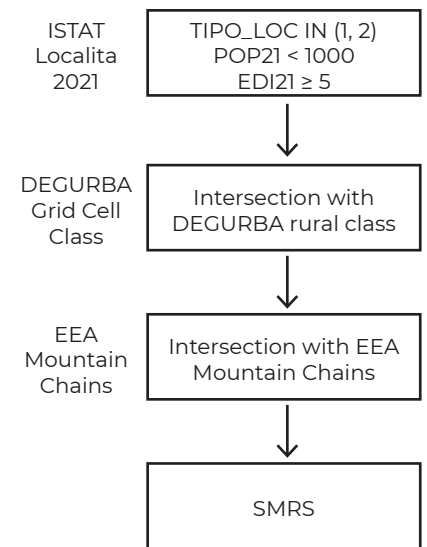


Figure 7. SMRS operational definition.
(Source: Author's elaboration)

A1. Map Of Small Settlements (SS)

And Territorial Context In Italy

Map A1 shows the baseline spatial classification of SS across Italy, while simultaneously establishing the physiographic boundaries of mountain areas and contextualizing the national territory into densely populated areas, intermediate density areas, and rural areas according to the Eurostat DEGURBA classification framework.

Legend

Settlements

Small Mountain Rural Settlements (SMRS)



Small Rural settlements (SRS)



Small Settlements (SS)



Mountain Chains in Italy

Alps



Apennines



Balkans/Southeast Europe



Western Mediterranean islands



DEGURBA

Predominantly Urban



Intermediate



Predominantly Rural



Reference System

WGS 84 / UTM zone 32N

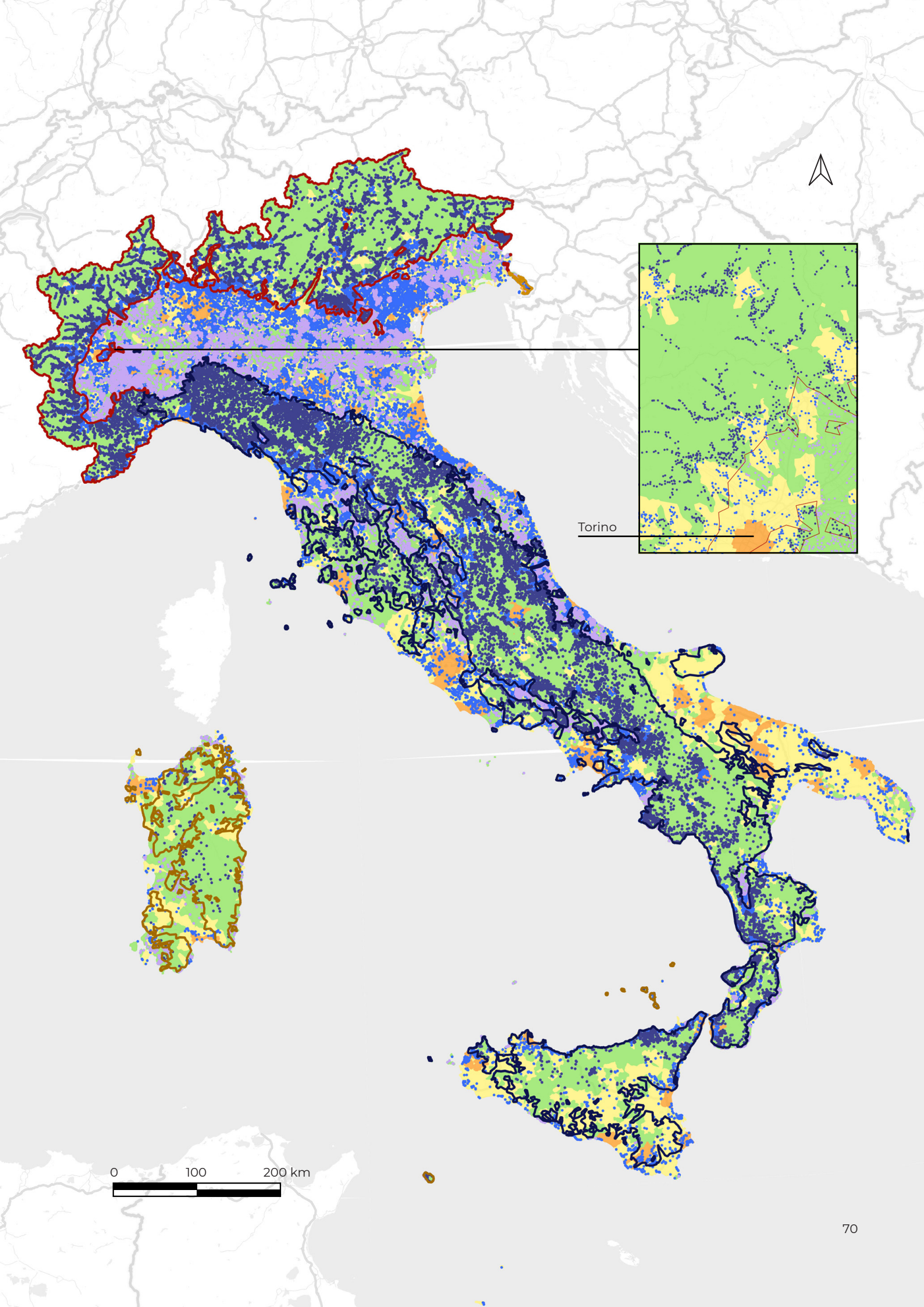
Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

EEA Geospatial catalog (v1 2008), Scale: 1:25,000;

© EuroGeographics / Eurostat (GISCO DEGURBA),

Scale: 1:1,000,000.



5.2 National Scale

5.2.6 Inner Areas (Aree Interne)

The concept of Internal Areas derives from the National Strategy for Inner Areas, or SNAI, which classifies Italian municipalities based on a functional accessibility model to essential services. The matrix maps travel-time distances from peripheral centers to designated Service Hubs that contain a complete secondary education offering, at least one emergency-tier hospital, and a transit station. Municipalities are categorized into six distinct structural classes, which are Service Centers, Inter-municipal Service Centers, Outlying Areas, Intermediate Areas, Peripheral Areas, and Ultra-peripheral Areas, as detailed in Table 14.

Code	Class Name	Definition and Service Catchment Criteria
A	Service center	Municipalities functioning as primary service hubs with transit, education, and health infrastructure.
B	Inner-municipal service center	Grouped clusters of small municipalities that collectively fulfill the service hub prerequisites.
C	Outlying areas	Municipalities with a travel-time distance to the closest service hub of under twenty minutes.
D	Intermediate areas	Territories with an intermediate accessibility classification, falling between twenty and forty minutes from hubs.
E	Peripheral areas	Territories characterized by significant service gaps, falling between forty and seventy-five minutes from hubs.
F	Ultra-peripheral areas	Maximally isolated contexts where travel time to essential service hubs exceeds seventy-five minutes.

Table 14. SNAI Accessibility and Service Deprivation Typology. (Source: Author’s elaboration)

While the first three classes represent urban poles or well-connected functional belts, the final three categories, spanning Classes D, E, and F, constitute the formal perimeter of Internal Areas, representing severe service deprivation, structural demographic contraction, and long-term economic marginalization.

Within this thesis, the SNAI classification is executed as a relational

5.2 National Scale

5.2.6 Inner Areas (Aree Interne)

attribute join linked directly to the SMRS vector layer, allowing for an integrated assessment of physical and institutional isolation. SMRS are structurally fragile precisely because they fall heavily within peripheral and ultra-peripheral municipal polygons, meaning that their physical geomorphological exposure is systematically compounded by severe service deficits. When a small village experiences a demographic decline, the closure of local schools and medical clinics forces the remaining population to travel extensive distances over vulnerable mountain roads to access basic needs, accelerating residential mobility and discouraging new settlement. By maintaining the SNAI accessibility classifications as a distinct variable within the settlement database, the methodology ensures that the evaluation of a territory's reinhabitation potential accounts for these structural service gaps, preventing planners from treating high-altitude hamlets as isolated physical units detached from broader regional networks.

To visualize these intersecting institutional and geographic challenges, the territorial distribution of service deprivation is comprehensively analyzed in Map A2. This cartographic product explicitly traces the spatial correlation between small, topographically constrained mountain settlements and the macro-level boundaries of the SNAI accessibility polygons across the Italian peninsula. By displaying the SMRS point assets directly on top of the colorful gradients of intermediate, peripheral, and ultra-peripheral zones, Map A2 functions as a critical spatial diagnostic tool that exposes the dual nature of alpine vulnerability. It allows planners to immediately identify which mountain hamlets are suffering from a state of double marginalization, where acute landslide, flood, or avalanche hazards are layered directly over long-term transport isolation and severe public infrastructure deficits.

Consequently, this multi-layered cartographic representation serves as a vital predictive filter within the decision-support workflow, establishing a clear baseline that guides targeted project selection and public resource allocation. Rather than directing regional revitalization funds uniformly across all mountain valleys, **Map A2 enables planners to prioritize settlements based on their actual accessibility context, separating relatively well-connected communities from those facing extreme, systemic isolation.** By providing this macroscopic overview of service accessibility, the map ensures that subsequent downscaled engineering interventions are deeply rooted within a realistic assessment of a village's functional connectivity. This analytical layer bridges high-level territorial cohesion goals with the local morphological realities of the building stock, ensuring that future socio-economic investments are directed toward the most strategic and resilient sectors of the alpine territory.

A2. Map Of Small Mountain Rural Settlements (SMRS)

And Inner Areas In Italy

Map A2 shows the baseline spatial classification SMRS, across Italy, while contextualizing the national territory into service centers, intermediate areas, peripheral areas, and ultra-peripheral areas according to SNAI service accessibility framework.

Legend

Small Mountain Rural Settlements (SMRS)

Ghost SMRS

Inhabited SMRS



Mountain Chains in Italy

Alps

Apennines

Balkans/Southeast Europe

Western Mediterranean islands



Inner areas

A. Service center

B. Inter-municipal service center

C. Outlying areas

D. Intermediate areas

E. Peripheral areas

F. Ultra-peripheral areas



Reference System

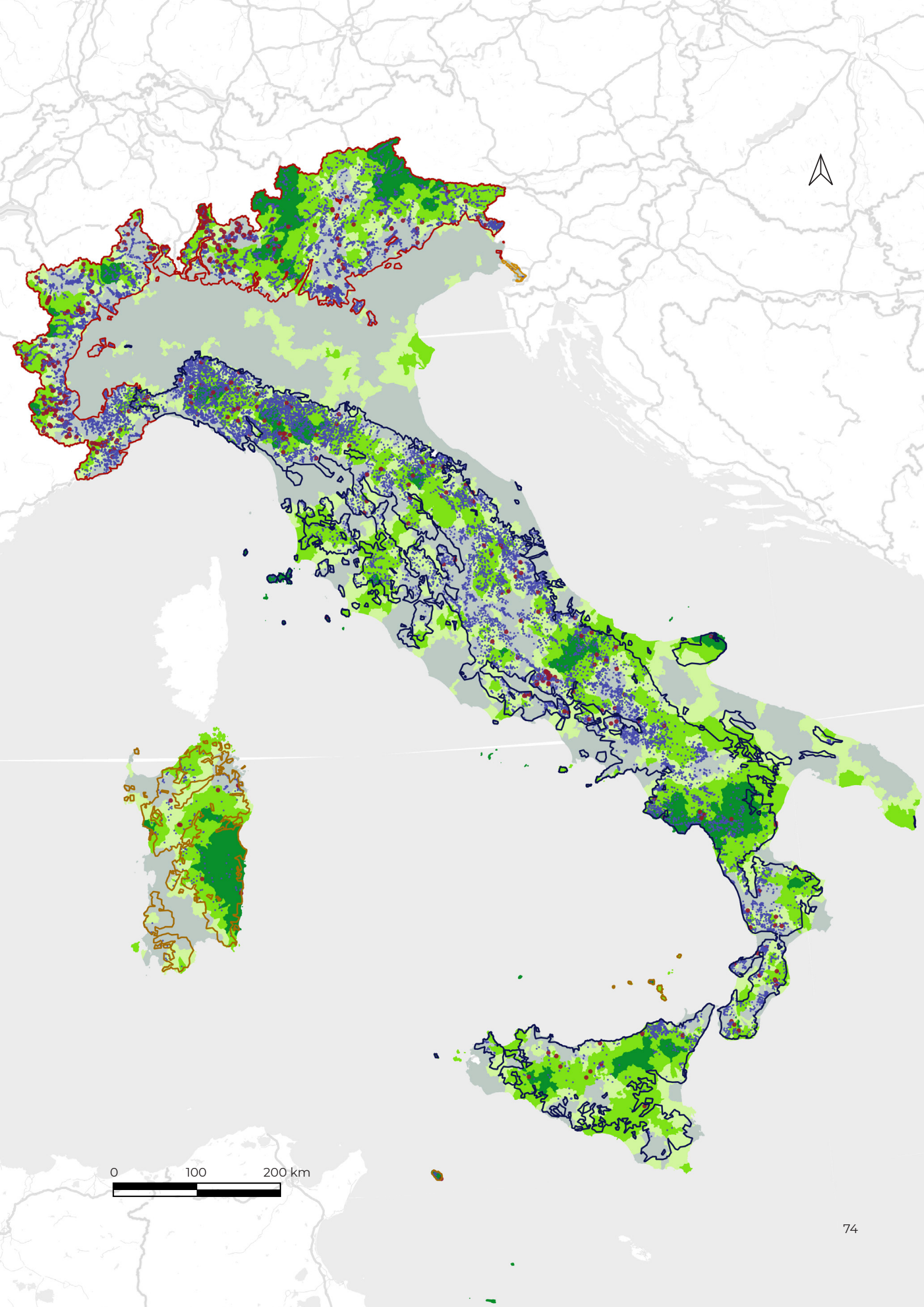
WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISTAT (Inner Areas 2020), CC BY 4.0;

EEA Geospatial catalog (v1 2008) , Scale: 1:25,000.



5.2 National Scale

5.2.7 The Borghi Più Belli D'Italia

The 'Borghi più belli d'Italia' dataset is integrated as an independent spatial overlay representing culturally curated Minor Historical Centers (<https://borghipiubelliditalia.it>; OpenStreetMap, 2026). This layer does not stem from official statistical definitions but reflects a qualitative selection based on historical significance, architectural integrity, and landscape value. To enter this network, individual municipalities must initiate an application process subjected to technical evaluation sheets containing dozens of parameters:

Prerequisites

The village must have a population of less than 15,000 inhabitants and must be able to boast at least one artistic or architectural asset of recognized value.

Aesthetic and architectural evaluation

The quality of the historic center, the integrity of the urban fabric, the conservation of the facades, materials and original decorative elements are analyzed. Squares, alleys, portals, fountains and churches contribute to forming an overall score.

State of Preservation

It is not enough to have a beautiful village originally; it needs to be kept in good condition, with restored buildings, well-kept streets and the absence of elements of visual degradation such as antennas, electrical cables and invasive signs.

Tourist Offer and reception

The presence of accommodation facilities, restaurants, visitor services, tourist signage and cultural initiatives is evaluated. A village that fails to welcome tourists adequately cannot aspire to certification.

Cultural initiatives and local identity

Festivals, museums, typical crafts, food and wine traditions and historical festivities help to define the identity of the place and its value for visitors.

The evaluation commission also carries out direct inspections before making a decision. Once admitted, the villages are subjected to periodic checks: those who do not maintain the

5.2 National Scale

5.2.7 The Borghi Più Belli D'Italia

required standards can be excluded from the circuit (Salvatore, 2026).

While the 'I Borghi più belli d'Italia' dataset serves as an important tool to acknowledge the existence of high-value cultural nodes, it possesses significant methodological limitations that restrict its direct utility as a baseline planning instrument. First, the entry requirement allows a population threshold of up to 15,000 inhabitants, a metric that is far too broad to capture the micro-scale realities of highly vulnerable or semi-abandoned alpine hamlets. Second, because entry into this network relies on an active application process initiated by individual municipalities, the dataset suffers from self-selection bias. Highly vulnerable settlements situated within weak administrative environments often lack the institutional capacity, staffing, or financial resources required to compile the necessary application parameters, rendering them completely invisible within this network despite their high heritage value.

Furthermore, the evaluation sheet places an overwhelming emphasis on aesthetic preservation and functional tourism reception, which overlooks structural inhabitability constraints, infrastructural accessibility, and active hydrogeological hazards. A certified village may boast perfectly restored facades and robust hospitality metrics while simultaneously suffering from extreme geomorphological instability, seasonal isolation, or a complete absence of local essential services. Consequently, this thesis treats the I Borghi più belli d'Italia dataset strictly as a superficial cultural indicator rather than a robust planning classification. By overlaying this curated network onto the strictly data-driven SMRS framework, the methodology exposes the spatial discrepancies between commercial tourism recognition and actual territorial vulnerability.

The geographic distribution of this network is evaluated in Map A3. This cartographic layout displays the culturally recognized nodes derived from the project directly over the baseline Italian territorial framework, functioning as an independent heritage indicator.

By mapping these certified locations relative to the broader distribution of Small Mountain Rural Settlements, or SMRS, **Map A3 exposes the structural fragmentation currently dividing aesthetic conservation from objective hazard awareness.** Consequently, this multi-layered cartographic representation serves as a critical diagnostic baseline within the study, demonstrating how administrative self-selection leaves highly fragile alpine hamlets mostly unmonitored while channeling public visibility toward resilient, tourism-oriented centers.

A3. Map Of MHCs In Italy

Identified Through “Borghi Piu Belli D'Italia” Project

Map A3 shows the baseline spatial distribution of culturally curated MHCs across Italy, while simultaneously establishing the physiographic boundaries of mountain areas and contextualizing their placement against the national territory's service centers, intermediate areas, peripheral areas, and ultra-peripheral areas according to the SNAI service accessibility framework.

Legend

Borghi Piu Belli D'Italia	
Mountain Chains in Italy	
Alps	
Apennines	
Balkans/Southeast Europe	
Western Mediterranean islands	
Inner areas	
A. Service center	
B. Inter-municipal service center	
C. Outlying areas	
D. Intermediate areas	
E. Peripheral areas	
F. Ultra-peripheral areas	

Reference System

WGS 84 / UTM zone 32N

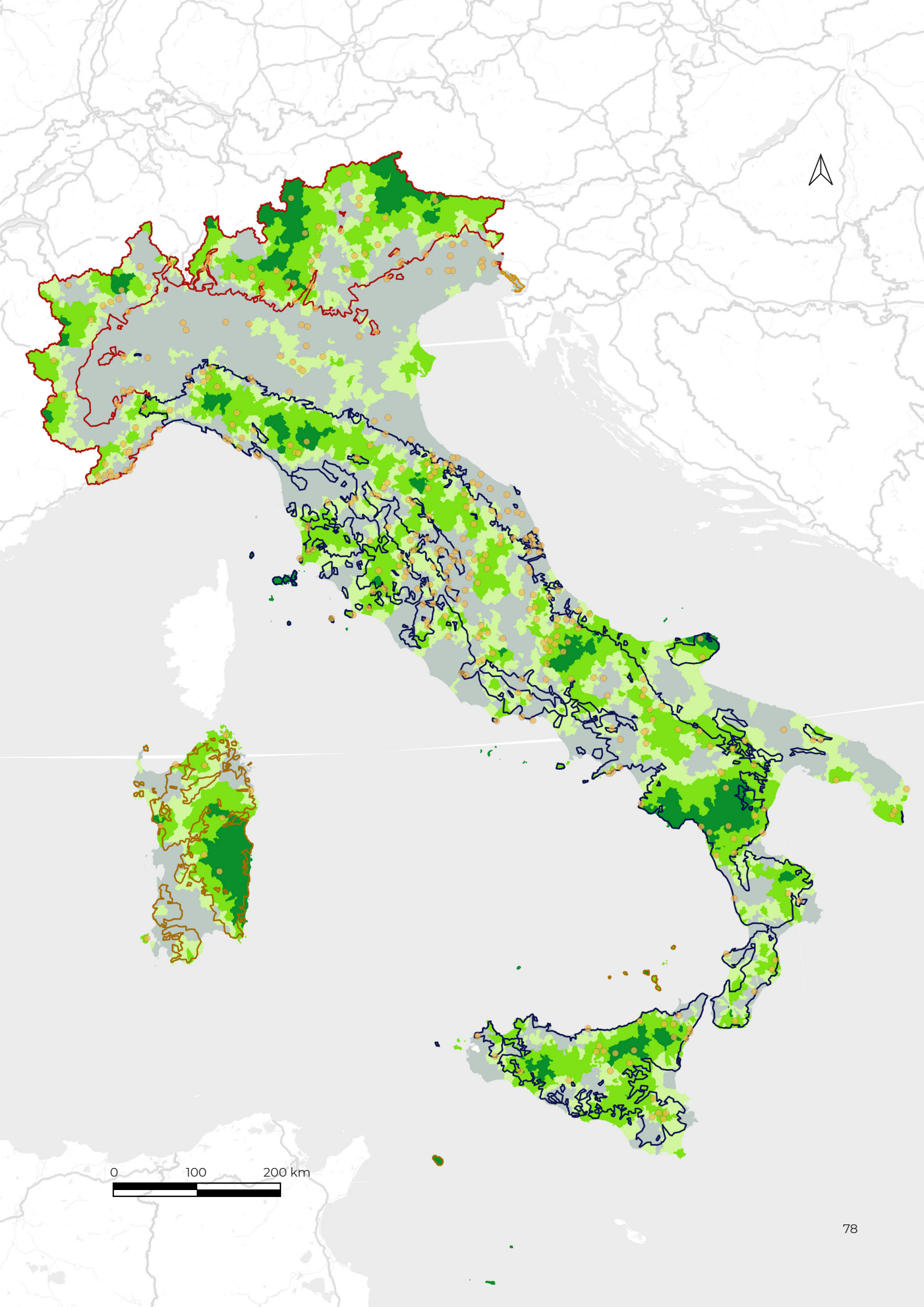
Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISTAT (Inner Areas 2020), CC BY 4.0;

EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;

OpenStreetMap contributors, Borghi più belli d'Italia via uMap.



5.2 National Scale

5.2.8 Technical Metadata and Processing Workflow

Table 15 provides a comprehensive operational summary of the spatial layers, datasets, and specific geoprocessing transformations executed to generate the national-scale identification framework.

Layer Name	Source & Coordinate System	Type & Scale	QGIS Operations	Role
Settlements	ISTAT Località 2021, (EPSG:32632).	Shape file/ Vector Polygon converted to Point Centroid 1:5.000	1. Topological geometry repair. 2. Attribute filtering. TIPO_LOC IN (1,2), POP21 <=1000, EDI21 >=5 3. Centroid extraction. 4. Classification by SS type.	Identification of baseline settlement universe and abandonment patterns.
Mountain Chains in Italy	EEA Mountain Chains 2008, (EPSG:3035).	Shape file/ Vector Polygon, 1:25,000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial extraction of Italian mountains. 4. Classification by mountain chain name (NAME_MM)	Delineation of physiographic mountain boundaries.
Rural–Urban Typology	Eurostat GISCO DEGURBA (LAU), (EPSG:4258).	Shape file/ Vector Polygon, 1:1,000,000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial extraction of Italian boundary. 4. Classification by class (DEGURBA).	Demographic-functional layer for rurality classification.
Inner Areas	SNAI Agenzia Coesione Territoriale.	CSV/ Tabular CSV joined to Polygon.	1. Attribute join to localita_21 layer. 2. Geometry validation. 3. Classification by class (Municipa 10).	Assessment of accessibility, remoteness and service deprivation.
Borghi Più Belli D'Italia	Open Street Map Borghi più belli d'Italia, (EPSG:4326).	GeoJSON/ Vector Point	1. GeoJSON string parsing 2. Reprojection to base CRS.	Independent cultural and heritage overlay layer.

Table 15. National Scale Geoprocessing Workflow and Layer Metadata. (Source: Author's elaboration)

5.3 Regional Scale

While the national scale delineates the spatial distribution of small settlements, the regional scale investigates the environmental conditions under which they exist. This section shifts focus to the Alpine macro-region, specifically targeting the Piedmont and Valle d'Aosta regions of Northwestern Italy, which are territories characterized by extreme topographic complexity, dynamic geomorphological processes, and widespread exposure to severe hydrogeological hazards.

To construct a standardized regional baseline, each institutional environmental hazard layer is treated as a vector polygon dataset and harmonized to the common coordinate reference system. The primary objective of the regional analysis is to establish a comparative, empirical framework that systematically quantifies settlement exposure across divergent regional administrative structures, identifying critical clusters where historical rural infrastructure directly intersects active environmental constraints.

5.3.1 Topographic Baseline and Hillshade Extraction

The continuous geomorphological terrain surface is derived from a 25-meter resolution Digital Terrain Model, or DTM25, acquired through the Geoportale SCT Valle d'Aosta and the Geoportale Piemonte spatial catalogs respectively. These independent regional raster files, which were originally formatted using native administrative coordinates, were seamlessly integrated within the GIS environment by executing a virtual mosaic operation in QGIS to produce a unified terrain model covering the entire study area. These continuous raster files were subsequently utilized to generate analytical hillshades, extracting the topographic structuring forces that govern mountain geomorphology.

To focus the diagnostic capabilities of the macro-region, the mountain regions of Italy dataset was also clipped to the specific regional perimeters of Piedmont and Valle d'Aosta to further show the relation between hazards and the mountainous nature of the area. Concurrently, the SMRS dataset, which was a result of the previous national-scale filtering model, was also trimmed to focus on the study area. By executing a spatial clip on the national settlement polygons using the merged regional boundary polygons, this step extracts a localized subset that represents the total universe of vulnerable mountain hamlets operating within the target catchments. This foundational geoprocessing workflow ensures that all subsequent regional environmental overlays remain anchored to a uniform, topographically validated spatial baseline.

5.3 Regional Scale

5.3.2 Flood Hazard Processing and Extraction Logic

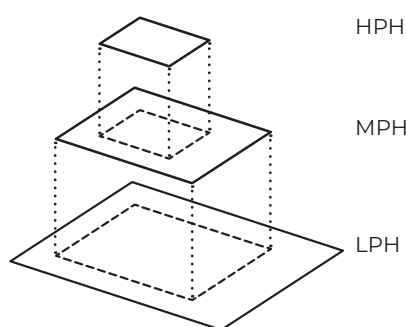


Figure 8. Independent layers of flood hazard zones.
(Source: Author's elaboration)

Hydraulic hazard inputs are sourced from the ISPRA hydraulic hazard mosaic, version 5.0, executing scenarios mandated by the European Flood Directive 2007/60/EC. These areas are structurally bounded into high, medium, and low probability flood zones, where each zone represents an independent layer, and the lowest probability zone geographically encompasses all the others, the relation between these layers is shown in Figure 8.

To preserve the absolute geometric integrity of the SMRS while capturing multi-tiered exposure data, a non-destructive Cascading Attribute Join Chain was used within QGIS. Rather than modifying or cutting the vector shapes, this workflow uses spatial location queries to systematically expand the attribute table horizontally.

The original, regional SMRS base layer was passed through three consecutive processing stages, using the output layer of each stage as the direct input for the next, and to ensure the worst case scenario was being considered for each SMRS, and because how the flood layers were nested in each other, the first attribution join was done for HPH layer.

Stage 1 (High Probability Hazard (HPH) Intersection):

A Join Attributes by Location operation was executed between the clean SMRS polygons and the raw HPH vector file. The tool scanned every settlement's patch. If an SMRS cluster geographically intersected the high probability flood zone, it extracted that hazard polygon's regulatory tracking parameters into the new column 'Flood P' as 'HPH'.

For settlement patches safely outside this boundary, the column cell values were populated as NULL (blank).

Stage 2 (Medium Probability Hazard (MPH) Intersection):

The temporary layer output from the first stage was passed back into the spatial join engine and intersected with the raw MPH vector file.

The intersection was logged into the same 'Flood P' field as 'MPH' but to ensure that the HPH intersections are not removed, it was logged only if the field was empty, ensuring that the HPH intersection is not being overwritten.

Stage 3 (Low Probability Hazard (LPH) Intersection):

The cumulative layer from the second stage was processed

Flood
Medium
Medium
Medium
High
High
High
Low
High
High
High
High
High

Figure 9. QGIS Flood Field for SMRS.
(Source: Author's elaboration)

5.3 Regional Scale

5.3.2 Flood Hazard Processing and Extraction Logic

through the final join configuration, intersecting it with the outer LPH hazard envelope.

The same logic of logging the LPH intersection in 'Flood P' was applied for the 3rd stage.

Upon completing this attribute-chaining pipeline shown in Figure 9, the regional SMRS geometries remained perfectly whole, unaltered, and un-fragmented. However, their underlying attribute matrices had been successfully enriched, storing all three spatial relation states. The remaining Null rows were then logged as 'Not Exposed'.

This methodology guarantees that high-intensity threat exposure takes absolute precedence over the broader, enveloping lower-probability zones, preventing severe hazard zones within these isolated alpine clusters from being obscured or downgraded. The resulting structured attribute matrix provides the mathematically sound, empirical baseline required to accurately map the SMRS flood classification displayed in Map B1.

To translate these complex, multi-tiered database intersections into an intuitive visualization for regional planning, the spatial outputs of the attribute model are synthesized in Map B1.

This cartographic product delineates the geographic intersections where the nested hydraulic risk boundaries of Northwest Italy directly overlap the polygons of the identified SMRS universe. To optimize clarity and prevent graphic clutter at this regional scale, the original SMRS polygons were transformed into centroids for enhanced visualization.

The color symbology for these SMRS points was purposefully selected to contrast against the underlying hydraulic hazard zones; while the flood layers are rendered in shades of blue, the SMRS centroids are classified using a high-visibility gradient ranging from red (high probability) to yellow (low probability), with green designating settlements that are "Not Exposed." By displaying these high, medium, and low probability exposure categories using this stark color gradient, Map B1 serves as the primary environmental diagnostic layer for regional-scale water vulnerabilities.

Consequently, this multi-layered cartographic layout allows planners to instantly identify which historical mountain hamlets are subject to active riverine surges, flashing torrents, or rare extreme floods, establishing a topographically validated reference framework that guides subsequent, site-specific infrastructure interventions.

B1. Flood Hazard Zone Map In Piedmont And Aosta Valley

And SMRS Intersection

Map B1 shows the intersection of flood hazard zones and SMRS, resulting in a classification of SMRS based on the worst case scenario of the hazard intersection.

Legend

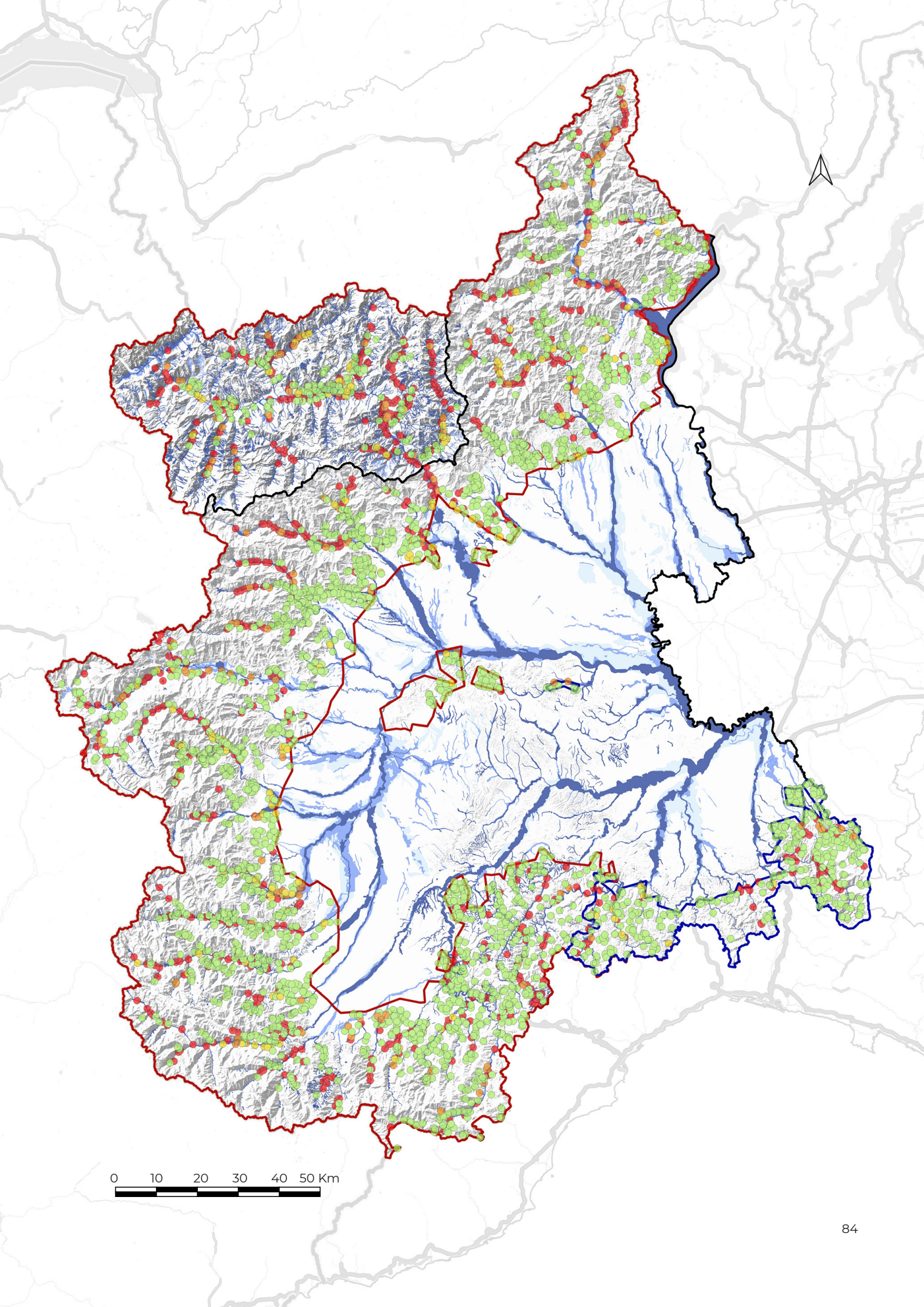
Piedmont and Aosta Valley	
Mountain Chains	
Alps	
Apennines	
Flood Hazard zones	
HPH	
MPH	
LPH	
SMRS	
High Hazard Exposure	
Medium Hazard Exposure	
Low Hazard Exposure	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;
ISPRA IdroGEO (v4.0 2021/v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Dati estratti dal Repertorio cartografico SCT della Regione Autonoma Valle d'Aosta, Scale: 1:10000.;
Geoportale Piemonte (DTM25), CC BY 4.0, Scale: 1:25000.



5.3 Regional Scale

5.3.3 Landslide Hazard Processing and Extraction Logic

Landslide datasets are extracted from the ISPRA mosaic database of River Basin District Authority Hydrogeological Setting Plans, or Piani di Assetto Idrogeologico, version 4.0. This comprehensive vector polygon dataset, compiled and distributed nationally through the institutional IdroGEO platform, classifies landslide danger across five distinct tiers, which are very high, high, medium, moderate, and attention zones. These tiers represent a standardized ordinal scale, cataloged as P4, P3, P2, P1, and AA respectively, reflecting both active slope mass movement inventories and multi-criteria territorial susceptibility indices. However, it is important to note that in the specific study regions of Piedmont and Valle d'Aosta, the last two classes do not exist in the official hazard mapping.

per_fr_ita	Landslide Rank
Molto Elevata P4	5
Elevata P3	4
Media P2	3

Figure 10. Relation between fields of Landslide layer in QGIS.
(Source: Author's elaboration)

To evaluate regional landslide exposure, the SMRS polygon layer was spatially joined with the comprehensive regional landslide dataset. First, an integer-based hazard scale ranging from 3 for medium, to 5 for Very High, was appended to the raw dataset to standardize the qualitative description fields.

This tabular reclassification was necessary to translate heterogeneous, text-based institutional indicators into a uniform numeric index capable of executing advanced geoprocessing algorithms. The precise mathematical relationship between the new "Landslide Rank" integer field and the "per_fr_ita" field, which contains the original downloaded data for this layer, is shown in Figure 10.

Because a single settlement can geographically overlap multiple hazard zones simultaneously, the 'Join Attributes by Location (Summary)' tool in QGIS was used, and the maximum numerical hazard value was automatically calculated and assigned to each intersecting settlement.

This conservative approach ensured that the worst-case hazard scenario took precedence over lower hazard tiers whenever a boundary overlap occurred. If a historical hamlet footprint lies mostly within a medium-hazard polygon but experiences even a minor, localized intersection with a very high landslide perimeter, the master database permanently records that asset under the maximum rank of 5.

This hazard-averse strategy guarantees that planning decisions account for absolute physical constraints, preventing localized pockets of slope failure from being statistically minimized. The resulting numeric attributes were then utilized to dynamically categorize the settlements, providing a structurally sound database for subsequent local analysis, generating the regional baseline, Map B2, and a zoomed layout for high-exposure clusters inside Valle d'Aosta, Map B3.

5.3 Regional Scale

5.3.3 Landslide Hazard Processing and Extraction Logic

To translate these complex, worst-case spatial calculations into an operational visual tool for broad territorial evaluation, the full distribution of exposure across the macro-region is synthesized in Map B2. This map overlays the SMRS centroids directly on top of the continuous regional landslide polygons, revealing the broad macro-scaled patterns of geomorphological vulnerability. By utilizing a high-contrast visual system where the point geometries remain clearly legible against the dense, underlying terrain hillshades, Map B2 allows planners to rapidly locate large macro-regional clusters where historical village structures are actively intersecting unstable mass movement perimeters. Consequently, this multi-layered cartographic output functions as the primary diagnostic index for large-scale hazard assessment, establishing an empirical baseline that separates relatively stable valley networks from sectors experiencing systemic, wide-ranging geomorphological instability.

Furthermore, because the Autonomous Region of Valle d'Aosta exhibits an exceptionally high concentration of acute mass movements and narrow, topographically compressed drainage networks, a specialized high-resolution visualization is required to support site-specific planning interventions. This downscaled diagnostic need is addressed in Map B3, which provides a zoomed geometric layout focusing exclusively on the internal valley corridors of the Aosta territory.

The color symbology for these SMRS points was purposefully selected to contrast against the underlying landslide hazard zones. While the institutional PAI mass movement polygons are rendered in a backdrop of dark burgundy and red fills, the SMRS centroids are classified using a high-visibility gradient composed of distinctive purple shades, with light purple denoting moderate susceptibility and deep purple highlighting a very high hazard rank, while green systematically designates settlements that are 'Not Exposed'.

By displaying these varying degrees of geomorphological slope exposure using this stark color gradient, **Map B2 and its localized downscaled counterpart, Map B3, serve as the primary environmental diagnostic layers for regional-scale slope vulnerabilities.**

B2. Landslide Hazard Zone Map In Piedmont And Aosta Valley

And SMRS Intersection

Map B2 shows the intersection of landslide hazard zones and SMRS, resulting in a classification of SMRS based on the worst case scenario of the hazard intersection.

Legend

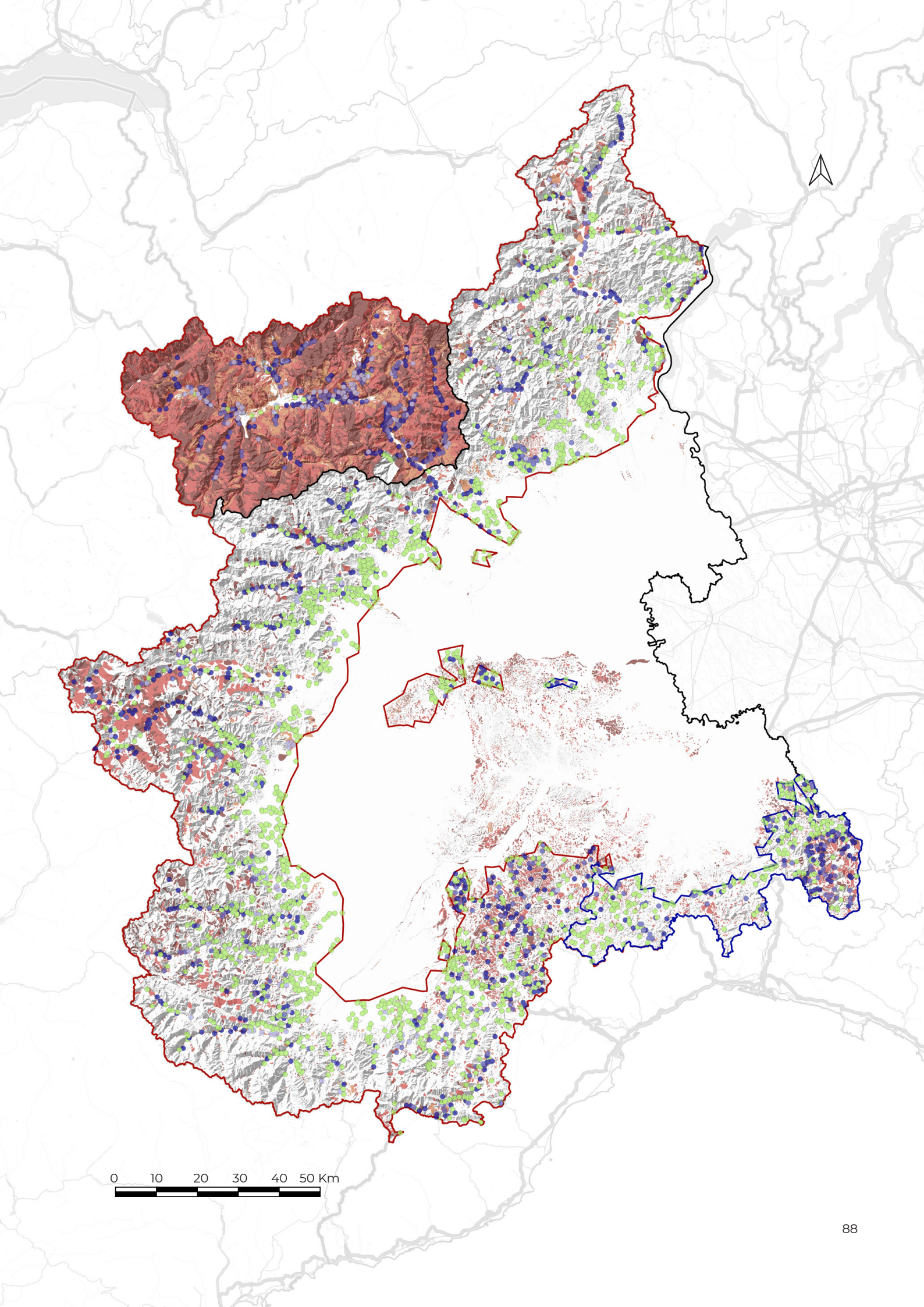
Piedmont and Aosta Valley	
Mountain Chains	
Alps	
Apennines	
Landslide Hazard Zones	
Very High P4	
High P3	
Medium P2	
SMRS	
Very High Hazard Exposure	
High Hazard Exposure	
Medium Hazard Exposure	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;
ISPRA IdroGEO (v4.0 2021/v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Dati estratti dal Repertorio cartografico SCT della Regione Autonoma Valle d'Aosta, Scale: 1:10000;
Geoportale Piemonte (DTM25), CC BY 4.0, Scale: 1:25000.



0 10 20 30 40 50 Km

B3. Landslide Hazard Zone Map Zoomed In Aosta Valley

And SMRS Intersection

Map B3 details the intersection of landslide hazard zones and SMRS in Aosta Valley, resulting in a classification of SMRS based on the worst case scenario of the hazard intersection.

Legend

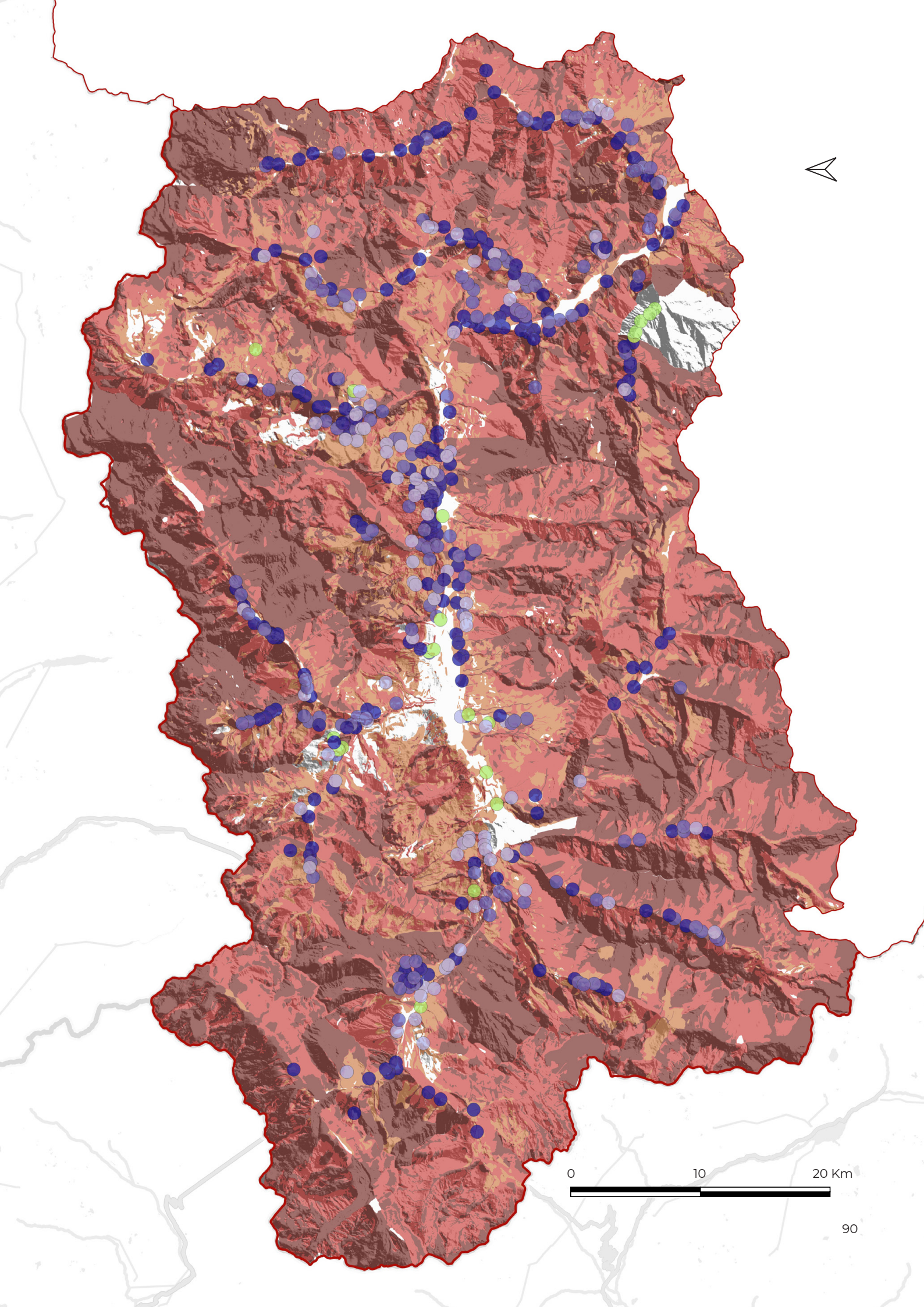
Mountain Chains	
Alps	
Apennines	
Landslide Hazard Zones	
P4 Very High	
P3 High	
P2 Medium	
SMRS	
Very High Hazard Exposure	
High Hazard Exposure	
Medium Hazard Exposure	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;
ISPRA IdroGEO (v4.0 2021/v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Dati estratti dal Repertorio cartografico SCT della Regione Autonoma Valle d'Aosta, Scale: 1:10000;



0 10 20 Km

5.3 Regional Scale

5.3.4 Avalanche Regional Protocols and Harmonization Gaps

Unlike the homogeneous national frameworks utilized for floods and landslides, avalanche data exhibits a fundamental structural divergence between the regional administrative territories of Italy. To evaluate winter geomorphological constraints across this macro-region, data had to be synthesized from two completely separate regional mapping agencies, which are the Catasto Regionale Valanghe managed by the Autonomous Region of Valle d'Aosta via the SCT repository, and the Banca dati valanghe compiled by ARPA Piemonte.

While Valle d'Aosta tracks both progressive regulatory zoning and historical event perimeters, the Piedmont dataset functions as a complex, non-ordinal multi-source inventory mapping distinct administrative perimeters and physical terrain mapping methodologies. To resolve this profound methodological mismatch, a localized protocol was structured for each individual territory to evaluate SMRS intersection dynamics without forcing non-equivalent, non-ordinal variables into an artificial or misleading cross-regional hazard hierarchy.

Because the avalanche dynamics of each region are inherently different, they are not forced to be merged into a single map, allowing each layout to employ customized color palettes optimized for its specific underlying data structures.

Piedmont

In the territory of Piedmont, where an ordinal hazard scale is completely absent from the master inventory, exposure was re-conceptualized based on institutional and environmental evidence types. The input vector layers were grouped into two distinct categories, which are Administrative Tiers, comprising the municipal master plans known as `pie_valprgc` and `pie_zoneprgc`, and Geomorphological Tiers, containing raw physical data from terrain-based susceptibility mapping (`pie_valterreno`), photo-interpretation (`pie_valfoto`), and geomorphological danger perimeters (`PIE_zoneper`).

Using the Select by Location tool in QGIS, a multi-stage spatial query was executed to parse these distinct classes. Settlements intersecting the municipal master plans were classified as experiencing Administrative Hazard Zone Exposure, prioritizing the legal and regulatory constraints imposed directly on the built environment. Settlements situated outside these legal boundaries but intersecting the physical data layers were classified as experiencing Geomorphological Hazard Zone Exposure, while completely unmapped features were categorized as Not Exposed. To prevent visual blending against the high-contrast hillshade base map, the physical geomorphological layers were cartographically rendered in

5.3 Regional Scale

5.3.4 Avalanche Regional Protocols and Harmonization Gaps

shades of purple and blue, while the administrative boundaries were symbolized in vibrant pink and magenta fills. For the SMRS point assets displayed on Map B4, a contrasting color strategy was deployed where Administrative Exposure is marked in red, Geomorphological Exposure is highlighted in orange, and unexposed units are symbolized in green, preventing visual camouflage.

Valle d'Aosta Protocol

The Valle d'Aosta Protocol executed a sequential overlay process that closely matches the nested hydraulic methodology, handling both regulatory hazard zones and mapped historical footprints. The data input includes regulatory hazard zones classified as V1 for very high, V2 for medium, and V3 for low danger, alongside historical footprints tracking Va for exposed paths and Vb for probable runout footprints. A new string field was generated within the SMRS attribute table, and a hierarchical CASE WHEN spatial query sequentially evaluated every geometric intersection. To maintain a conservative, worst-case scenario approach, the layers were processed from the lowest regulatory priority up to the maximum legal restriction tier. During this attribution step, the acute historical paths (Va) were merged directly with the highest regulatory zone (V1), while the broader probable runout footprints (Vb) were grouped with the medium hazard zone (V2), ensuring that historical footprints and zoning intensities were nested accurately without obscuring severe exposure. This approach isolated the maximum institutional hazard tier overriding a settlement's footprint, classifying assets into high, medium, low, or unexposed categories. Because of the critical hazard clustering observed along narrow, topographically compressed alpine valley corridors, a detailed zoomed layout was compiled for this region to enhance cartographic legibility, generating Map B5.

The cartographic visualization strategy for Map B5 utilizes a dedicated, high-contrast palette tailored specifically to the unique institutional layers of the Aosta Valley. The underlying avalanche hazard polygons are rendered using a continuous gradient of deep purple and light violet tones, which separates the extreme V1 and Va vectors from the intermediate and low-tier zones.

To achieve absolute legibility against this dense purple background, the intersecting SMRS point centroids are displayed in red, Medium Hazard Exposure transitions to dark orange, and Low Hazard Exposure as bright yellow, while all settlements outside the active tracks are filled with solid green.

B4. Avalanche Hazard Zone Map In Piedmont

And SMRS Intersection

Map B4 shows the intersection of avalanche hazard zones and SMRS in Piedmont, resulting in a classification of SMRS based on the hazard intersection.

Legend

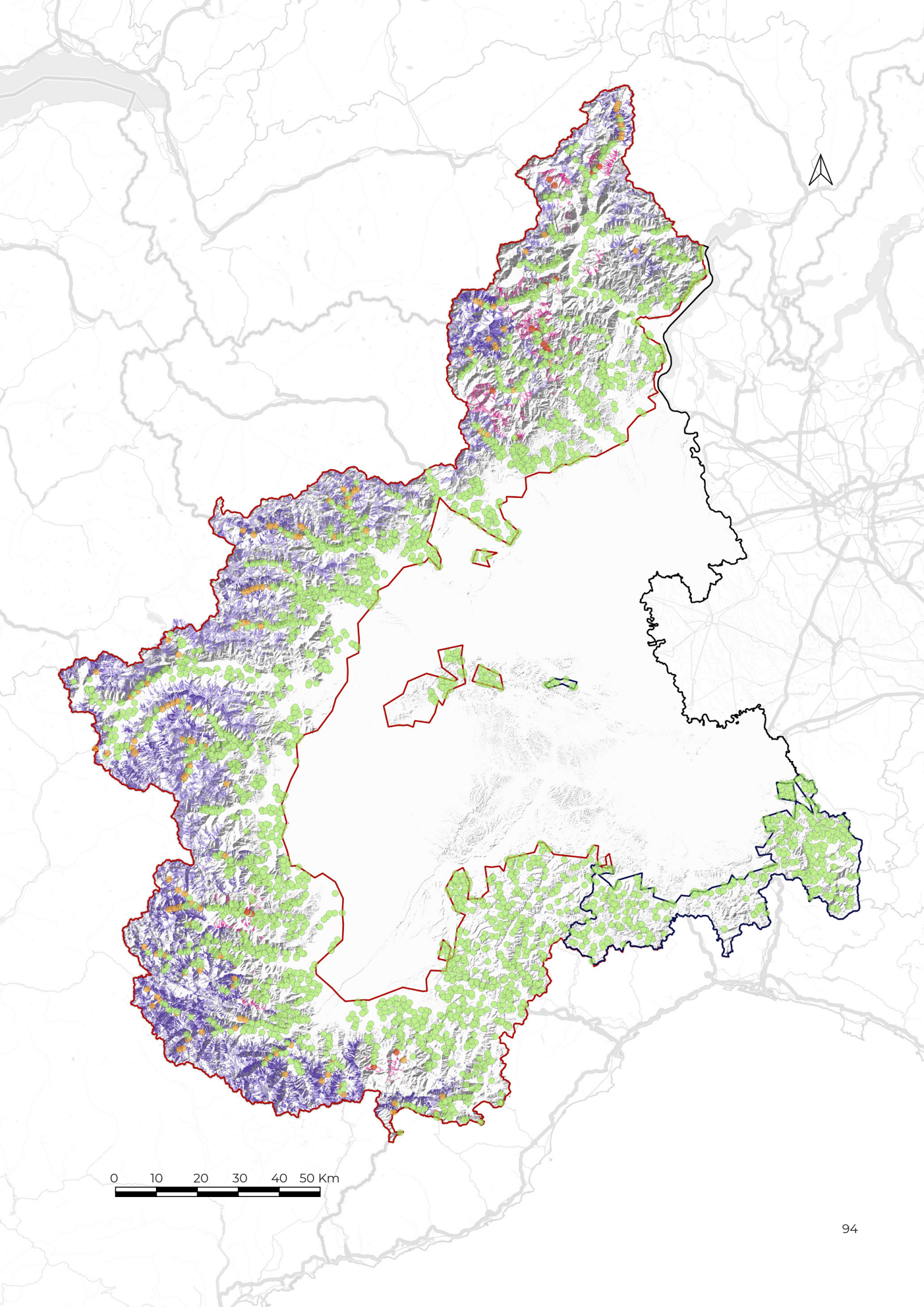
Mountain Chains	
Alps	
Apennines	
Geomorphological Avalanche Hazard Zones	
Historical Photo-Interpreted Footprints	
Morphological Terrain Susceptibility	
Geomorphological Danger Perimeters	
Administrative Avalanche Hazard Zones	
PRGC Regulatory Avalanche Paths	
PRGC Municipal Hazard Zoning	
SMRS	
Administrative Hazard Zone Exposure	
Geomorphological Hazard Zone Exposure	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;
ARPA Piemonte (Banca dati valanghe), Scale: 1:25000.0;
Geoportale Piemonte (DTM25), CC BY 4.0, Scale: 1:25000.



B5. Avalanche Hazard Zone Map Zoomed In Aosta Valley

And SMRS Intersection

Map B5 details the intersection of avalanche hazard zones and SMRS in Aosta Valley, resulting in a classification of SMRS based on the worst case scenario of the hazard intersection.

Legend

Mountain Chains

Alps



Avalanche Hazard

V1 Very high



Va Exposed Path



Vb Probable Runout Footprint



V2 Medium Hazard Zone



V3 Low Hazard Zone



SMRS

High Hazard Exposure



Medium Hazard Exposure



Low Hazard Exposure



Not Exposed



Reference System

WGS 84 / UTM zone 32N

Data Source:

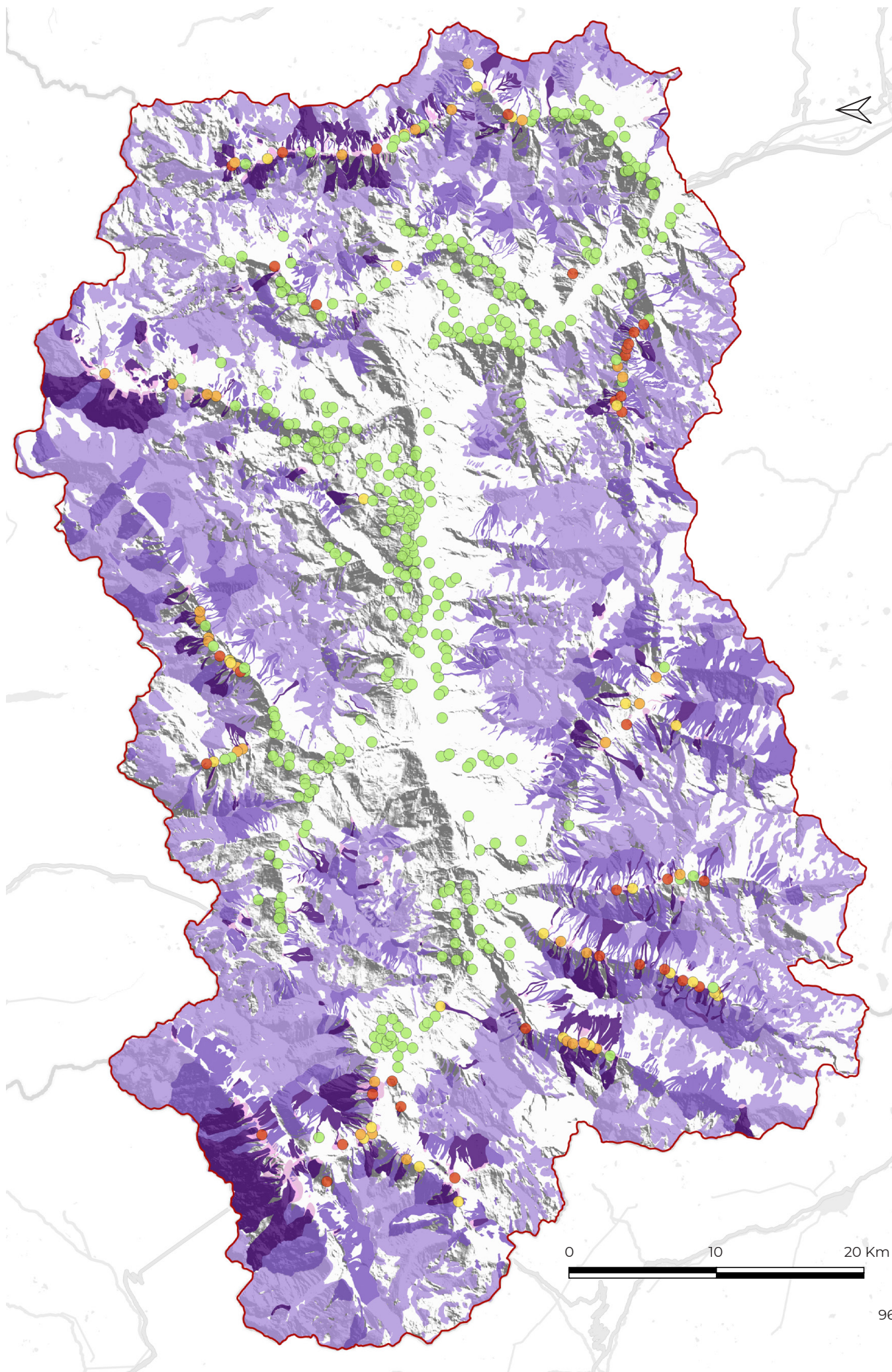
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;

Dati estratti dal Repertorio cartografico SCT della Regione Autonoma Valle d'Aosta, Scale: 1:10000;

Regione Autonoma Valle d'Aosta (Catasto Regionale Valanghe), CC BY 4.0, Scale: 1:10000;

Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1:10000.



5.3 Regional Scale

5.3.5 Multi-Hazard Intersection Logic and Synthesis Layer Generation

The regional analysis does not merely display coincidental hazard boundaries, but instead algorithmically quantifies the cumulative, hazard-aware exposure status of each individual SMRS. This is achieved by executing a multi-criteria intersection and spatial join pipeline, which systematically overlays the complex vector boundaries of the municipal Località polygons with the independent flood, landslide, and avalanche hazard layers processed in the preceding steps. Because settlement **safety** functions as a non-negotiable prerequisite for any viable re-inhabitation policy, the processing workflow applies a strict, hazard-averse thresholding rule during the primary overlay stage. If an individual SMRS polygon exhibits any degree of spatial intersection with multiple qualitative hazard severity tiers, the settlement database entry automatically inherits the **absolute highest hazard classification** encountered within its perimeter. For example, if a settlement's physical footprint lies ninety percent within a low-probability or moderate-hazard zone but experiences a minor, ten percent spatial overlap with a very high-hazard perimeter, the entire settlement entity is categorized under that **maximum** hazard tier. This conservative priority rule guarantees that subsequent regional-scale planning decisions account for worst-case scenario constraints, completely preventing localized pockets of extreme geomorphological danger from being obscured or statistically downgraded.

Upon completing these independent exposure calculations, the geoprocessing engine executes a parallel attribute harmonization workflow to reconcile the disparate regional schemas of the two input spatial datasets, which are SMRS_Piedmont and SMRS_Valle_d_Aosta. Due to significant discrepancies in how avalanche layers are organized between the two regional administrative authorities, a customized, conditional SQL-based algorithm was implemented via the **QGIS Field Calculator** for each layer. The primary objective of this programming step was to compute a standardized numerical index field, titled 'Hazard Count' which scales as a uniform integer from zero, representing settlements situated entirely outside all active institutional hazard perimeters, up to a maximum score of three, indicating critical locations where a single community concurrently overlaps flood, landslide, and avalanche zones.

In the Piedmont layer, the dataset recorded flood and landslide risks qualitatively or numerically, while avalanche exposure was stored in a specialized text field (Avalan_PIE) using local administrative classifications. Features completely unexposed to avalanches were explicitly denoted by the string literal 'Not Exposed'. To ensure absolute data integrity, the parsing expression utilized string trimming and case-insensitive

5.3 Regional Scale

5.3.5 Multi-Hazard Intersection Logic and Synthesis Layer Generation

transformations to account for variations in manual data entry, following the conditional logic where **Hazard_Count** equals the sum of Flood, Landslide, and Avalan PIE fields. Within this equation shown in Figure 11, each component resolves to 1 if the respective field is not null, not empty, and not equal to 'Not Exposed', and otherwise resolves to 0:

```
(CASE WHEN "Flood" IS NOT NULL AND trim("Flood") != " THEN 1 ELSE 0 END) +  
(CASE WHEN "Landslide" IS NOT NULL AND trim("Landslide") !=  
" THEN 1 ELSE 0 END) +  
(CASE WHEN "Avalan PIE" IS NOT NULL AND trim("Avalan PIE")  
!= " AND lower(trim("Avalan PIE")) != 'not exposed' THEN 1 ELSE  
0 END)
```

Conversely, the Valle d'Aosta layer framework utilized a standardized numeric matrix for avalanche risk ranging from 0 to 3, where a value of 0 represented a lack of hazard exposure. The conditional SQL logic was adapted to treat 0 values as unexposed alongside empty cells, executing the calculation as follows:

```
(CASE WHEN "Flood" IS NOT NULL AND trim("Flood") != " THEN 1 ELSE 0 END) +  
(CASE WHEN "Landslide" IS NOT NULL AND trim("Landslide") !=  
" THEN 1 ELSE 0 END) +  
(CASE WHEN "Avalanche" > 0 THEN 1 ELSE 0 END)
```

By transitioning from independent hazard summaries to a single, multi-criteria **vulnerability index** through this field standardization, the synthesis workflow exposes the hidden geographic clusters where physical threats are systemically compounded. This process provides planners with a diagnostic tool to separate single-exposure sites from areas experiencing multi-hazard convergence across different administrative regions.

To ensure cartographic legibility across the macro-region, a geometric conversion is applied to the final database layer before generating the map layout. Although the underlying topological intersection calculations are executed using the detailed, complex vector boundaries of the municipal Località polygons to preserve structural precision, these shapes are converted to point centroids for rendering at the regional scale. To visualize these overlapping environmental challenges, **the total cumulative exposure data is synthesized in Map B6**. By transitioning away from isolated danger perimeters toward an integrated representation of total hazard count, Map B6 highlights the geographic bottlenecks where sustainable reinhabitation faces multiple, concurrent physical barriers.

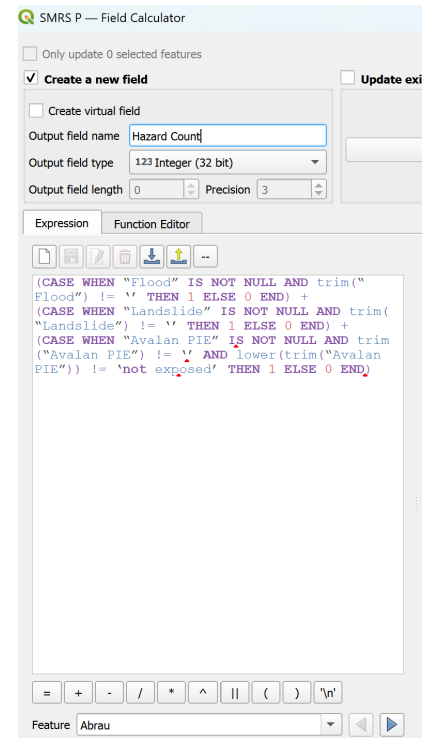


Figure 11. QGIS field calculator for Hazard count field.
(Source: Author's elaboration)

B6. SMRS Multi-Hazard Intersection Synthesis Map

Across Piedmont And Valle d'Aosta

Map B6 shows the baseline spatial synthesis of multi-hazard exposure across Piedmont and Valle d'Aosta, while simultaneously establishing the physiographic boundaries of mountain areas and contextualizing the cumulative vulnerability of SMRS.

Legend

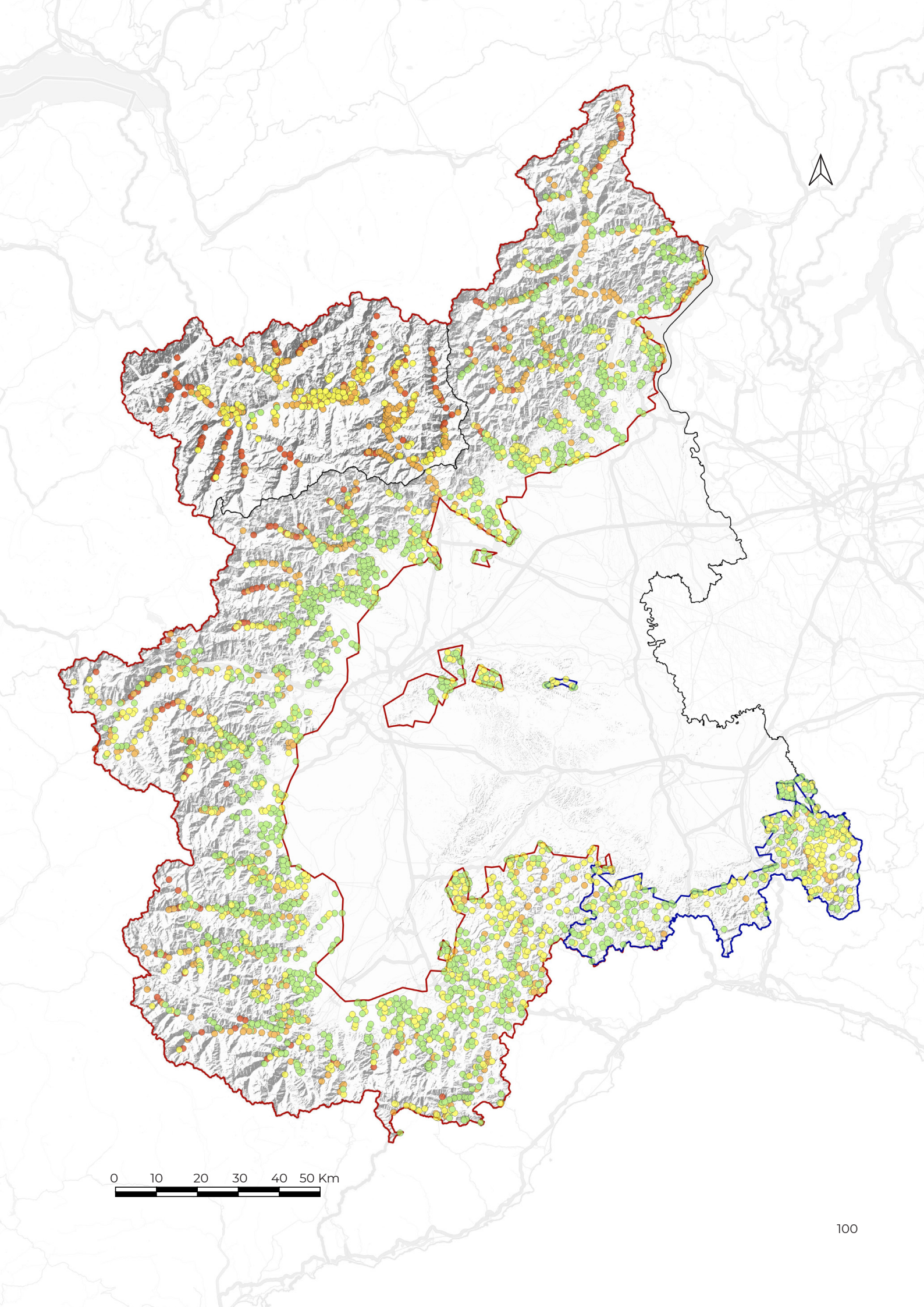
Piedmont and Aosta Valley	
Mountain Chains	
Alps	
Apennines	
SMRS	
Exposed to 3 Hazards	
Exposed to 2 Hazards	
Exposed to 1 Hazard	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
EEA Geospatial Catalog (v1 2008), Scale: 1:25,000;
Geoportale Piemonte (DTM25), CC BY 4.0, Scale: 1:25000;
Dati estratti dal Repertorio cartografico SCT della Regione Autonoma Valle d'Aosta, Scale: 1:10000;
Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1:10000.



0 10 20 30 40 50 Km

5.3 Regional Scale

5.3.6 Technical Metadata and Processing Workflow

Table 16 provides a comprehensive operational summary of the spatial layers, datasets, and specific geoprocessing transformations executed to generate the regional-scale maps.

Layer Name	Source & Coordinate System	Type & Scale	QGIS Operations	Role
Settlements	Derived from national scale model, (EPSG:32632).	Shape file/ Vector Polygon converted to Point Centroid, 1:5.000	1. Filter to regional boundaries. 2. Spatial intersection with hazard vectors. 3. Spatial join execution. 4. Centroid conversion.	Operational spatial footprint for hazard exposure mapping.
Mountain Chains	Derived from national EEA Mountain Chains 2008, (EPSG:32632).	Shape file/ Vector Polygon, 1:25,000	1. Filter to regional boundaries. 2. Classification by mountain chain name (NAME_MM)	Delineation of physiographic mountain boundaries.
Flood Hazard Layers (HPH, MPH, LPH)	ISPRA IdroGEO Platform v5.0, (EPSG:3035).	Shape file/ Vector Polygon, 1:5000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to study regions. 4. Hydraulic perimeter extraction.	Identification of flood hazard zones.
Landslide Hazard Layer	ISPRA IdroGEO Platform PAI v4.0, (EPSG:32632).	Shape file/ Vector Polygon, 1:5000	1. Topological geometry repair. 2. Spatial clip to study regions. 3. Hazard perimeter extraction.	Identification of landslide hazard zones.
Avalanche Hazard Layers Piedmont (PIE layers)	ARPA Piemonte (Banca dati valanghe), (EPSG:32632).	Shape file/ Vector Polygon, 1:25000	1. Topological geometry repair. 2. Categorization of layers. 3. Hazard perimeter extraction.	Identification of avalanche hazard zones in Piedmont.

Table 16. Regional Scale Geoprocessing Workflow and Layer Metadata.
(Source: Author's elaboration)

5.3 Regional Scale

5.3.6 Technical Metadata and Processing Workflow

Avalanche Hazard Layer Aosta Valley	Regione Autonoma Valle d'Aosta (Catasto Regionale Valanghe), CC BY 4.0, (EPSG:3035).	Shape file/ Vector Polygon, 1:10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Hazard perimeter extraction.	Identification of avalanche hazard zones in Aosta Valley.
Digital Terrain Model (25) Piedmont	Geoportale SCT Valle d'Aosta	Raster TIF, 1:10000	1. Raster tile mosaic. 2. Extraction of analytical hillshade	Base physical terrain layer and slope orientation.
Digital Terrain Model (25) Aosta Valley	Geoportale Piemonte Catalog	Raster TIF, 1:25000	1. Raster tile mosaic. 2. Extraction of analytical hillshade	Base physical terrain layer and slope orientation.

5.4 Territorial Scale

The downscaled territorial analysis shifts from national macro-categorizations to a high-resolution, site-specific diagnostic focusing on three targeted Alpine valley segments, which are treated as cohesive geomorphological and functional catchments.

These deep-valley study regions comprise the Valpelline Valley Corridor (focusing on the Ollomont catchment branch in Valle d'Aosta), the Anzasca Valley Corridor (focusing on the Macugnaga catchment in Piedmont), and the Maira Valley Corridor (focusing on the Elva catchment in Piedmont). By isolating these distinct micro-scale valley transects, the geoprocessing framework leverages high-precision datasets extracted from the Geoportale SCT Valle d'Aosta and the Geoportale Piemonte spatial catalogs respectively.

This step links local architectural building stocks with active topographic forcing factors and infrastructural choke points, standardizing the localized analysis across four consistent analytical map categories for each case study.

5.4 Territorial Scale

5.4.1 Land Cover Harmonization and Reclassification

To establish a consistent environmental and surface baseline across differing regional administrative datasets, the local scale processes land cover data to trace the precise spatial relationships between protective vegetative buffers, historical agricultural pastures, and urbanized interfaces. Due to structural differences between the two regional mapping frameworks, a parallel geoprocessing and reclassification pipeline was executed to standardize the disparate datasets into six core thematic planning environments.

For the Ollomont catchment in Valle d'Aosta, the primary input was extracted from the regional 'uso suolo copertura suolo 2020' dataset. A rule-based configuration was implemented in the original dataset. This layer was structured using alphanumeric string attributes mapping across two hierarchically nested levels (LCC-1 through LCC-3, refined down to sub-classes such as LCC-2_1_1 for trees or LCC-3_2_2 for glaciers). To resolve these rules alongside underlying raster grid codes, a conditional reclassification matrix grouped the diverse local cover variables (including specialized high-altitude categories like Zone umide alpine, Roccia affiorante, and Praterie naturali e pascoli alpini) into 6 categories including Urban & Built-up Area, Pastures & Meadows, Forests & Shrublands, Bare Rock & Alpine Tundra, Glaciers & Permanent Snow, and Rivers & Lakes. Conversely, for the Macugnaga and Elva catchments in Piedmont, the methodology integrated the 'CP SUOLO' dataset acquired through the regional spatial catalog. Unlike the descriptive rule-based attributes of Valle d'Aosta, the Piedmont dataset stores spatial variations using highly fragmented, six-digit numerical class codes (e.g., 010101, 020102, 050301). To overcome this classification mismatch, these numbers were first translated to qualitative expressions using the attribute table and categorized into 6 categories, matching the specific Piedmont classifications with the equivalent Valle d'Aosta geomorphological themes. This harmonization step guarantees that forested zones, hazardous rocky outcroppings, alluvial valley floors, and built-up areas share identical semantic and structural attributes across the regional borders, ensuring that subsequent multi-hazard masks remain perfectly comparable.

5.4.2 Topographic Modeling and Slope Division

To isolate the structural landform components that actively drive geomorphological hazards, the methodology processes elevations to derive secondary terrain layers. The primary input for the terrain modeling pipeline was the "Curve 10" vector layer, acquired from the regional geoportals, which contains

5.4 Territorial Scale

5.4.2 Topographic Modeling and Slope Division

detailed elevation contours and topographic mass points. This vector dataset was directly utilized as the source input for a Triangular Irregular Network, or 'TIN interpolation' within QGIS. The interpolation engine used the vector nodes and lines to construct a continuous three-dimensional terrain mesh. From this interpolated baseline raster surface, secondary topographic outputs were extracted to map the specific geomorphological characteristics of each valley catchment. First, an analytical multi-directional hillshade layer was computed to map surface relief variations, drainage channels, and slope texture breaks. Concurrently, a continuous slope angle map was generated, calculating the maximum rate of change in elevation for each cell in degrees. To convert this continuous gradient into a functional territorial planning instrument, the continuous degree raster was reclassified into five standardized geomorphological brackets bounded at 9°, 17°, 27°, and 35°. The five brackets follow the principal morphodynamic thresholds established across the Alpine geomorphological and natural hazard literature. The 9° lower bound delineates terrain where gravitational stress is insufficient to initiate mass movement under typical Alpine soil conditions (Çellek, 2022). The 17° and 27° boundaries subdivide the primary landslide susceptibility band, within which studies consistently record the highest landslide frequency and density (Çellek, 2022). The 35° upper threshold reflects the established avalanche release criterion, formalized by the WSL Institute for Snow and Avalanche Research (SLF), whereby slopes exceeding 35° are classified as active avalanche release zones in both Swiss federal geodata standards and the European Alpine avalanche bulletin framework (opendata swiss, 2024; WSL Institute for Snow and Avalanche Research, 2024).

5.4.3 Linear Infrastructure Network Fragility

To evaluate network accessibility fragility as a core structural planning metric, this scale executes a topological overlay within the GIS environment. The local alpine road network footprint, represented by vector layers extracted from regional technical maps, is spatially intersected with the high-severity hazard polygon layers. Road segments directly overlapping these hazard polygons are isolated using the Clip and Intersect tools, highlighting the specific geographic points where critical infrastructure is physically exposed to geomorphological blockages. The final assessment component tracks the evacuation and supply corridors outward from each isolated settlement point cluster down to the principal valley floor junction. Where a historical mountain hamlet relies on a singular provincial or municipal road carved into a steep rock face, its entire operational lifeline is structurally tied to that narrow corridor.

5.4 Territorial Scale

5.4.3 Linear Infrastructure Network Fragility

When spatial tracing confirms that a community's singular exit vector crosses a mapped hazard intersection box, the asset is logged in the spatial database under active road blockage tags, tracking landslide constraints within the field column titled 'RB LandS', avalanche within 'RB Avalan', and hydraulic exposure within 'RB Flood'. Rather than analyzing infrastructure threats in isolation, the database aggregates these constraints into a standardized integer metric. A conditional tracking algorithm implemented via the QGIS Field Calculator evaluates the descriptive road blockage entries to generate a consolidated Infrastructure Hazard Count using the following conditional expression. Note that the avalanche condition includes an additional string exclusion (!= 'not exposed'); this reflects a dataset-specific encoding difference. The exclusion prevents false-positive hazard counts on confirmed safe corridors:

```
(CASE WHEN "RB LandS" IS NOT NULL AND trim("RB LandS") != "" THEN 1 ELSE 0 END) + (CASE WHEN "RB Avalan" IS NOT NULL AND trim("RB Avalan") != "" AND lower(trim("RB Avalan")) != 'not exposed' THEN 1 ELSE 0 END) + (CASE WHEN "RB Flood" IS NOT NULL AND trim("RB Flood") != "" THEN 1 ELSE 0 END)
```

The resulting score yields a clear operational hierarchy for regional planning and disaster mitigation, translating cumulative attribute counts into four distinct Road Accessibility Classifications. An intersection score of zero designates a Secure Access Corridor, meaning the transportation network remains entirely free of active hazard intersections and represents a reliable long-term reinhabitation axis. A value of one indicates Single-Sector Vulnerability, where the access route is exposed to a single environmental threat, such as historical snow avalanche paths, which remains manageable through targeted seasonal monitoring or active engineering barriers. A score of two identifies Compounded Structural Risk, where the exit corridor faces dual geomorphological constraints that create a high probability of temporary isolation during severe climate events. Finally, a maximum score of three designates an Extreme Multi-Hazard Choke Point, indicating locations where the community's singular link to the valley floor is concurrently compromised by landslide, avalanche, and flood, a condition that may render sustainable reinhabitation unviable without substantial civil engineering intervention.

5.4.4 Historical Context and Cartographic Layouts

To fully contextualize the downscaled geoprocessing models, the historical and territorial evolution of the three chosen valley catchments must be explained. Understanding the historical

5.4 Territorial Scale

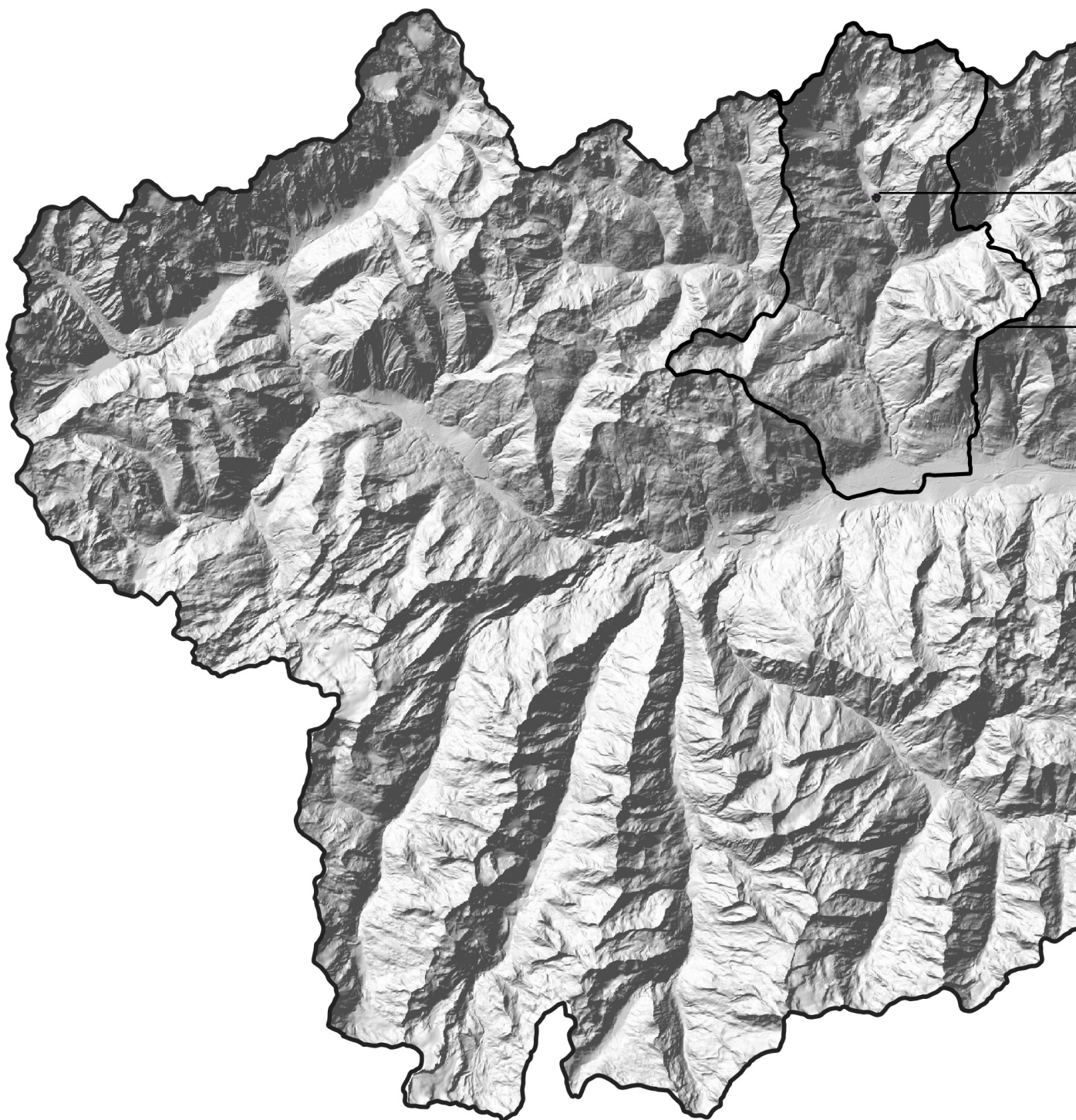
5.4.4 Historical Context and Cartographic Layouts

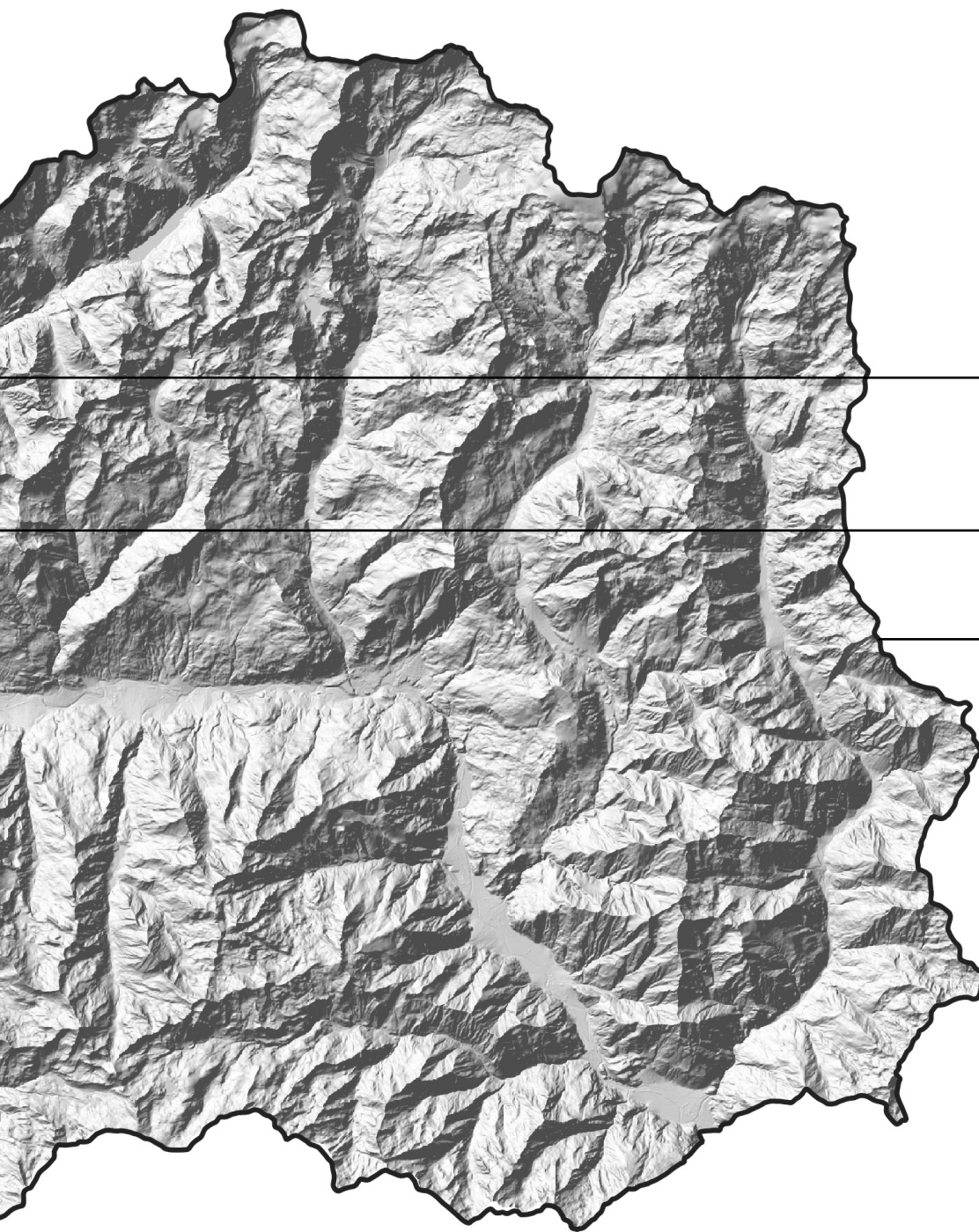
pathways of these distinct alpine valleys explains why vulnerable architectural building stocks exist within active hazard zones today, and provides a structural baseline for evaluating current demographic and physical decline.

Historically, the Valpelline Valley, where Ollomont is located, was governed by the *alpeggio* system, a traditional vertical zoning of seasonal pastoral migration. However, eighteenth- and nineteenth-century copper mining transformed Ollomont into an industrial outpost, pulling permanent infrastructure closer to unstable slopes and torrent beds to service the shafts. Following the mid-twentieth-century closure of these mines, the valley faced demographic marginalization. Recent revitalization efforts have repurposed these historic mining networks into ‘mine-parks’ open for public tourism and community use (Unité des Communes valdôtaines Grand-Combin, 2024). The municipality encompasses several distinct hamlets, Ollomont, Vouece, Le Clapey, and Le Morion, each representing a discrete settlement cluster within the broader valley catchment analyzed at the settlement scale. The Anzasca Valley, where Macugnaga is located, was profoundly shaped by thirteenth-century Walser colonization. This Germanic culture developed specialized timber-and-stone architecture (*blockbau*) and structured decentralized hamlets on high moraine terraces to avoid the valley floor’s torrential flood discharge and glacial meltwater from the Monte Rosa massif. This traditional spatial equilibrium was disrupted in the late nineteenth and early twentieth centuries by gold mining and large-scale alpine tourism, which forced infrastructure to encroach onto hazardous alluvial cones and avalanche runout zones (Municipality of Macugnaga, n.d.). The settlement fabric is distributed across two primary hamlets, Staffa and Pecetto, which present markedly different spatial relationships to the active hazard zones documented in the following cartographic series.

Finally, the Maira Valley Corridor, where the ultra-peripheral Elva catchment is situated in southwest Piedmont, is defined by extreme geographical isolation. Elva was developed as a high-altitude ridge settlement perched 1,600 meters above sea level, because the lower valley’s deep limestone gorges were impassable until late nineteenth-century military roads were blasted into the rock. This isolation forced high-density landscape terracing for subsistence farming, altering local soil and drainage dynamics. Following a post-war demographic collapse, this unmaintained, rock-cut network remains highly vulnerable to landslides and rockfalls (Consorzio Turistico Valle Maira, 2026). The municipality is composed of six dispersed hamlets, Serre, Gorio, Martini, Villar, Clari, and Rinaud, distributed along the high ridge system, each constituting a distinct building cluster analyzed individually at the settlement scale.

Valpelline Corridor And Ollomont Location





Ollomont

Territorial
segments of the
Valpelline Corridor

Aosta Valley

0 10 20 Km

C1. Hazard And Landcover Map Of The Valpelline Corridor

With Flood And Avalanche Overlay

Legend

Flood	
HPH	
MPH	
LPH	
Avalanche Hazard	
V1 Very high	
Va Exposed Path	
Vb Probable Runout Footprint	
V2 Medium Hazard Zone	
V3 Low Hazard Zone	
SMRS	
Land Cover	
Urban & Built-up Area	
Pastures & Meadows	
Forests & Shrublands	
Bare Rock & Alpine Tundra	
Glaciers & Permanent Snow	
Rivers & Lakes	
Roads & Streets	

Reference System

WGS 84 / UTM zone 32N

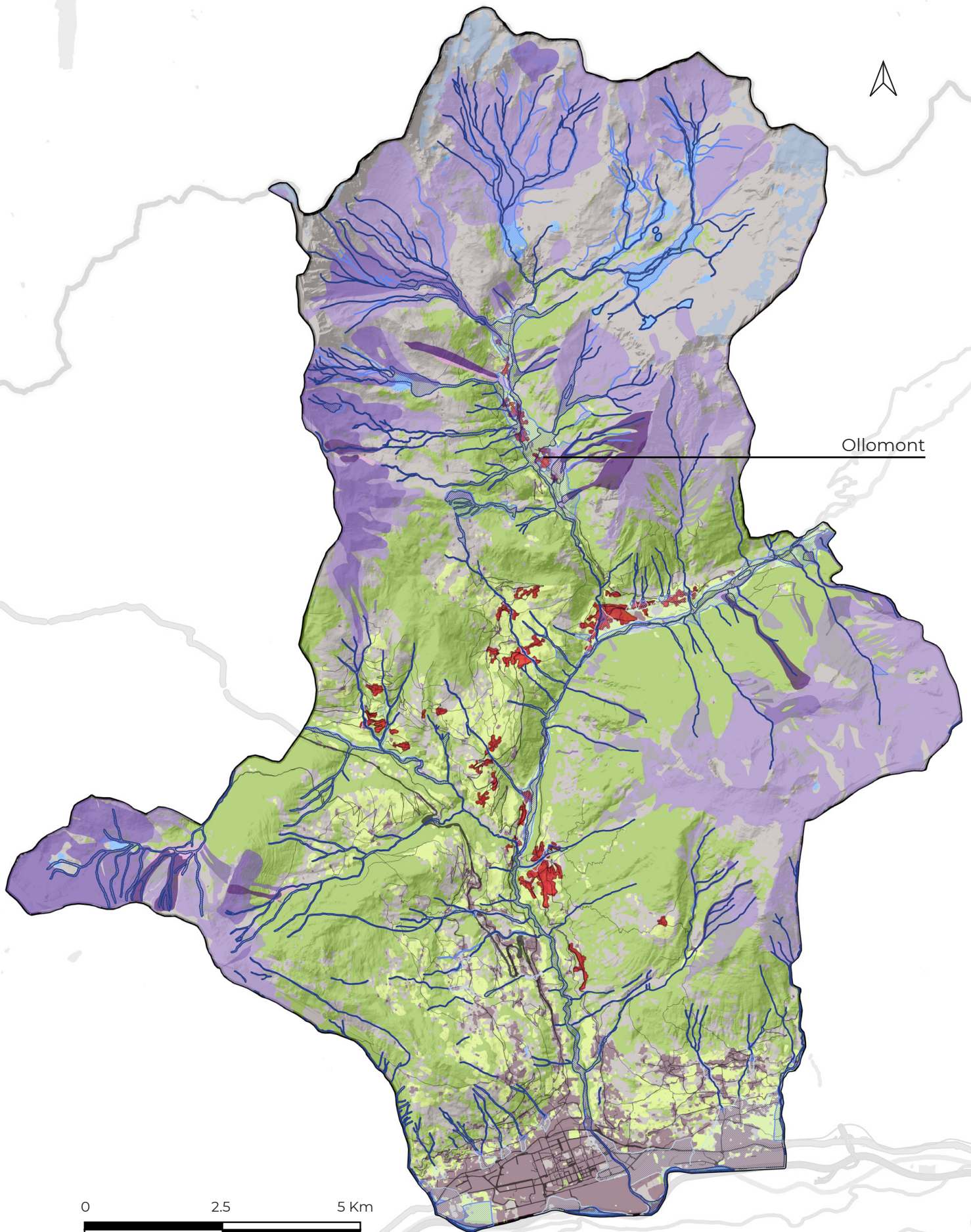
Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1:10000;

Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1:10000.



Ollomont

0 2.5 5 Km

C2. Landslide Hazard Map Of The Valpelline Corridor

Legend

SMRS



Landslide Hazard Zones

P4 Very High



P3 High



P2 Medium



Land Cover

Urban & Built-up Area



Rivers & Lakes



Roads & Streets



Reference System

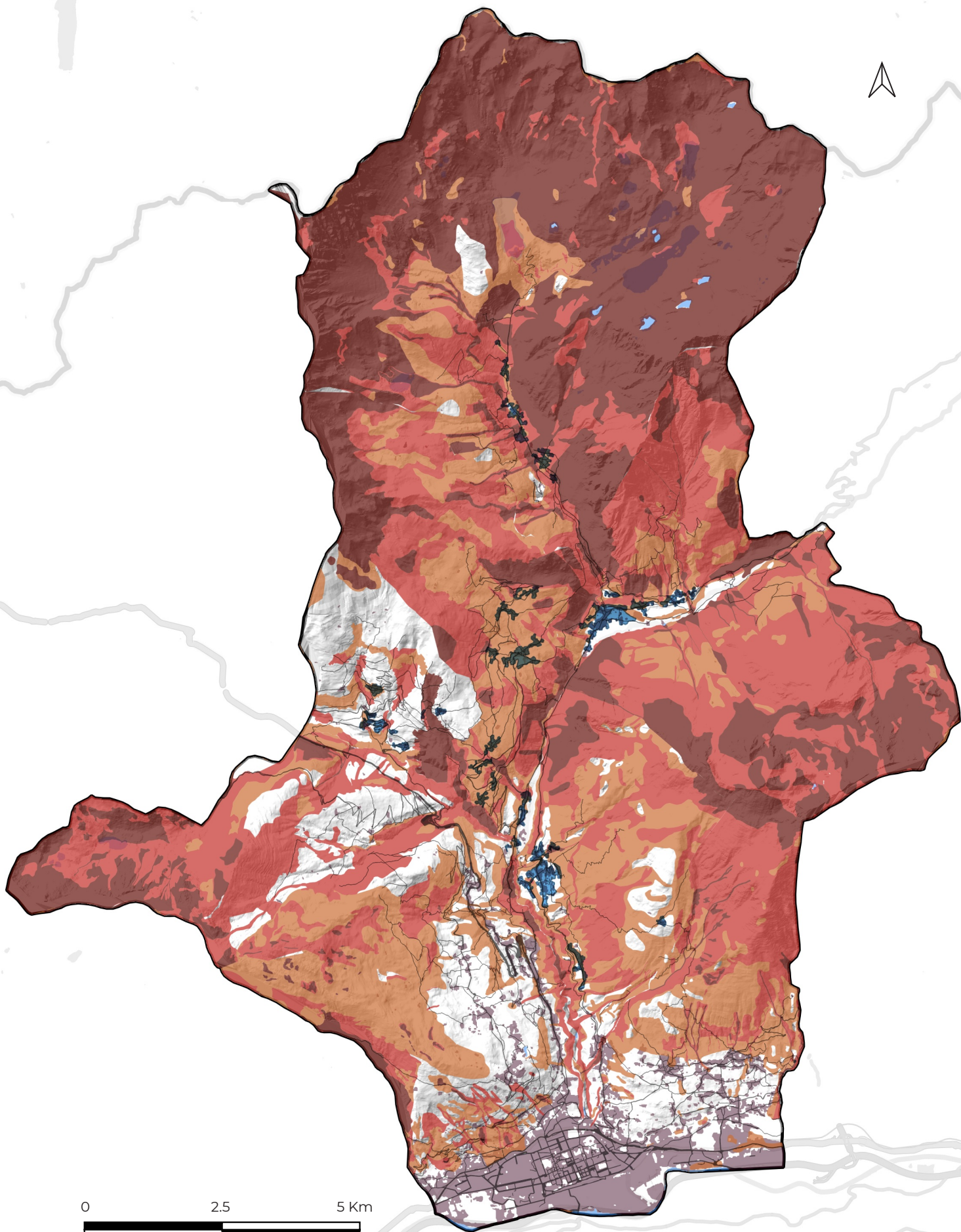
WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1:10000;



0 2.5 5 Km

C3. Slope Analysis Map Of The Valpelline Corridor

And SMRS Intersection

Legend

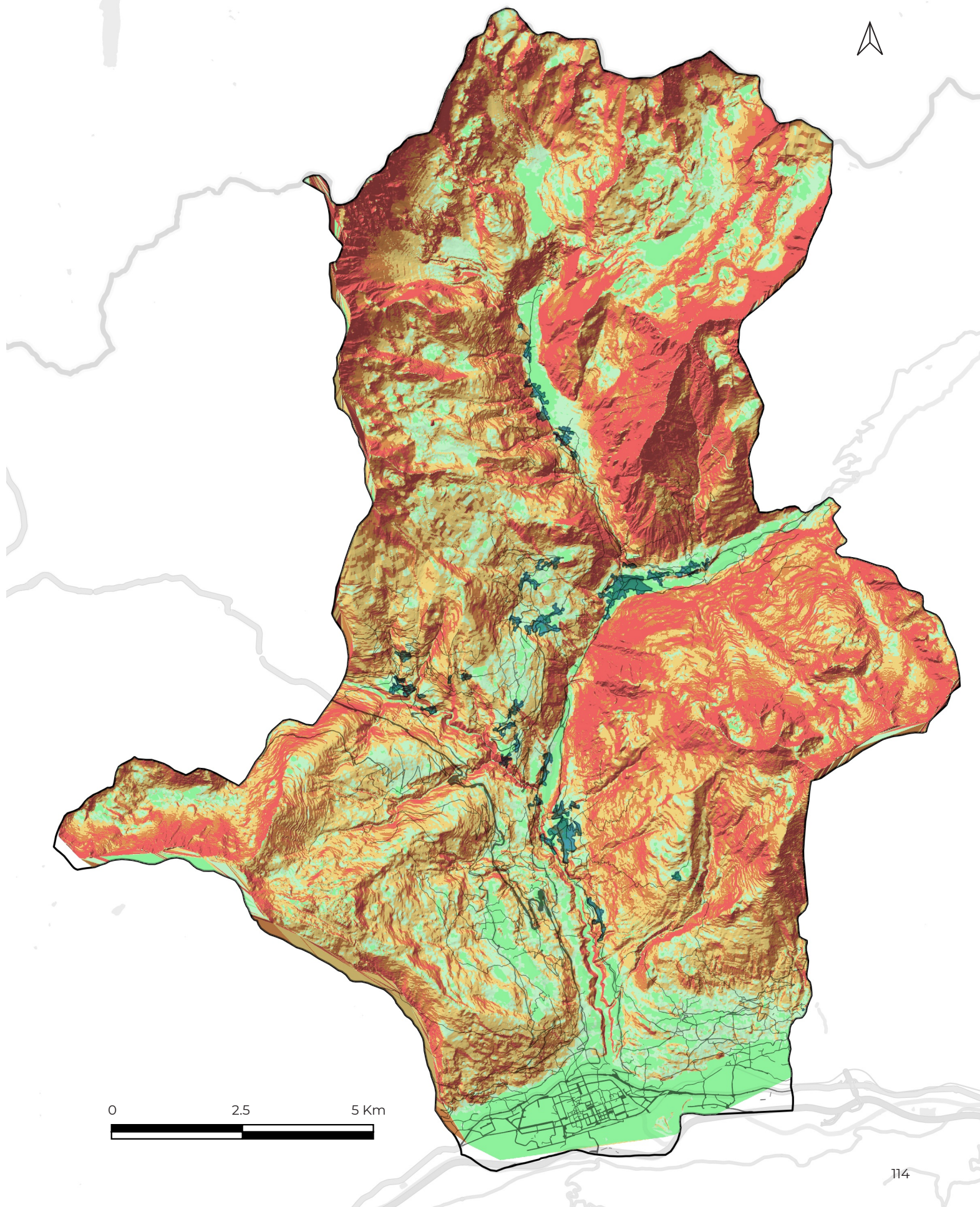
SMRS	
Roads & Streets	
Slope Analysis	
<= 9°	
9° - 17°	
17° - 27°	
27° - 35°	
> 35°	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0,
Scale: 1:10000;



C4. Accessibility Fragility Map Of The Valpelline Corridor

And SMRS Intersection

Legend

SMRS Accessibility Assessment

Access Blockage due to 3 Hazard

Access Blockage due to 2 Hazards

Access Blockage due to 1 Hazards

Not Exposed to Access Blockage



Road Accessibility Classification

Road & Streets Not Exposed to Hazards

Road Blockage due to Avalanche

Road Blockage due to Flooding

Road Blockage due to Landslide



Reference System

WGS 84 / UTM zone 32N

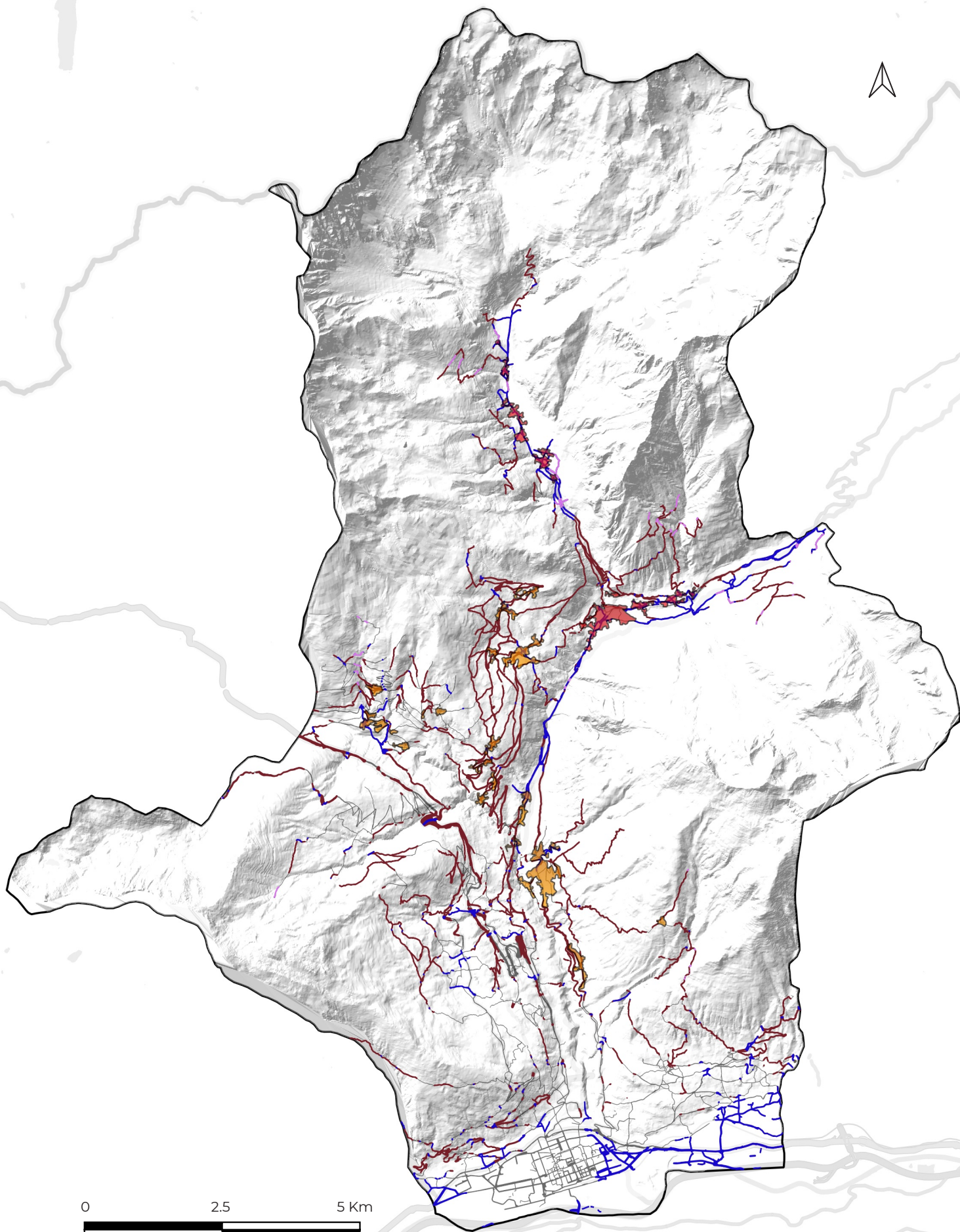
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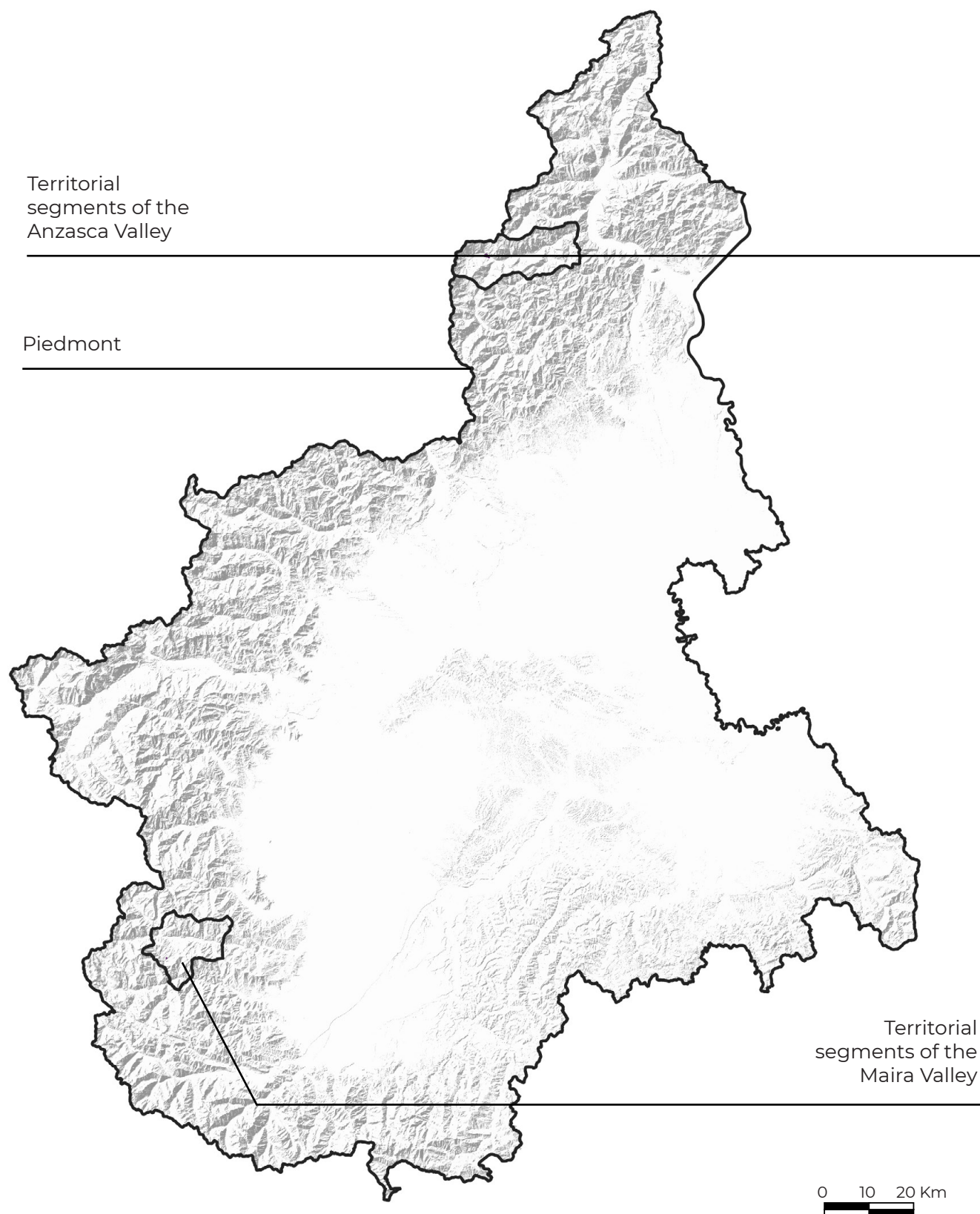
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

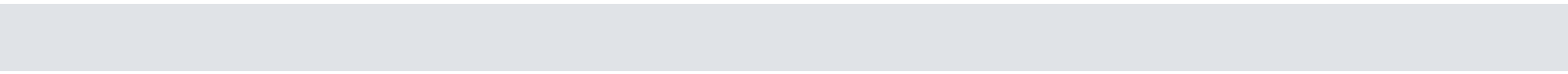
Regione Autonoma Valle d'Aosta (Catasto Regionale Valanghe),
CC BY 4.0, Scale: 1:10000;

Repertorio cartografico SCT (Carta delle Localizzazioni Probabili
delle Valanghe), Scale: 1:10000.

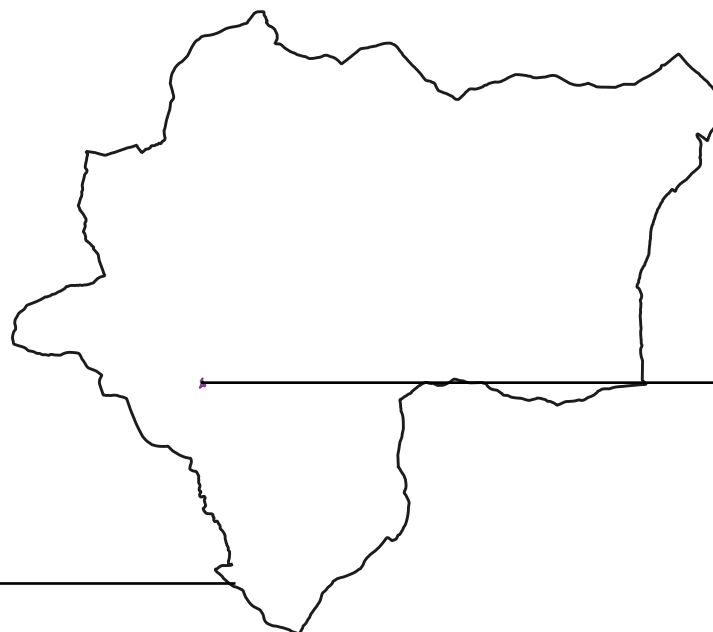


Anzasca And Maira Valley, Macugnaga And Elva Location





Macugnaga



Elva

C5. Hazard And Landcover Map Of The Anzasca Valley

With Flood And Avalanche Overlay

Legend

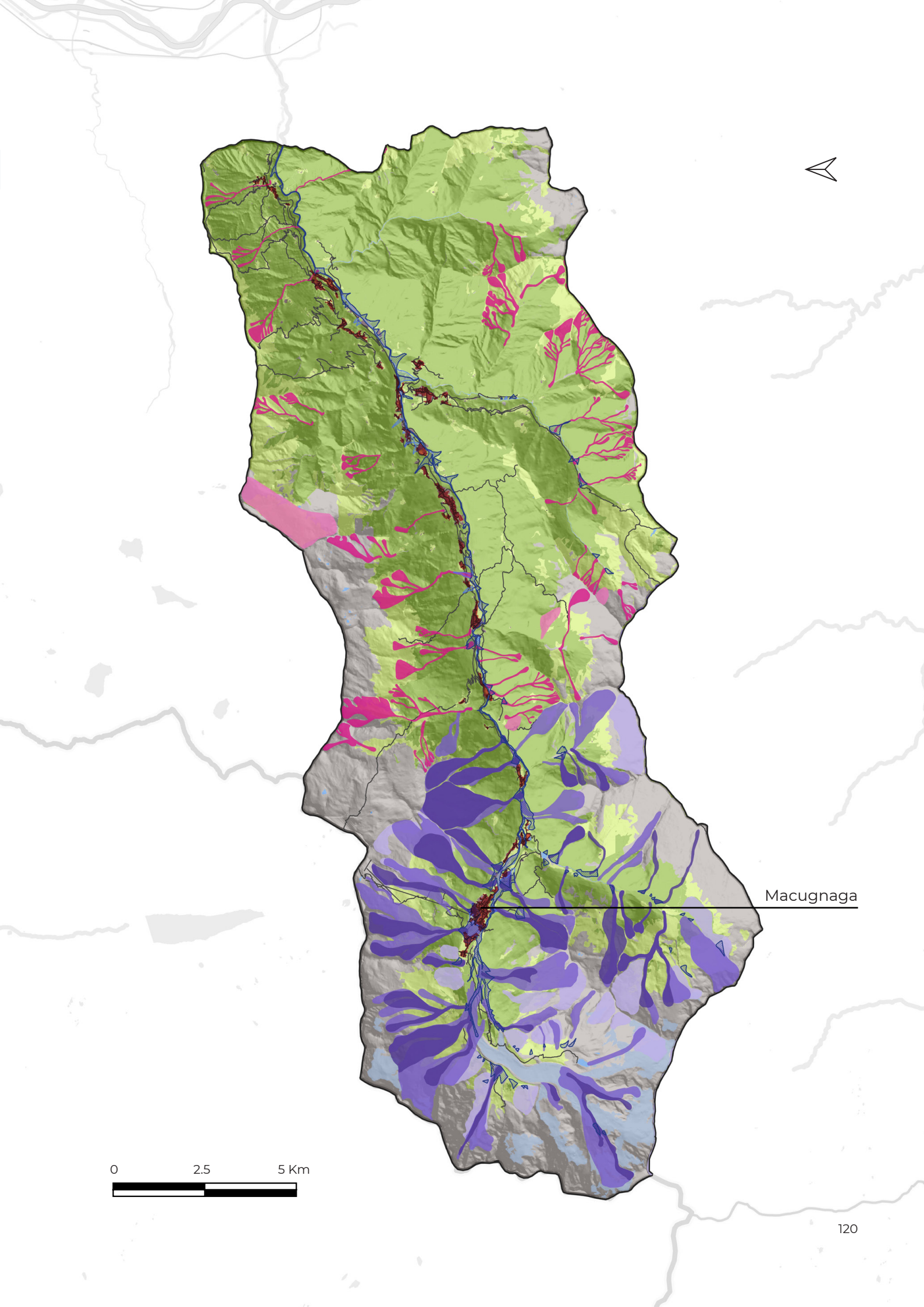
Flood	
HPH	
MPH	
LPH	
Geomorphological Avalanche Hazard Zones	
Historical Photo-Interpreted Footprints	
Morphological Terrain Susceptibility	
Geomorphological Danger Perimeters	
Administrative Avalanche Hazard Zones	
PRGC Regulatory Avalanche Paths	
PRGC Municipal Hazard Zoning	
SMRS	
Land Cover	
Urban & Built-up Area	
Pastures & Meadows	
Forests & Shrublands	
Bare Rock & Alpine Tundra	
Glaciers & Permanent Snow	
Rivers & Lakes	
Roads & Streets	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021/v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
ARPA Piemonte (Banca dati valanghe), Scale: 1:25000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000;
Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000.



Macugnaga

0 2.5 5 Km

C6. Landslide Hazard Map Of The Anzasca Valley

Legend

SMRS



Landslide Hazard Zones

P4 Very High



P3 High



P2 Medium



Land Cover

Glaciers & Permanent Snow



Rivers & Lakes



Roads & Streets



Reference System

WGS 84 / UTM zone 32N

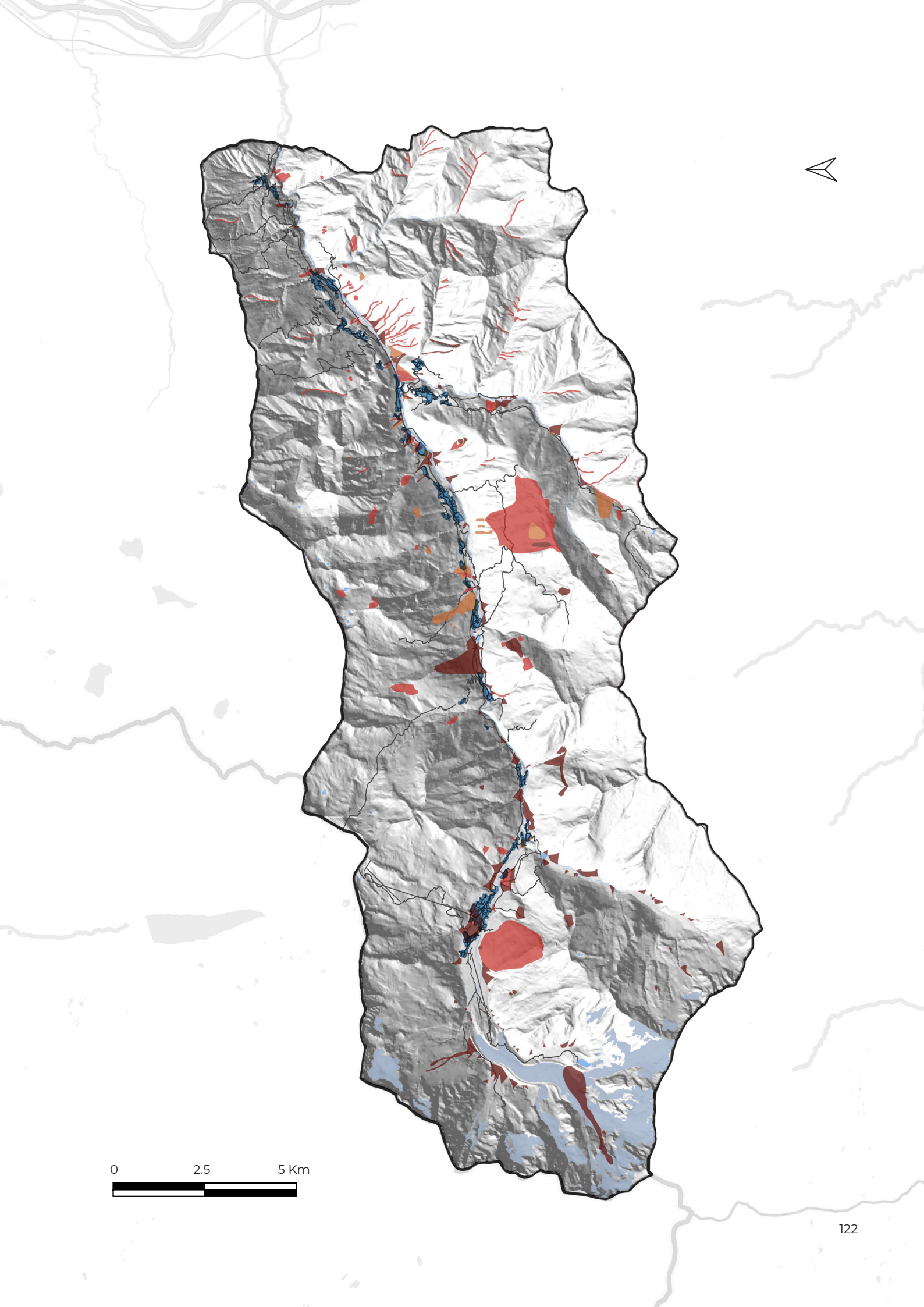
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ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;

Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

C7. Slope Analysis Map Of The Anzasca Valley

And SMRS Intersection

Legend

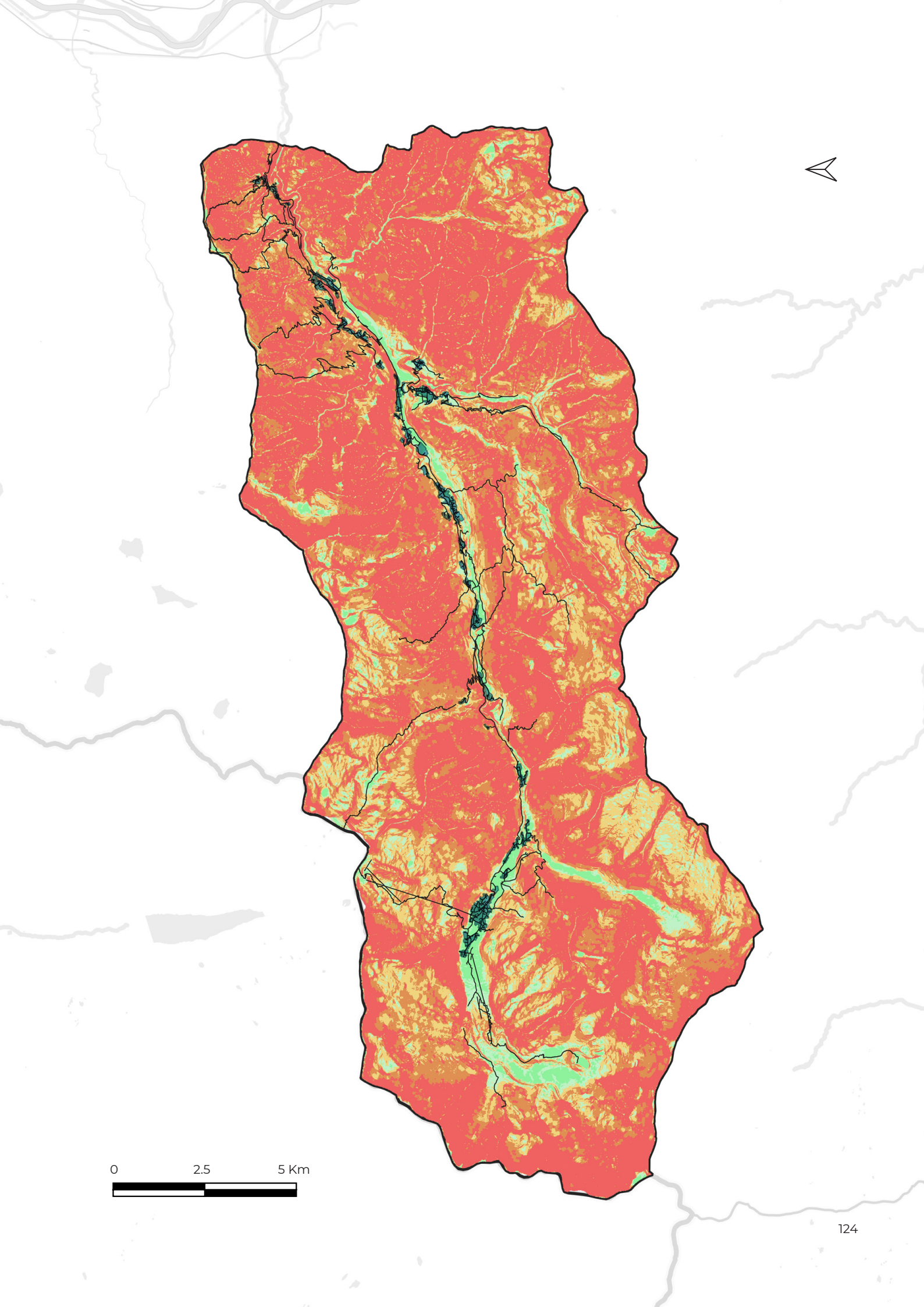
SMRS	
Roads & Streets	
Slope Analysis	
<= 9°	
9° - 17°	
17° - 27°	
27° - 35°	
> 35°	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

C8. Accessibility Fragility Map Of The Anzasca Valley

And SMRS Intersection

Legend

SMRS Accessibility Assessment

Access Blockage due to 3 Hazard



Access Blockage due to 2 Hazards



Access Blockage due to 1 Hazards



Not Exposed to Access Blockage



Road Accessibility Classification

Road & Streets Not Exposed to Hazards

Road Blockage due to Avalanche



Road Blockage due to Flooding



Road Blockage due to Landslide



Reference System

WGS 84 / UTM zone 32N

Data Source:

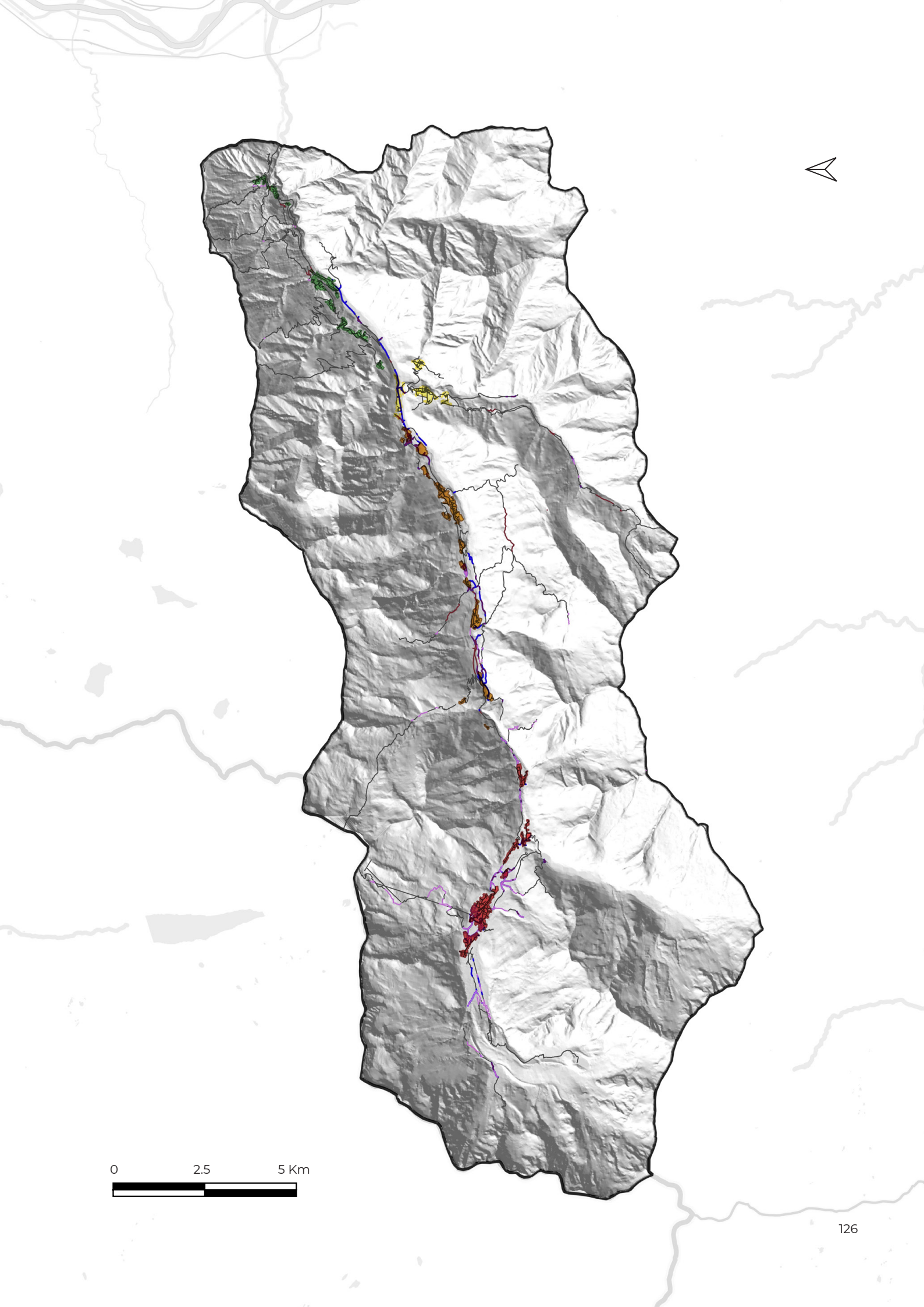
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISPRA IdroGEO (v4.0 2021/v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

ARPA Piemonte (Banca dati valanghe), Scale: 1:25000;

Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;

Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

C9. Hazard And Landcover Map Of The Maira Valley

With Flood And Avalanche Overlay

Legend

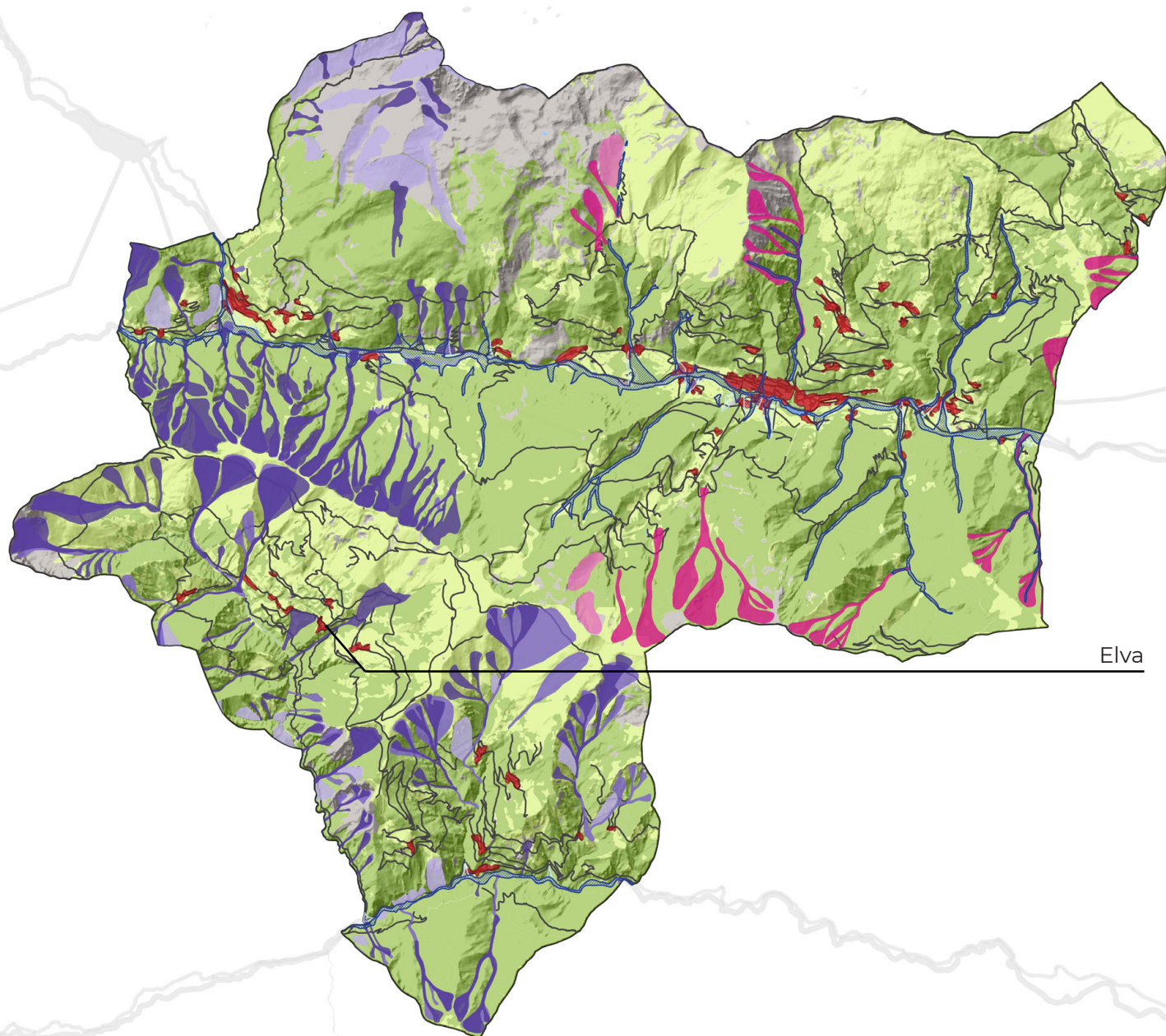
Flood	
HPH	
MPH	
LPH	
Geomorphological Avalanche Hazard Zones	
Historical Photo-Interpreted Footprints	
Morphological Terrain Susceptibility	
Geomorphological Danger Perimeters	
Administrative Avalanche Hazard Zones	
PRGC Regulatory Avalanche Paths	
PRGC Municipal Hazard Zoning	
SMRS	
Land Cover	
Urban & Built-up Area	
Pastures & Meadows	
Forests & Shrublands	
Bare Rock & Alpine Tundra	
Glaciers & Permanent Snow	
Rivers & Lakes	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
ARPA Piemonte (Banca dati valanghe), Scale: 1:25000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000;
Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000.



Elva

0 2.5 5 Km

C10. Landslide Hazard Map Of The Maira Valley

Legend

SMRS



Landslide Hazard Zones

P4 Very High



P3 High



P2 Medium



Land Cover

Rivers & Lakes



Roads & Streets



Reference System

WGS 84 / UTM zone 32N

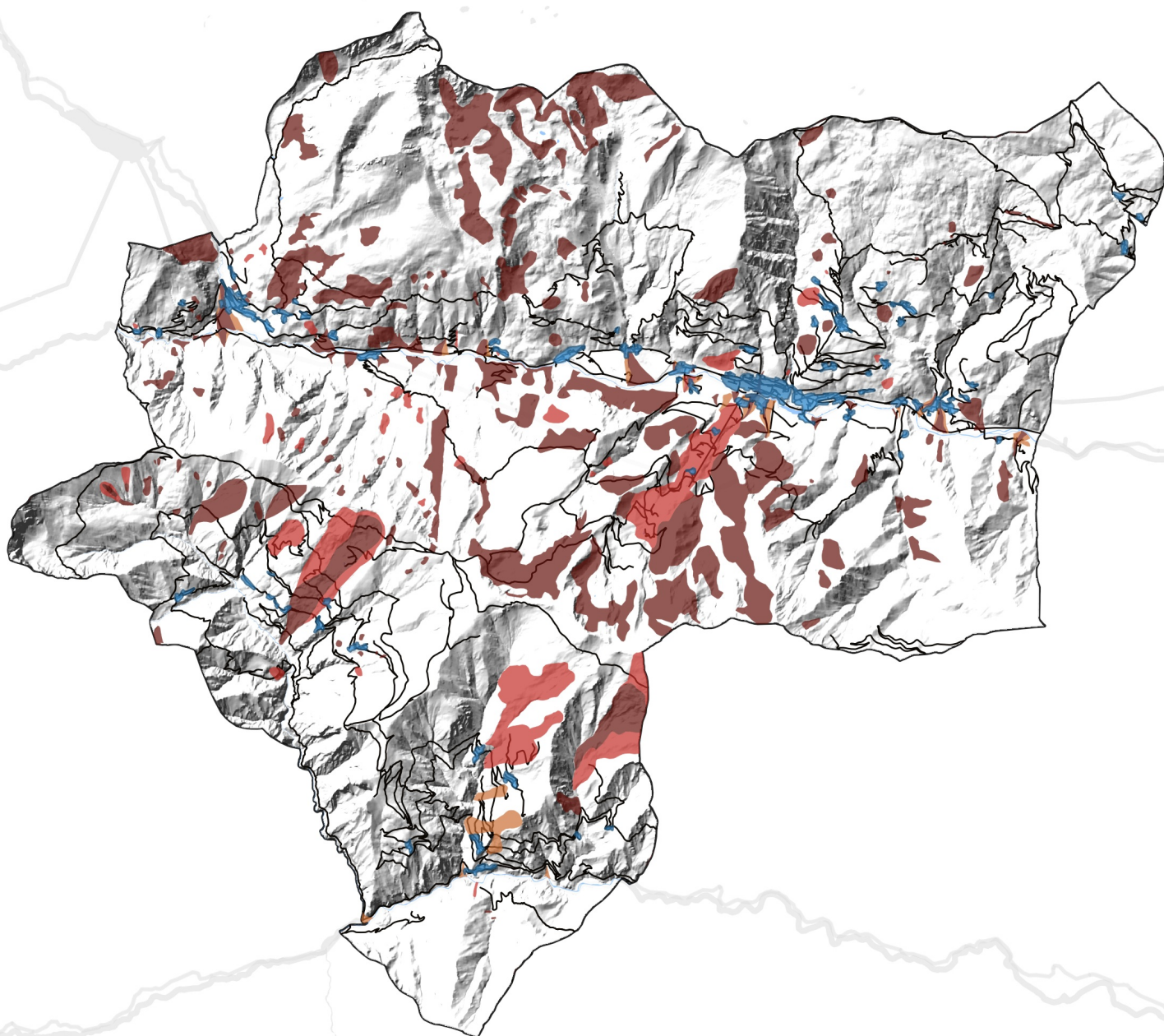
Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;

Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

A horizontal scale bar with three segments. The first segment is labeled '0', the second '2.5', and the third '5 Km'. The bar is black with white text.

C11. Slope Analysis Map Of The Maira Valley

And SMRS Intersection

Legend

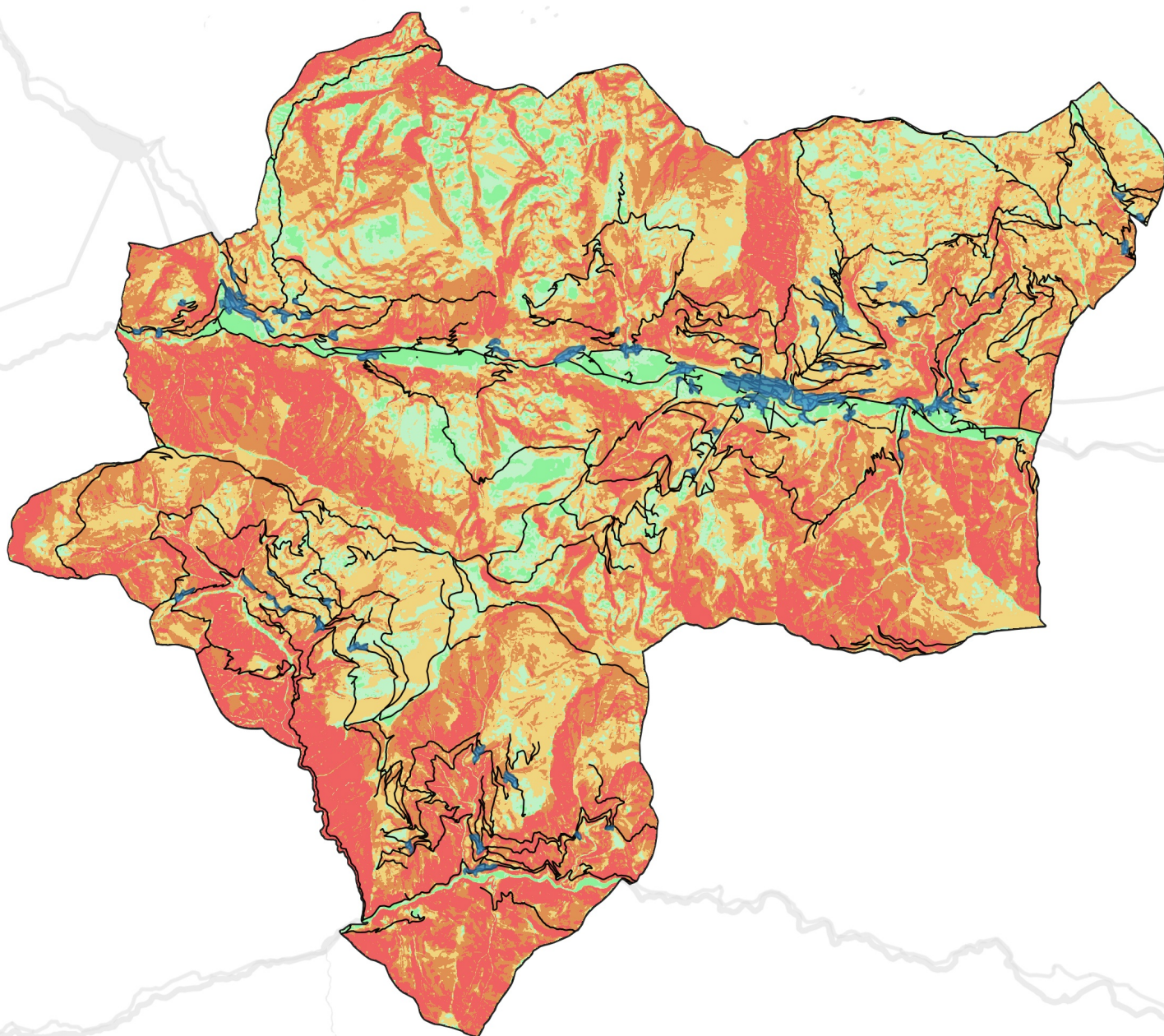
SMRS	
Roads & Streets	
Slope Analysis	
<= 9°	
9° - 17°	
17° - 27°	
27° - 35°	
> 35°	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

C12. Accessibility Fragility Map Of The Maira Valley

And SMRS Intersection

Legend

SMRS Accessibility Assessment

Access Blockage due to 3 Hazard



Access Blockage due to 2 Hazards



Access Blockage due to 1 Hazards



Not Exposed to Access Blockage



Road Accessibility Classification

Road & Streets Not Exposed to Hazards



Road Blockage due to Avalanche



Road Blockage due to Flooding



Road Blockage due to Landslide



Reference System

WGS 84 / UTM zone 32N

Data Source:

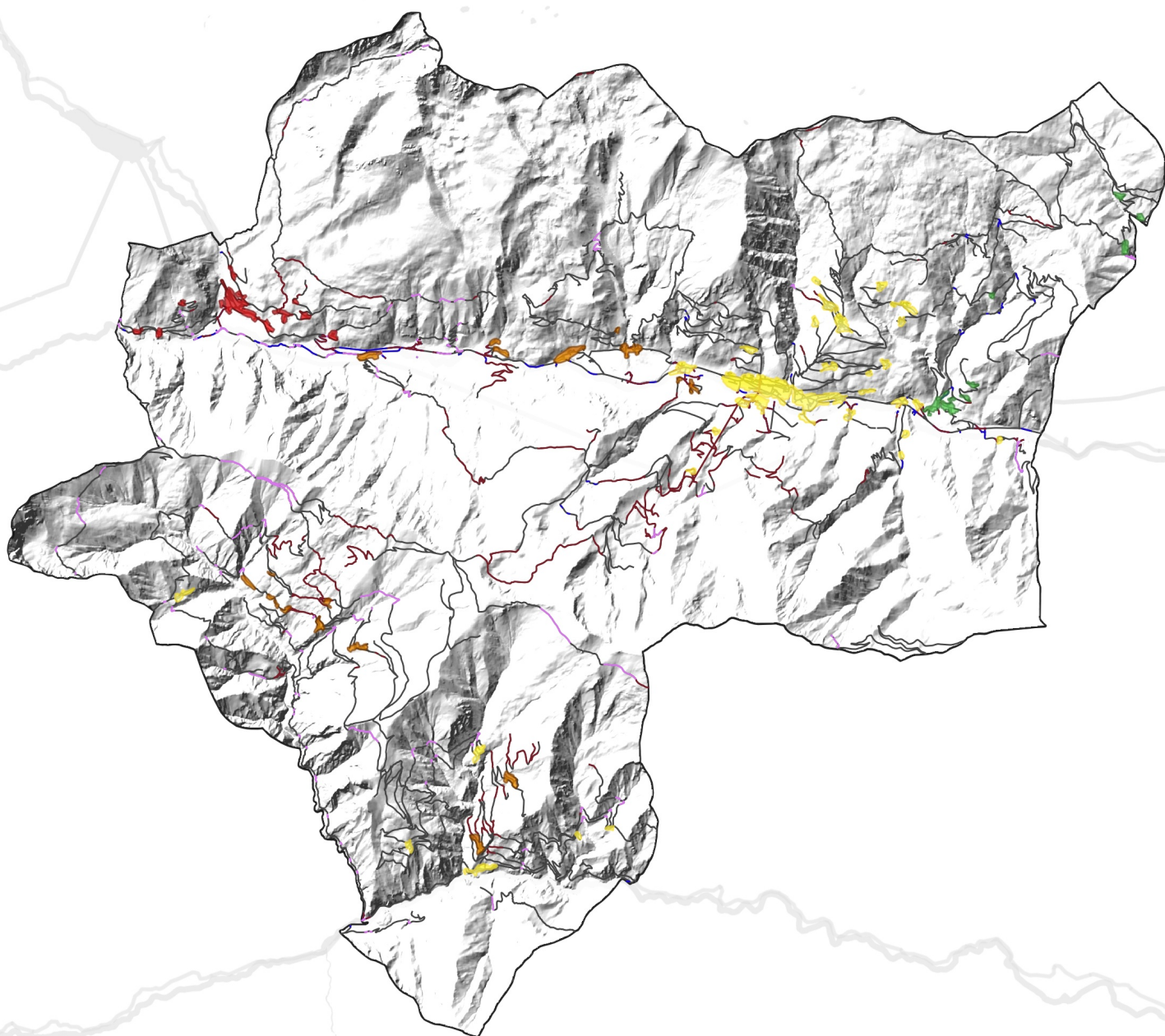
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;

ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;

ARPA Piemonte (Banca dati valanghe), Scale: 1:25000;

Geoportale Piemonte (Curva 10), CC BY 4.0, Scale: 1:10000;

Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000.



0 2.5 5 Km

5.4 Territorial Scale

5.4.5 Technical Metadata and Processing Workflow

Table 17 provides a comprehensive operational summary of the spatial layers, datasets, and specific geoprocessing transformations executed to generate the territorial-scale maps.

Layer Name	Source & Coordinate System	Type & Scale	QGIS Operations	Role
Settlements	Derived from national scale model, (EPSG:32632).	Shape file/ Vector Polygon converted to Point Centroid, 1:5.000	1. Filter to territorial boundaries. 2. Isolation analysis. 3. classification based on Road Blockage due to Hazard Count	Operational spatial footprint for Road Blockage due to hazard classification.
Flood Hazard Layers (HPH, MPH, LPH)	Derived from regional scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:5000	1. Spatial clip to study regions. 2. Spatial intersection with road networks.	Identification of flood hazard zones and how they intersect with road networks.
Landslide Hazard Layer	Derived from regional scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:5000	1. Spatial clip to study regions. 2. Spatial intersection with road networks.	Identification of landslide hazard zones and how they intersect with road networks.
Avalanche Hazard Layers Piedmont (PIE layers)	Derived from regional scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:25000	1. Spatial clip to study regions. 2. Spatial intersection with road networks.	Identification of avalanche hazard zones in Piedmont and how they intersect with road networks.
Avalanche Hazard Layer Aosta Valley	Derived from regional scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:10000	1. Spatial clip to study regions. 2. Spatial intersection with road networks.	Identification of avalanche hazard zones in Aosta Valley and how they intersect with road networks..
Roads and Streets Piedmont	Geoportale Piemonte (BDTRE via WFS), (EPSG:32632).	WFS to Shape file/ Vector Lines, 1:10000	1. WFS vector data extraction. 2. Topological geometry repair. 3. Spatial clip to study region.	Infrastructure exposure mapping and accessibility analysis in Piedmont.

Table 17. Territorial Scale Geoprocessing Workflow and Layer Metadata.
(Source: Author's elaboration)

5.4 Territorial Scale

5.4.5 Technical Metadata and Processing Workflow

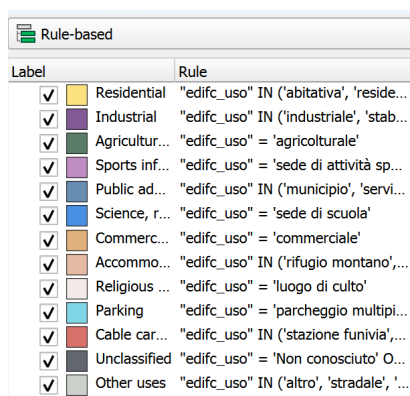
Roads and Streets Aosta Valley	Geoportale SCT Valle d'Aosta (Uso suolo strade 2024), (EPSG:23032).	Shape file/ Vector Polygon, 1: 10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to study region.	Infrastructure exposure mapping and accessibility analysis in Aosta Valley.
Landcover Piedmont	Geoportale Piemonte (BDTRE via WFS), (EPSG:32632).	WFS to Shape file/ Vector Lines, 1: 10000	1. WFS vector data extraction. 2. Topological geometry repair. 3. Spatial clip to study region. 4. Reclassification into 6 main categories.	Environmental baseline and surface roughness classification for Piedmont.
Landcover Aosta Valley	Geoportale SCT Valle d'Aosta (Uso suolo copertura), (EPSG:23032).	Shape file/ Vector Polygon, 1: 10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to study region. 4. Reclassification into 6 main categories.	Environmental baseline and surface roughness classification for Aosta Valley.
Contours (Curve 10) Piedmont	Geoportale Piemonte (BDTRE via WFS), (EPSG:32632).	Shape file/ Vector Lines to Raster TIF, 1:10000	1. WFS vector data extraction. 2. Topological geometry repair. 3. TIN Interpolation generation. 4. Derivation of analytical hillshade and slope. 5. Spatial clip to study area.	High-resolution terrain, slope, and aspect analysis for Piedmont.
Contours (Curve 10) Aosta Valley	Geoportale SCT Valle d'Aosta, (EPSG:23032).	Shape file/ Vector Lines to Raster TIF, 1: 10000	1. Reprojection to base CRS. 2. Spatial clip to study region. 3. TIN Interpolation generation. 4. Derivation of analytical hillshade and slope.	High-resolution terrain, slope, and aspect analysis for Aosta Valley.

5.5 Settlement Scale

The settlement scale represents the highest spatial resolution of the analytical framework, descending from valley-wide catchment diagnostics to individual building-unit exposure mapping. While the territorial scale identifies where hazard zones intersect the road network and land surface, this final scale asks a more precise question: which specific structures, within the fabric of each SMRS, are physically exposed to environmental risk, and to how many concurrent hazard types? Rather than aggregating exposure by zone, this analysis assigns discrete hazard intersection scores to each building footprint, producing a spatially explicit vulnerability inventory of the built environment.

The settlement-scale analysis is organized into a sequential series of map outputs. For Ollomont, four maps are produced: D1 intersects the building stock with flood and avalanche hazards, D2 combines landslide exposure with micro-topographic aspect flow vectors, D3 introduces the debris flow hazard layer as a supplementary output, and D4 synthesizes all results into a unified building hazard assessment. For Macugnaga and Elva, three maps are produced for each settlement following the same logic, with D5 and D8 corresponding to D1, D6 and D9 corresponding to D2, and D7 and D10 corresponding to D4. The debris flow layer is absent from the Piedmont case studies for reasons discussed in 5.5.3.

5.5.1 Building Footprint Vector Intersection



Label	Rule
☒ Residential	"edifc_uso" IN ('abitativa', 'reside...
☒ Industrial	"edifc_uso" IN ('industriale', 'stab...
☒ Agricultur...	"edifc_uso" = 'agricolturale'
☒ Sports inf...	"edifc_uso" = 'sede di attività sp...
☒ Public ad...	"edifc_uso" IN ('municipio', 'servi...
☒ Science, r...	"edifc_uso" = 'sede di scuola'
☒ Commerc...	"edifc_uso" = 'commerciale'
☒ Accommo...	"edifc_uso" IN ('rifugio montano', ...
☒ Religious ...	"edifc_uso" = 'luogo di culto'
☒ Parking	"edifc_uso" = 'parcheggio multipli...
☒ Cable car...	"edifc_uso" IN ('stazione funivia', ...
☒ Unclassified	"edifc_uso" = 'Non conosciuto' O...
☒ Other uses	"edifc_uso" IN ('altro', 'stradale', '...

Figure 12. QGIS rule-based categories for building stock functions.
(Source: Author's elaboration)

Building geometry and functional classification are derived from two distinct regional sources, reflecting the administrative data structure of each case study. For Ollomont, building footprints are extracted from the 'uso suolo fabbricato' layer of the Geoportale SCT Valle d'Aosta, which classifies each structure through an alphanumeric typology encoding functional use at cadastral resolution. For Macugnaga and Elva, the footprints and functional classification are sourced from the edificio layer (v_edifc) of the BDTRE (Base Dati Territoriale di Riferimento degli Enti), accessed through the Geoportale Piemonte municipal GeoPackage downloads. The BDTRE encodes functional destination through the edifc_uso attribute field, which provides a named categorical classification for each structure. To ensure cross-case comparability, a harmonized legend is applied across all three settlements, grouping building types into shared categories including Residential, Agricultural Infrastructure, Commercial Services, Public Administration, Accommodation and Catering Services, Religious Services, Sports Infrastructure, and Unclassified, which are detailed in Figure 12. Where the source dataset provides greater

5.5 Settlement Scale

5.5.1 Building Footprint Vector Intersection

typological granularity than the harmonized baseline, additional categories are retained rather than collapsed, preserving the full informational content of the richer dataset. For Macugnaga specifically, the BDTRE edifc_uso classification reveals building typologies specific to the tourism and industrial economy of the Anzasca Valley, including Cable Car and Ski Infrastructure. Former mining infrastructure is documented separately in both Ollomont and Macugnaga through dedicated mining asset layers, reflecting the shared but institutionally distinct mining heritage of the two valleys, and is treated as a parallel asset class in the hazard intersection analysis.

5.5.2 Flood and Avalanche Hazard Intersection

Maps D1, D5, and D8 intersect the building stock simultaneously with flood probability zones and avalanche hazard datasets, combining the two principal hydraulic and gravitational snow hazards into a single cartographic output. Flood inputs are consistent across all three case studies, derived from the ISPRA IdroGEO hydraulic hazard mosaic and structured into high, medium, and low probability zones (HPH, MPH, LPH) as established at the regional scale.

The avalanche datasets, however, differ substantially between the two regional administrative frameworks and require separate methodological treatment. For the Ollomont catchment in Valle d'Aosta, avalanche hazard zones follow the standardized regional classification system organized into five categories: V1 Very High, Va Exposed Path, Vb Probable Runout Footprint, V2 Medium Hazard Zone, and V3 Low Hazard Zone. These zones are derived from the regional hazard mapping program and carry direct regulatory force under Valle d'Aosta land use planning law. For the Macugnaga and Elva catchments in Piedmont, the avalanche input is sourced from the ARPA Piemonte Banca dati valanghe, a dedicated regional avalanche database that encodes hazard information through two structurally distinct layer types. The first, geomorphological hazard zones, captures the physical evidence of past avalanche activity through three sub-categories: Historical Photo-Interpreted Footprints, representing documented runout extents derived from aerial photograph interpretation; Morphological Terrain Susceptibility zones, identifying terrain units with favorable morphological conditions for avalanche release; and Geomorphological Danger Perimeters, delineating the outer boundary of geomorphologically active avalanche terrain. The second layer type, administrative hazard zones, translates this physical evidence into regulatory instruments through PRGC Regulatory Avalanche Paths, formally designated corridors embedded in

5.5 Settlement Scale

5.5.2 Flood and Avalanche Hazard Intersection

municipal land use plans (Piano Regolatore Generale Comunale), and PRGC Municipal Hazard Zoning, which encodes the legally binding hazard classification adopted at the municipal planning scale. This dual-layer structure, combining empirical geomorphological evidence with its regulatory translation, reflects a more institutionally layered approach to avalanche governance than the unified zonal classification used in Valle d'Aosta, and both dimensions are retained in the settlement-scale intersection to preserve the full institutional meaning of the Piedmont dataset.

5.5.3 Landslide Hazard and Aspect Vector Mapping

Maps D2, D6, and D9 combine landslide hazard polygon intersections with a micro-topographic aspect flow visualization, allowing the reader to see not only which buildings fall inside classified landslide zones but also the precise downhill direction and relative surface flow intensity acting on the terrain surrounding each structure. Landslide inputs are sourced from the regional PAI datasets as established at the territorial scale, structured into Medium (P2), High (P3), and Very High (P4) susceptibility categories in these two regions. The aspect and slope flow vectors are derived from the TIN-interpolated terrain model constructed at the territorial scale, trimmed to the settlement boundary and resampled to cadastral resolution. A uniform point sampling matrix is overlaid on the study area, centroids are extracted, and the Sample Raster Values tool appends terrain aspect in degrees and slope steepness onto each vector point. These points are rendered as directional arrow glyphs, with orientation driven by a data-defined rotation expression that forces each symbol to point downhill:

$\text{Glyph Rotation} = \text{coalesce}(\text{"A1"}, 0) + 180^\circ$

Arrow size is dynamically scaled to slope steepness, representing gravity-driven surface flow intensity visually:

$\text{Marker Size} = \text{coalesce}(\text{"slp_1"}, 0) \times 0.08$

The combined output makes visible where steep contributing slopes channelize water and debris directly into historical building walls, a spatial relationship that aggregate hazard polygons alone cannot communicate at this resolution. For the Ollomont case study, forest cover is retained in this layer to illustrate the vegetative buffering role of intact woodland between upslope source areas and the building fabric. Map D3 introduces an additional hazard dimension specific to the

5.5 Settlement Scale

5.5.3 Landslide Hazard and Aspect Vector Mapping

Ollomont catchment: the approved debris flow hazard polygons (DF1 High Hazard Area, DF2 Medium Hazard Area, DF3 Low Hazard Area) published by the Regione Autonoma Valle d'Aosta geoportal. These formally validated torrent and debris flow runout zones carry direct regulatory weight under regional land use planning law and represent a physically distinct hazard process, channelized torrent discharge transporting solid material, that is not captured by the diffuse slope instability encoded in the PAI landslide polygons. This layer is produced for Ollomont alone due to a structural data availability gap between the two regional administrations. The debris flow intersection methodology demonstrated here is nonetheless directly transferable to any settlement where equivalent certified datasets are available, and could equally be extended to other hazard process types, including higher-resolution landslide typology sub-classifications or rockfall runout extents, wherever regional geoportals publish the requisite data. The Ollomont output therefore functions both as a standalone analytical result and as a proof of concept for the scalability of this settlement-level intersection framework.

Forest and meadow cover polygons derived from the harmonized land cover dataset are retained in Map D3 to contextualize the interaction between debris flow runout zones and natural surface buffers.

5.5.4 Settlement-Scale Synthesis and Building Hazard Assessment

Maps D4, D7, and D10 consolidate all individual hazard intersection results into a unified structural exposure assessment for each case study settlement. A vector polygon intersection is executed between each building footprint layer and each hazard input. Each intersection appends a binary flag to the building attribute table recording confirmed geometric contact with that specific hazard type. A Hazard Count field is generated in the building attribute table via the QGIS Field Calculator, summing the binary hazard flags appended across all preceding intersection operations into a single integer score per footprint. Buildings are symbolized on a four-class scale from 'Not Exposed' through 'Exposed to 3 Hazards', producing a spatially explicit picture of cumulative multi-hazard exposure across the entire building stock. For the Ollomont catchment, the mine park footprints are assessed in parallel using the same scoring logic and displayed as a distinct symbol class, preserving their functional distinction from residential assets while ensuring that the hazard exposure of these repurposed heritage structures is formally documented alongside the inhabited building fabric.

Ollomont



Vouece



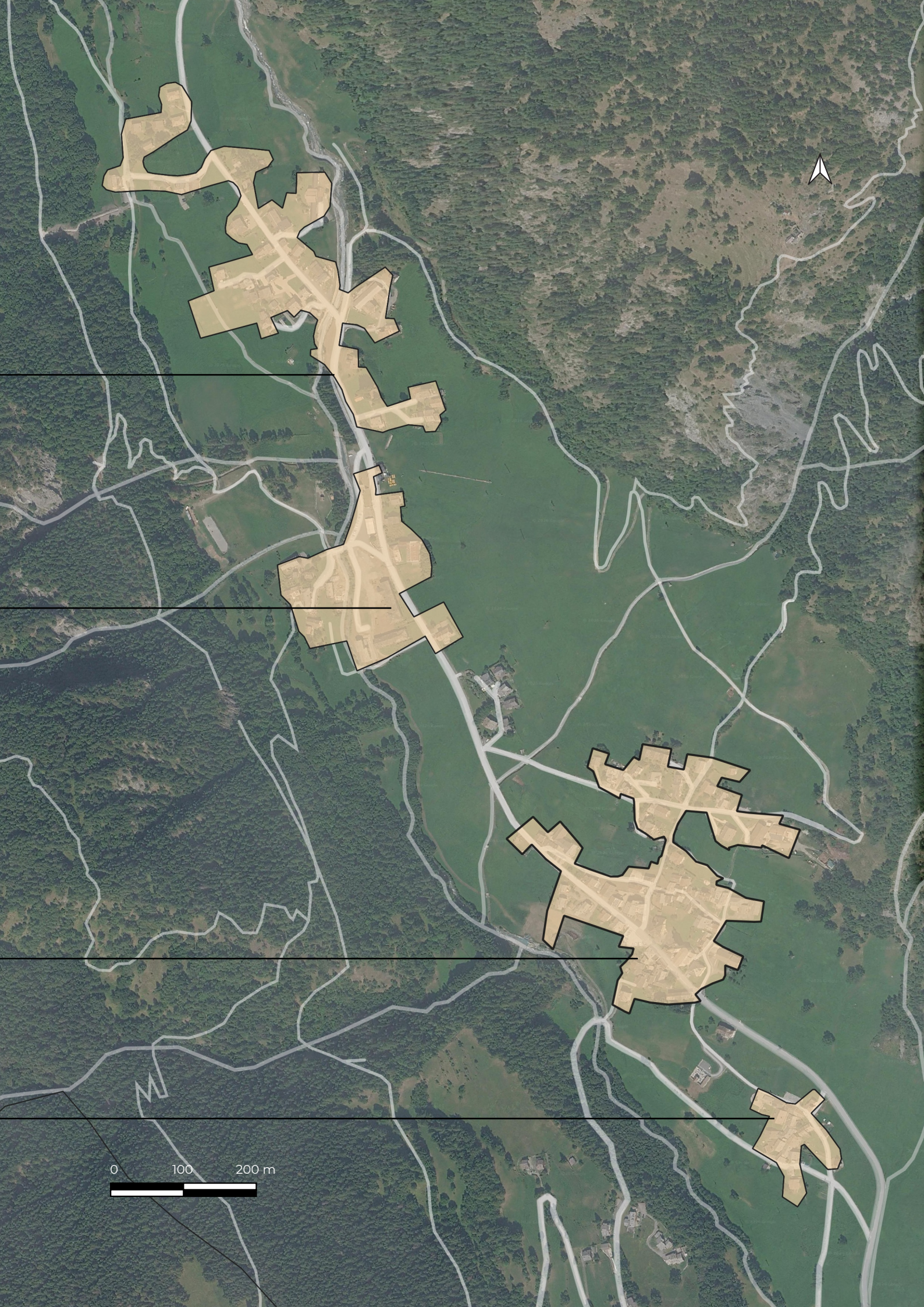
Le Morion



Ollomont

Clapey

Figure 13–15. Photographs of Ollomont village.
Photo credit: Fateme Sobhani.



0 100 200 m

D1. Settlement Scale Flood And Avalanche Map Of Ollomont

Spatial Intersection With Building Footprints

Legend

Flood	
HPH	
MPH	
LPH	
Avalanche Hazard	
V1 Very high	
Va Exposed Path	
Vb Probable Runout Footprint	
V2 Medium Hazard Zone	
V3 Low Hazard Zone	
SMRS	

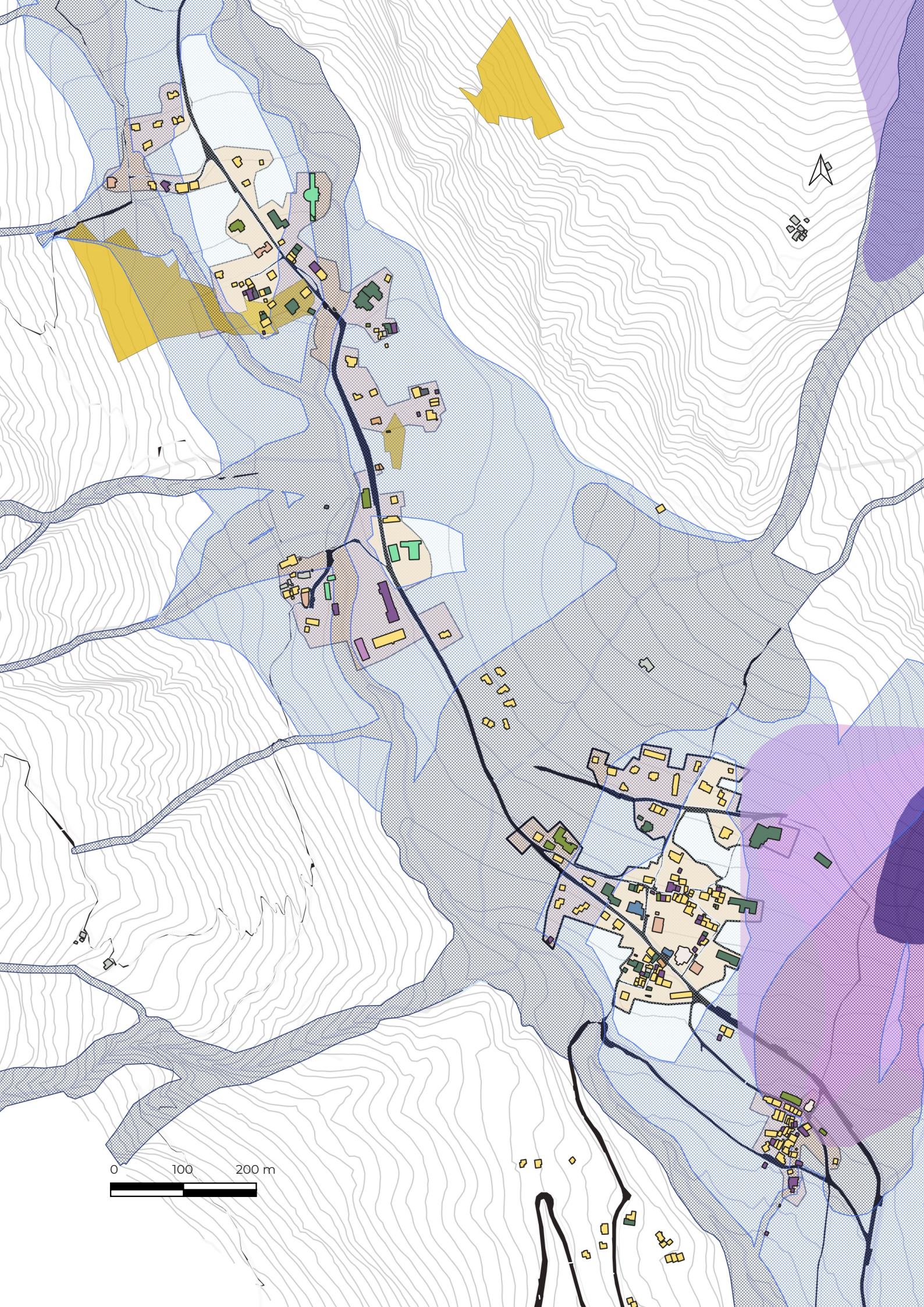
Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1: 10000;
Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1: 10000.

Building Stock by Functional Use	
Residential	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Health and social services	
Stables, outbuildings, sheds, and garages	
Unclassified	
Other uses	
Mines	
Roads & streets	



D2. Settlement Scale Landslide Hazard Map Of Ollomont

Spatial Intersection With Slope Flow and Building Footprints

Legend

Landslide Hazard Zones	
P4 Very High	
P3 High	
P2 Medium	
Slope Flow Direction & Severity	
SMRS	

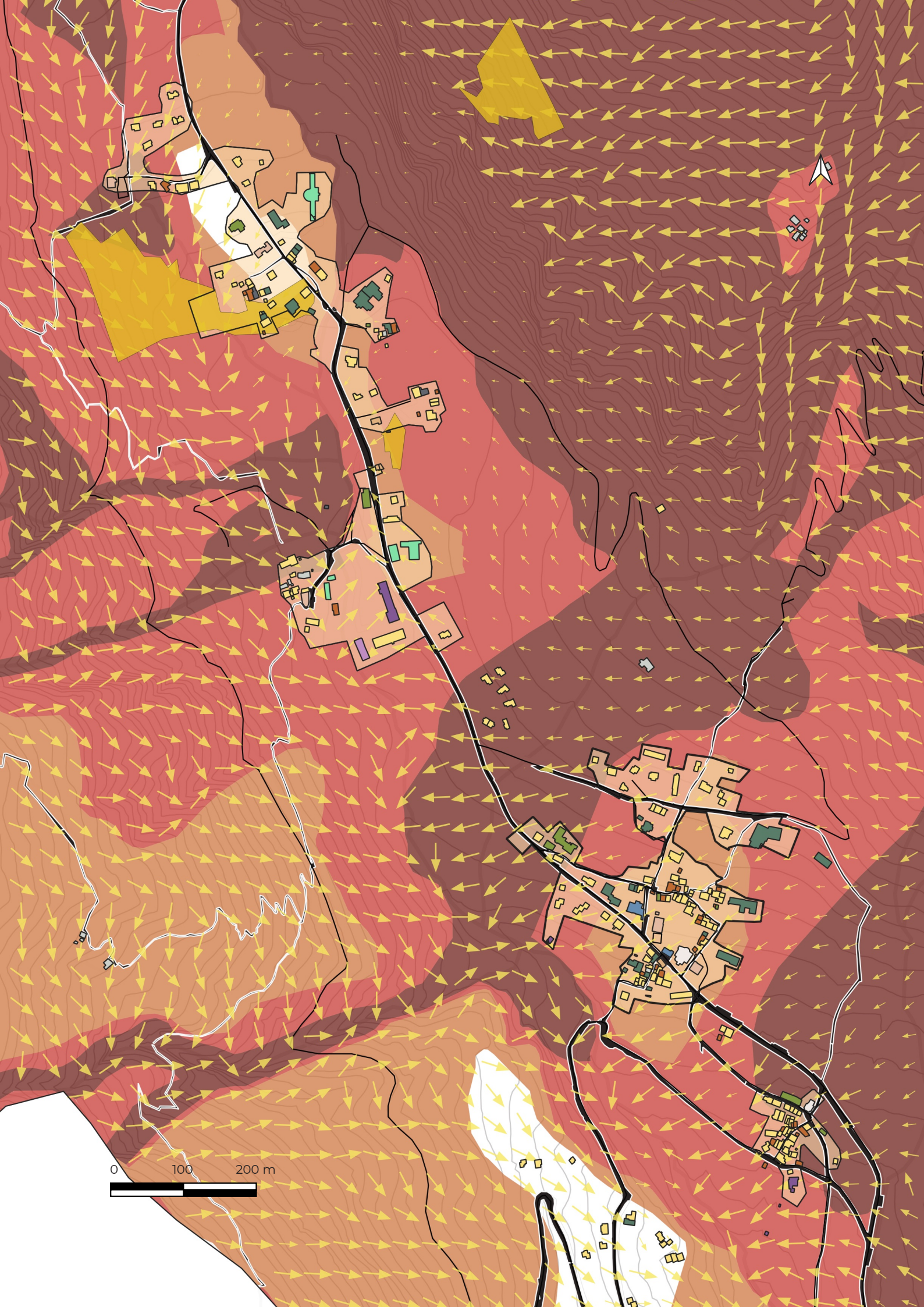
Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1: 10000;
Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1: 10000.

Building Stock by Functional Use	
Residential	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Health and social services	
Stables, outbuildings, sheds, and garages	
Unclassified	
Other uses	
Mines	
Roads & streets	



0 100 200 m

D3. Settlement Scale Debris Flow Hazard Map Of Ollomont

Spatial Intersection With Vegetative Cover and Building Footprints

Legend

Approved Debris Flow Zones	
DF1. High Hazard Area	
DF2. Medium Hazard Area	
DF3. Low Hazard Area	

SMRS	
------	-------------

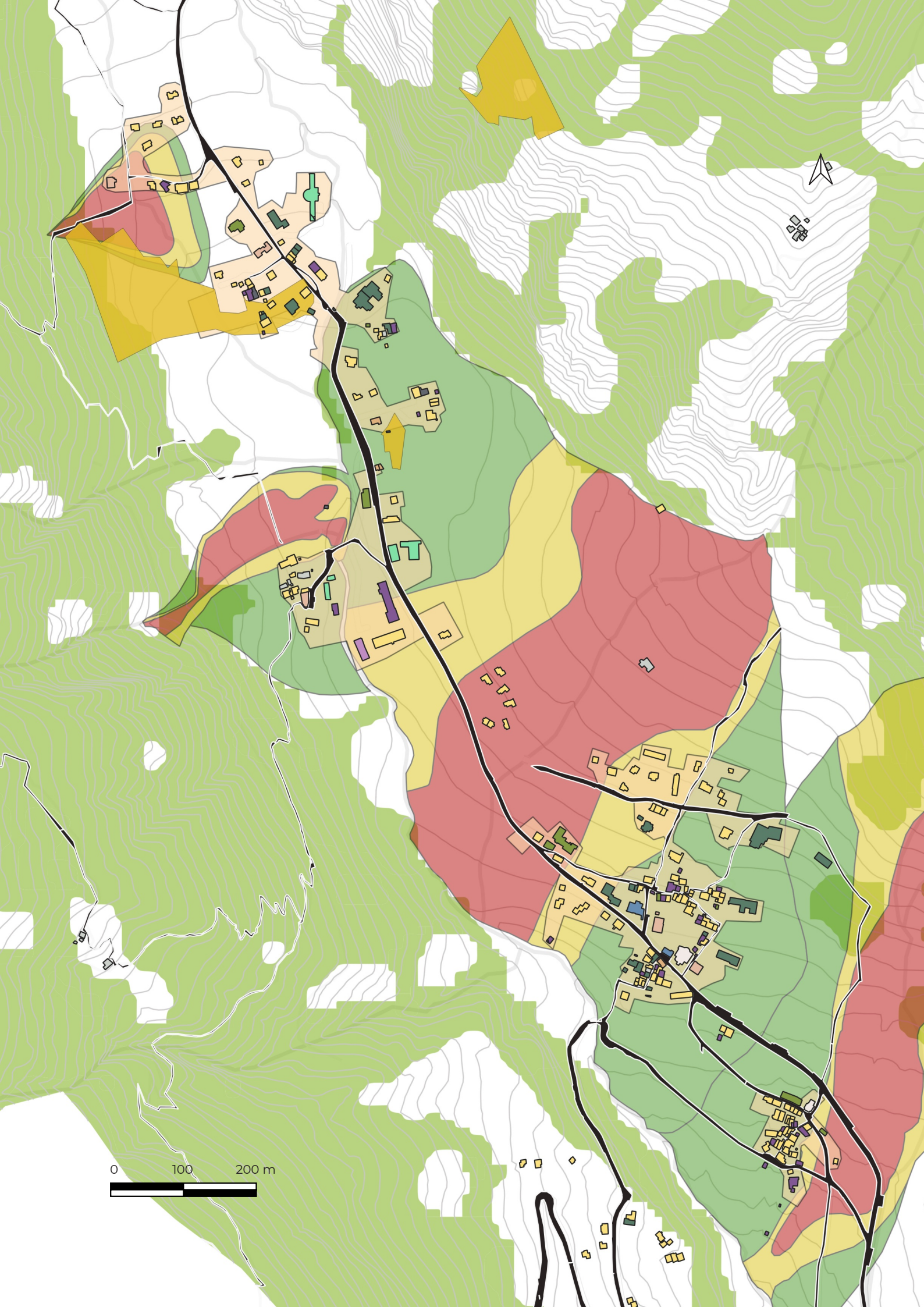
Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1: 10000;
Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1: 10000.

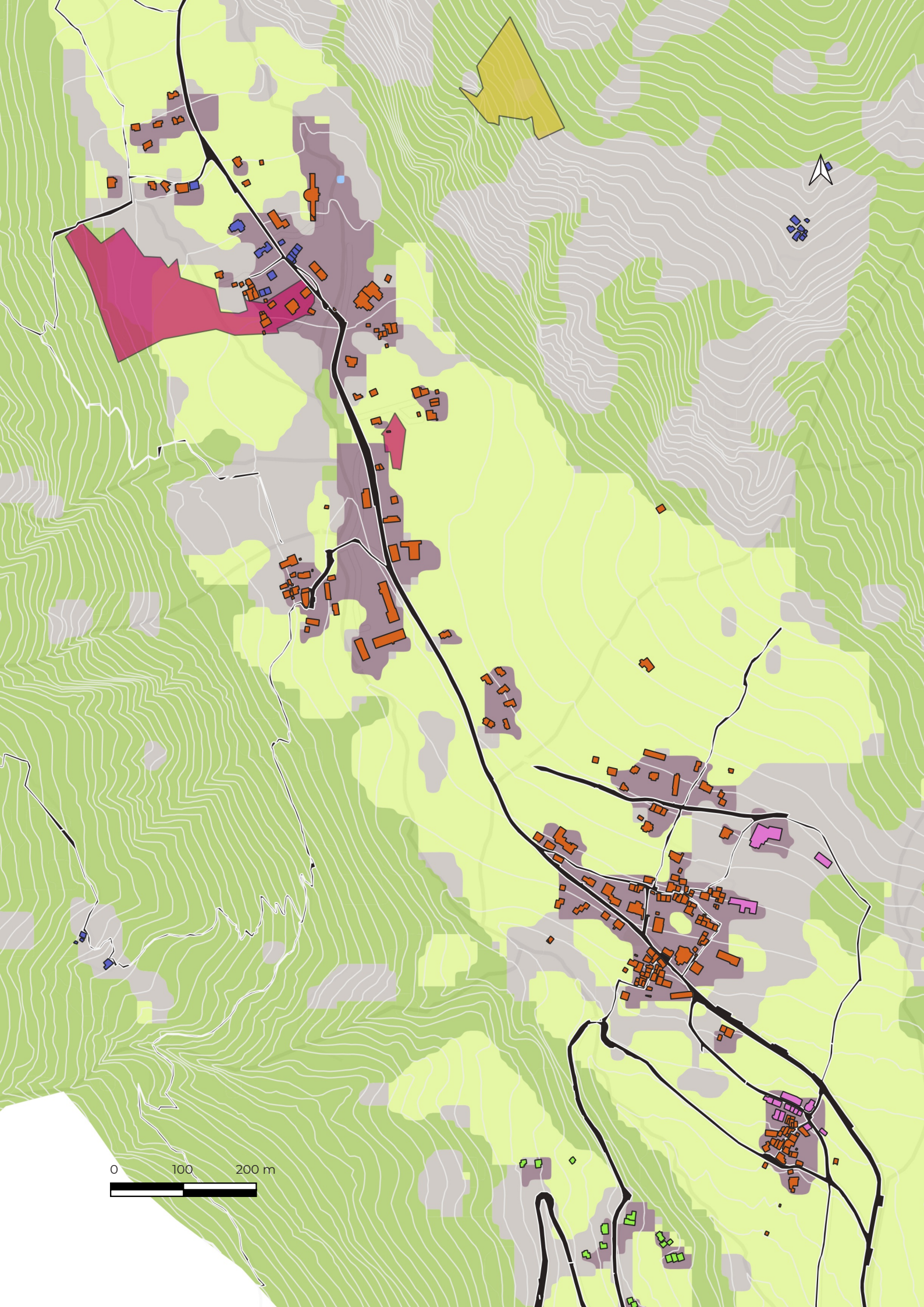
Building Stock by Functional Use	
Residential	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Health and social services	
Stables, outbuildings, sheds, and garages	
Unclassified	
Other uses	
Mines	
Roads & streets	
Forests & Shrublands	



D4. Settlement Scale Multi-Hazard Exposure Map Of Ollomont

Building Footprint Hazard Assessment

	Legend	
	Buildings Hazard Assessment	
	Exposed to 3 Hazard	
	Exposed to 2 Hazards	
	Exposed to 1 Hazards	
	Not Exposed	
Reference System		
WGS 84 / UTM zone 32N		
Data Source:	Mines Hazard Assessment	
	Exposed to 3 Hazards	
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;	Exposed to 2 Hazards	
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;	SMRS	
Regione Autonoma Valle d'Aosta (Catasto Regionale), CC BY 4.0, Scale: 1: 10000;	Land Cover	
Repertorio cartografico SCT (Carta delle Localizzazioni Probabili delle Valanghe), Scale: 1: 10000;.	Urban & Built-up Area	
	Pastures & Meadows	
	Forests & Shrublands	
	Bare Rock & Alpine Tundra	
	Rivers & Lakes	
	Roads & Streets	



Macugnaga



Centro Abitato Testa



Comune di Macugnaga
Staffa



Pecetto

Figure 16–18. Photographs of Macugnaga village.
Photo credit: Elisabetta Colucci.



0 100 200 m

D5. Settlement Scale Flood And Avalanche Map Of Macugnaga

Spatial Intersection With Building Footprints

Legend

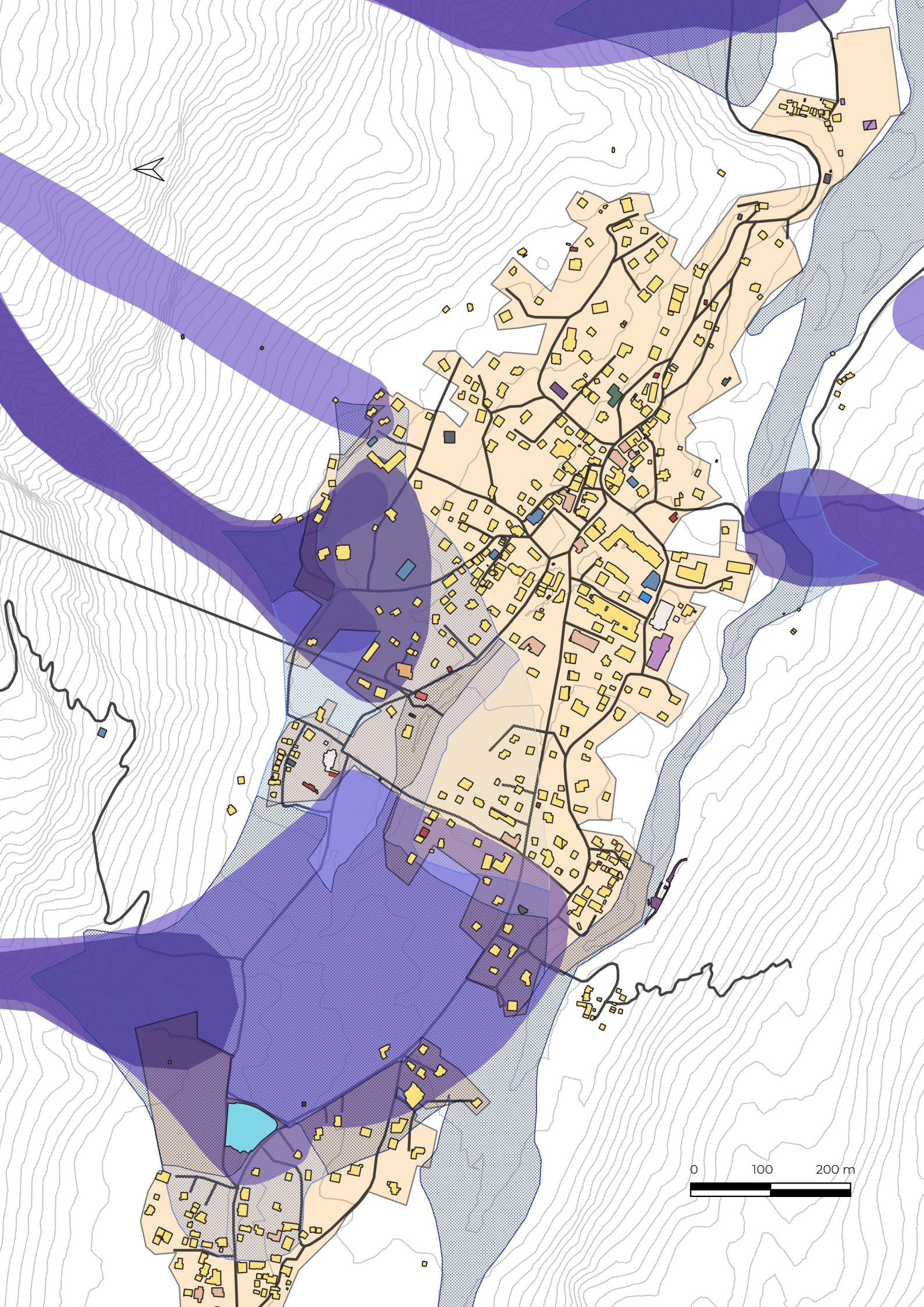
Flood	
HPH	
MPH	
LPH	
Geomorphological Avalanche Hazard Zones	
Historical Photo-Interpreted Footprints	
Morphological Terrain Susceptibility	
Geomorphological Danger Perimeters	
SMRS	
Building Stock by Functional Use	
Residential	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Parking	
Cable car and ski infrastructure	
Unclassified	
Other uses	
Mining Concession Zones	
Mining Buildings	
Roads & streets	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
ARPA Piemonte (Banca dati valanghe), Scale: 1:25000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000;
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.



D6. Settlement Scale Landslide Hazard Map Of Macugnaga

Spatial Intersection With Slope Flow and Building Footprints

Legend

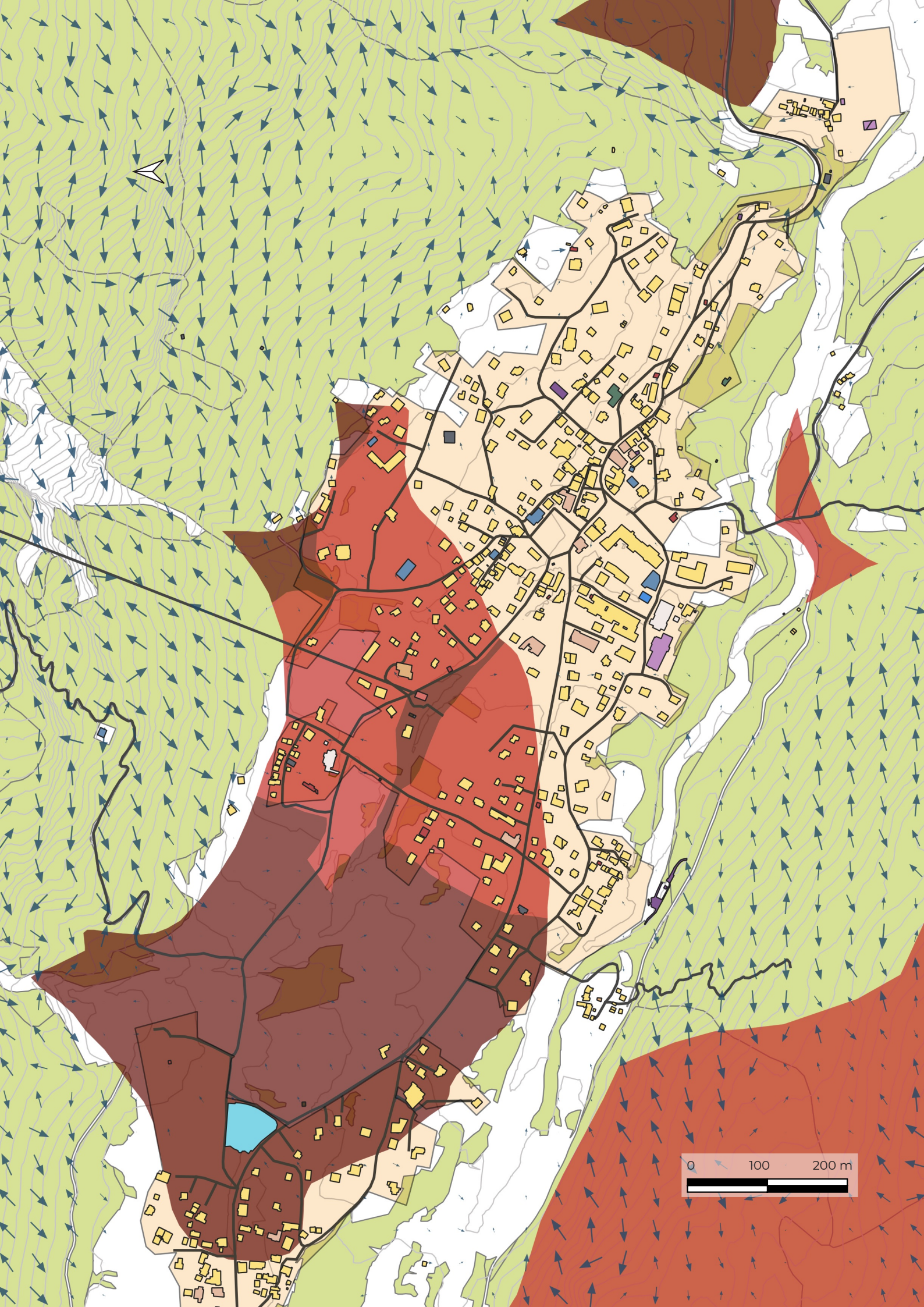
Landslide Hazard Zones	
P4 Very High	
P3 High	
P2 Medium	
Slope Flow Direction & Severity	
SMRS	
Building Stock by Functional Use	
Residential	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Parking	
Cable car and ski infrastructure	
Unclassified	
Other uses	
Mining Concession Zones	
Mining Buildings	
Roads & streets	
Forests & Shrublands	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000;
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.



D7. Settlement Scale Multi-Hazard Exposure Map Of Macugnaga

Building Footprint Hazard Assessment

Legend

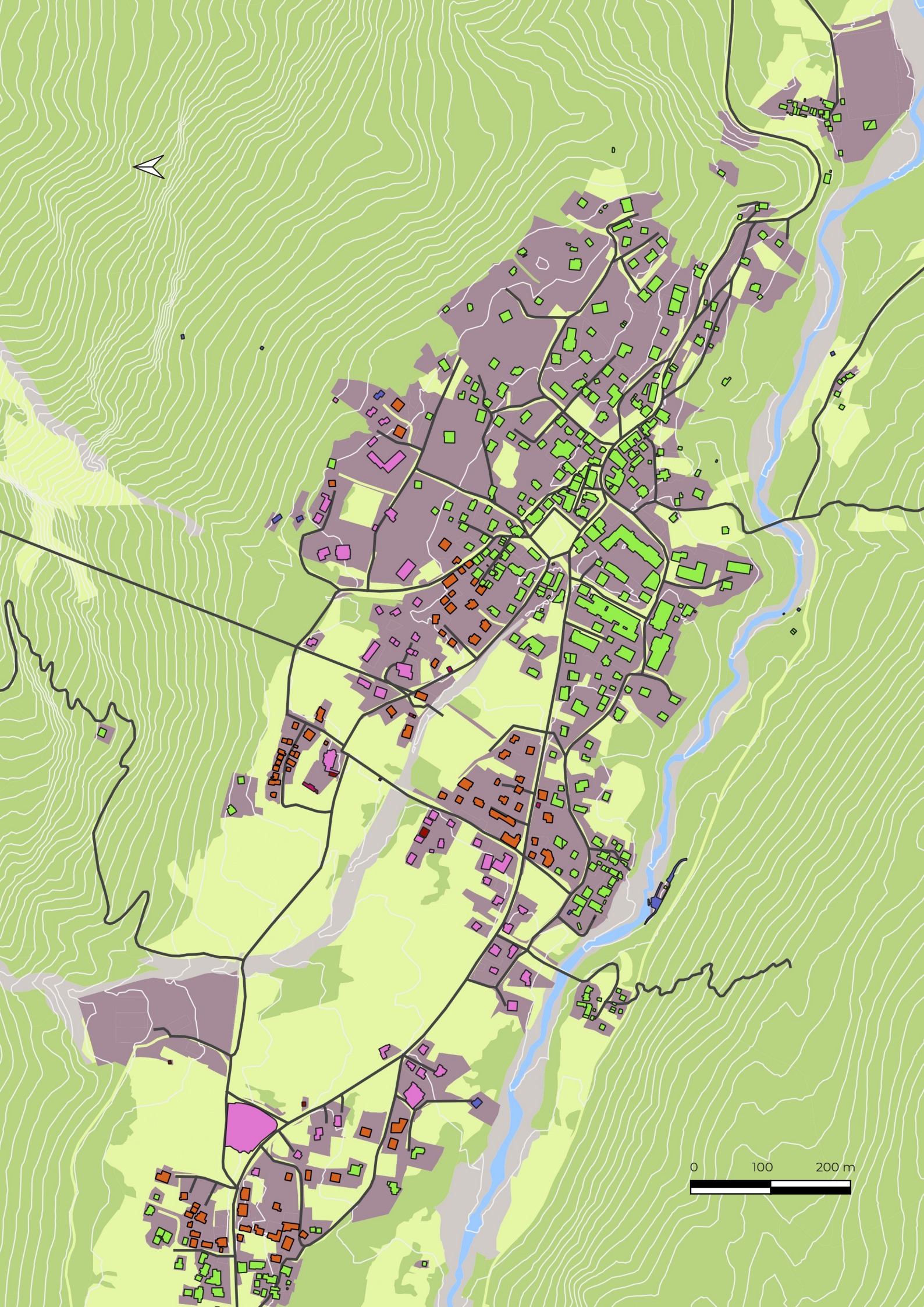
Buildings Hazard Assessment	
Exposed to 3 Hazard	
Exposed to 2 Hazards	
Exposed to 1 Hazards	
Not Exposed	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;	Mines Hazard Assessment	
	Exposed to 3 Hazards	
	Exposed to 2 Hazards	
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;	Land Cover	
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1:25000;	Urban & Built-up Area	
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.	Pastures & Meadows	
	Forests & Shrublands	
	Bare Rock & Alpine Tundra	
	Rivers & Lakes	
	Roads & Streets	



Elva



Goria

Martini



Comune di Elva
Serre



Villar

Rinaud

Clari

Figure 19–21. Photographs of Elva village.
Photo credit: Elisabetta Colucci.



0 100 200 m

D8. Settlement Scale Flood And Avalanche Map Of Elva

Spatial Intersection With Building Footprints

Legend

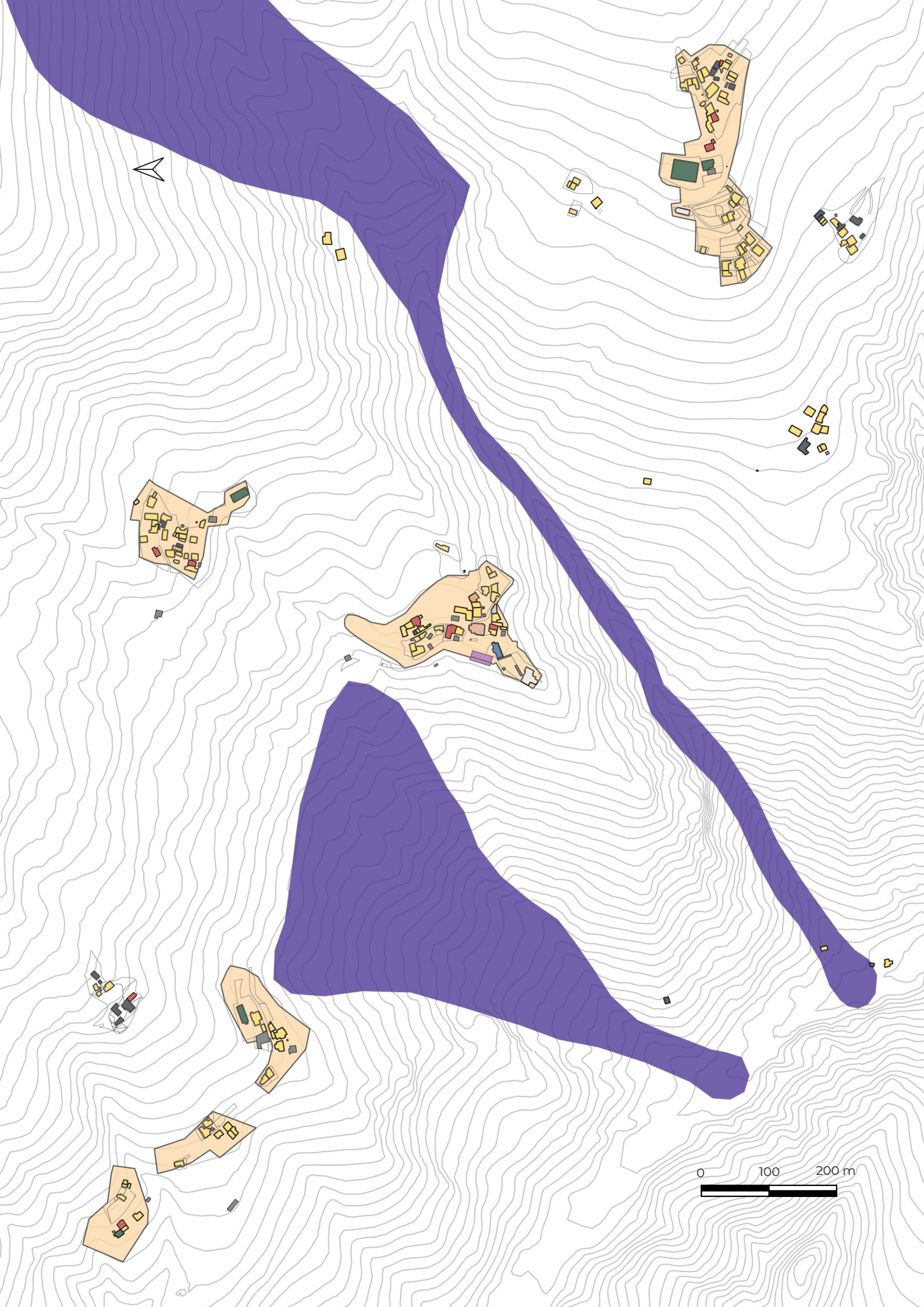
Flood	
HPH	
MPH	
LPH	
Geomorphological Avalanche Hazard Zones	
Historical Photo-Interpreted Footprints	
Morphological Terrain Susceptibility	
Geomorphological Danger Perimeters	
SMRS	
Building Stock by Functional Use	
Residential	
Rural buildings	
Minor buildings	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Roof element	
Monumental structure & urban furnishing	
Unclassified	
Other uses	
Roads & streets	

Reference System

WGS 84 / UTM zone 32N

Data Source:

ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
ARPA Piemonte (Banca dati valanghe), Scale: 1: 25000;
Geoportale Piemonte (PAI), CC BY 4.0 Scale: 1: 25000.
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.



D9. Settlement Scale Landslide Hazard Map Of Elva

Spatial Intersection With Slope Flow and Building Footprints

Legend

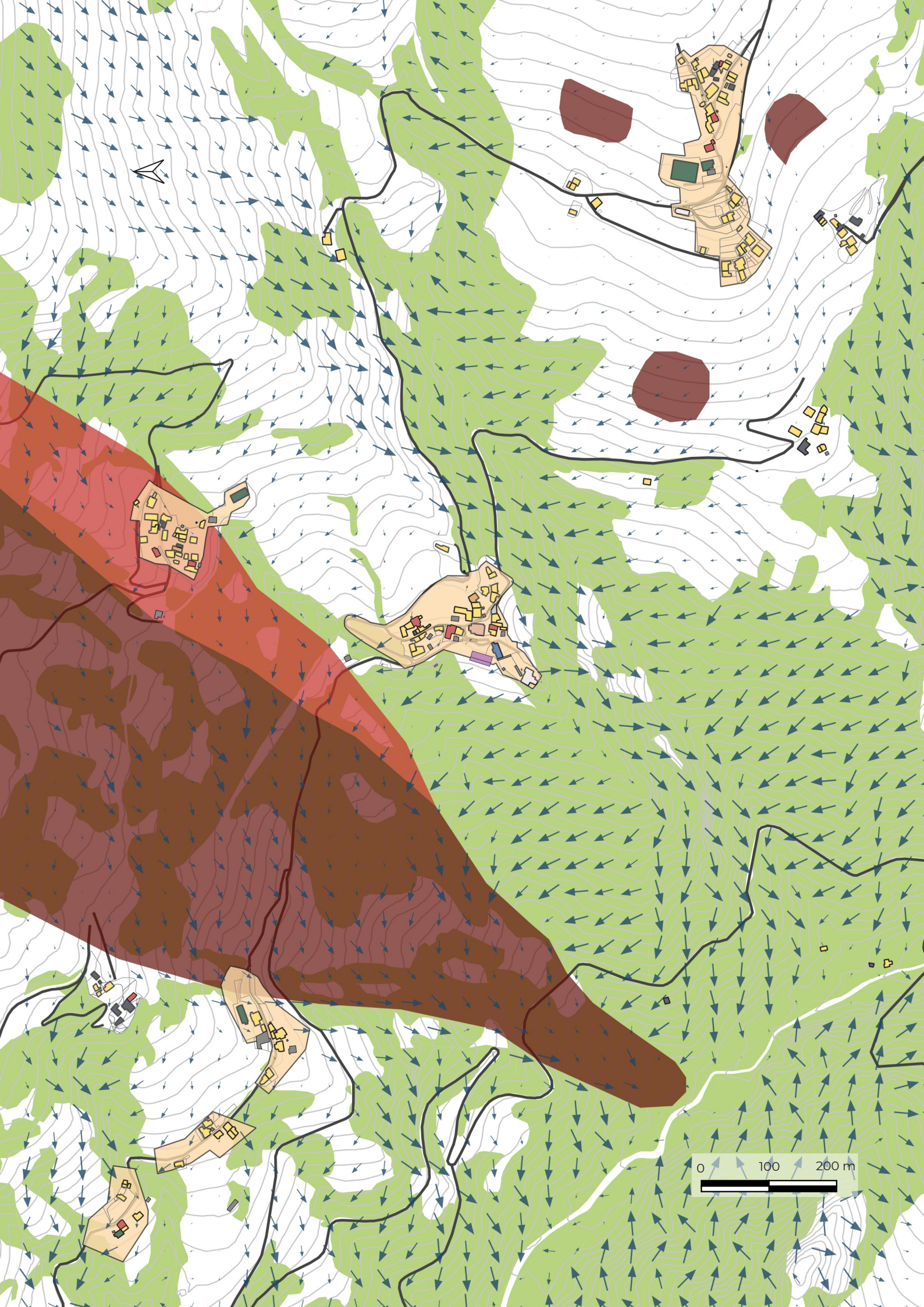
Landslide Hazard Zones	
P4 Very High	
P3 High	
P2 Medium	
Slope Flow Direction & Severity	
	
SMRS	
	
Building Stock by Functional Use	
Residential	
Rural buildings	
Minor buildings	
Industrial	
Agricultural infrastructure	
Sports infrastructure	
Public administration and security	
Commercial services	
Accommodation and catering services	
Religious services	
Roof element	
Monumental structure & urban furnishing	
Unclassified	
Other uses	
Roads & streets	
	
Forests & Shrublands	
	

Reference System

WGS 84 / UTM zone 32N

Data Source:

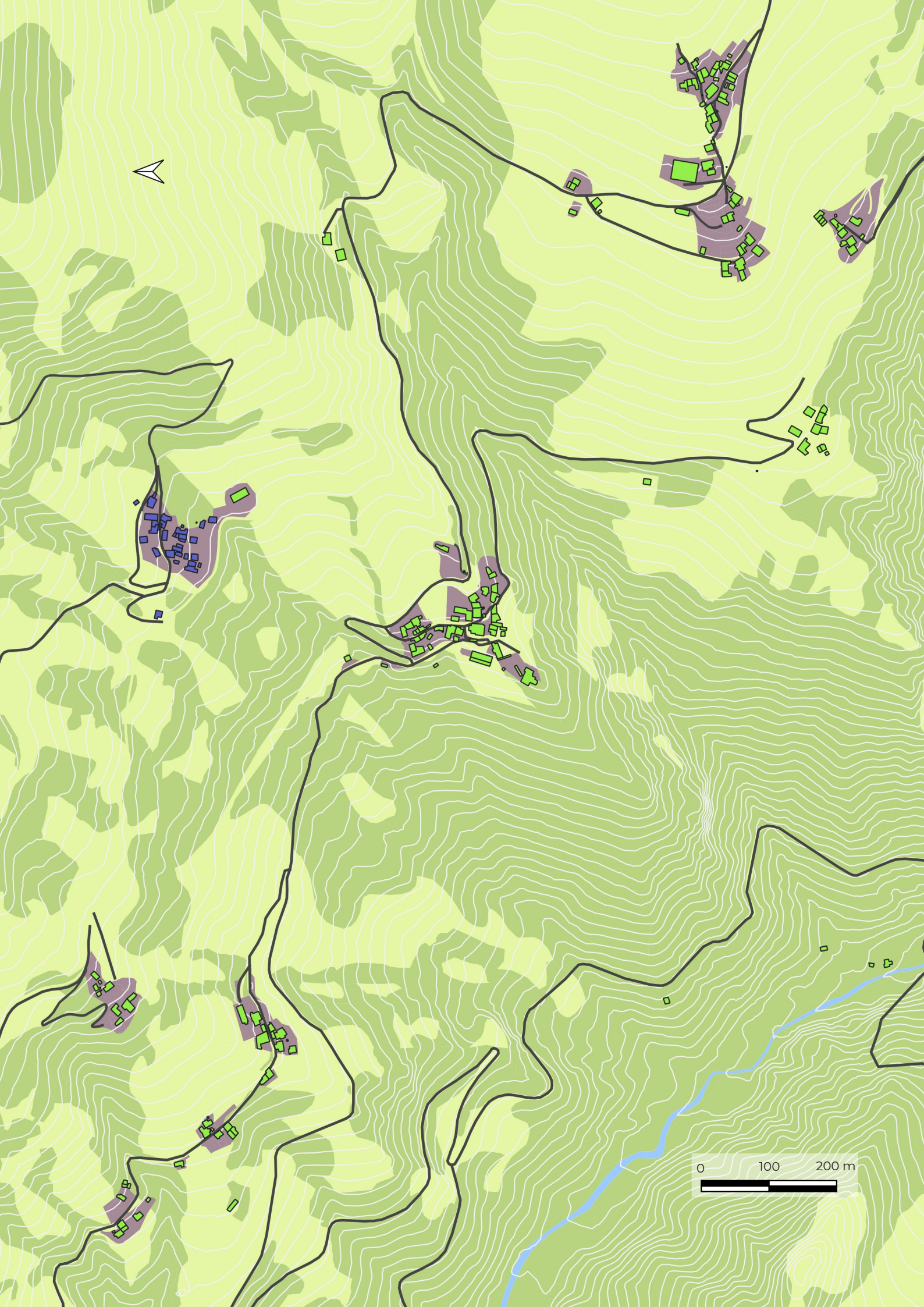
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;
Geoportale Piemonte (PAI), CC BY 4.0 Scale: 1: 25000.
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.



D10. Settlement Scale Multi-Hazard Exposure Map Of Elva

Building Footprint Hazard Assessment

	Legend	
	Buildings Hazard Assesment	
Reference System	Exposed to 3 Hazards	
	Exposed to 2 Hazard	
WGS 84 / UTM zone 32N	Exposed to 1 Hazards	
Data Source:	Not Exposed	
		
ISTAT (Località 2021), CC BY 4.0, Scale: 1:5.000;	SMRS	
ISPRA IdroGEO (v4.0 2021 / v5.0 2020), CC BY-SA 4.0, Scale: 1:5000;	Land Cover	
Geoportale Piemonte (PAI), CC BY 4.0, Scale: 1: 25000.	Urban & Built-up Area	
Geoportale Piemonte (BDTRE), CC BY 4.0, Scale: 1:10000.	Pastures & Meadows	
	Forests & Shrublands	
	Bare Rock & Alpine Tundra	
	Rivers & Lakes	
	Roads & Streets	



5.5 Settlement Scale

5.5.5 Technical Metadata and Processing Workflow

Table 18 provides a comprehensive operational summary of the spatial layers, datasets, and specific geoprocessing transformations executed to generate the settlement-scale maps.

Layer Name	Source & Coordinate System	Type & Scale	QGIS Operations	Role
Settlements	Derived from national scale model, (EPSG:32632).	Shape file/ Vector Polygon converted to Point Centroid, 1:5.000	1. Filter to territorial boundaries. 2. Isolation analysis. 3. classification based on Road Blockage due to Hazard Count	Operational spatial footprint for Road Blockage due to hazard classification.
Building Footprints (Valle d'Aosta)	Geoportale SCT Valle d'Aosta, uso suolo fabbricato (EPSG:23032).	Shapefile / Vector Polygon, 1:10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Attribute classification by functional use. 4. Spatial clip to settlement boundary. 5. Vector polygon intersection with hazard layers. 6. Hazard Count field generation.	Structural asset inventory for building-level hazard exposure mapping. Functional use classification from uso suolo fabbricato alphanumeric typology.
Building Footprints (Piedmont)	Geoportale Piemonte, BDTRE Municipal GeoPackage (EPSG:32632).	GeoPackage / Vector Polygon, 1:10000	1. GeoPackage extraction. 2. Topological geometry repair. 3. Attribute classification by functional use via edifc_uso field. 4. Harmonization to cross-case legend. 5. Spatial clip to settlement boundary. 6. Vector polygon intersection with hazard layers. 7. Hazard Count field generation.	Structural asset inventory for building-level hazard exposure mapping. Includes building footprints, roof elements, minor buildings, and monumental structures from BDTRE classification.

Table 18. Settlement Scale Scale Geoprocessing Workflow and Layer Metadata.
(Source: Author's elaboration)

5.5 Settlement Scale

5.5.5 Technical Metadata and Processing Workflow

Mining Footprints (Valle d'Aosta)	Geoportale SCT Valle d'Aosta, Catasto Regionale (EPSG:23032).	Shapefile / Vector Polygon, 1:10000	1. Reprojection to base CRS. 2. Spatial clip to settlement boundary. 3. Vector polygon intersection with hazard layers. 4. Hazard Count field generation.	Heritage mining infrastructure exposure assessment for repurposed industrial assets in the Valpelline corridor. Treated as parallel asset class to residential building stock.
Mining Footprints (Piedmont)	Geoportale Piemonte, BDTRE Municipal GeoPackage (EPSG:32632).	GeoPackage / Vector Polygon, 1:10000	1. GeoPackage extraction. 2. Spatial clip to settlement boundary. 3. Vector polygon intersection with hazard layers. 4. Hazard Count field generation.	Former mining heritage infrastructure exposure assessment for the Anzasca Valley. Includes mining concession zones and mining buildings from BDTRE classification.
Flood Hazard Layers (HPH, MPH, LPH)	Derived from Territorial scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:5000	1. Spatial clip to settlement boundary. 2. Vector polygon intersection with building footprints. 3. Binary flag appended to building attribute table.	Identification of flood-exposed building assets at settlement scale. Consistent across all three case studies.
Landslide Hazard Layer	Derived from Territorial scale model, (EPSG:32632).	Shape file/ Vector Polygon, 1:5000	1. Spatial clip to settlement boundary. 2. Vector polygon intersection with building footprints. 3. Binary flag appended to building attribute table.	Identification of landslide-exposed building assets. Consistent across all three case studies. P1 Moderate and AA Attention Zone categories present in the national PAI dataset but not mapped within any of the three study settlement boundaries.

5.5 Settlement Scale

5.5.5 Technical Metadata and Processing Workflow

Avalanche Hazard Layer Aosta Valley	Repertorio Cartografico SCT Valle d'Aosta, Carta delle Localizzazioni Probabili delle Valanghe (EPSG:23032).	Shape file/ Vector Polygon, 1: 10000	1. Reprojection to base CRS. 2. Spatial clip to settlement boundary. 3. Vector polygon intersection with building footprints. 4. Binary flag appended to building attribute table.	Identification of avalanche-exposed building assets in the Valpelline corridor. Zonal classification follows the regional Valle d'Aosta hazard mapping system.
Avalanche Hazard Layers Piedmont (PIE layers)	ARPA Piemonte, Banca dati valanghe (EPSG:32632).	Shape file/ Vector Polygon, 1: 25000	1. Spatial clip to settlement boundary. 2. Vector polygon intersection with building footprints. 3. Binary flag appended to building attribute table.	Identification of avalanche-exposed building assets in the Anzasca and Maira valleys. Dual-layer structure retains both geo morphological evidence.
Debris Flow Zones (Ollomont only)	Geoportale SCT Valle d'Aosta (EPSG:23032).	Shape file/ Vector Polygon, 1: 25000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to settlement boundary.	Supplementary hazard layer for Ollomont. Formally validated torrent and debris flow runout zones. Equivalent data not available at cadastral resolution for Piedmont case studies.
Roads and Streets Piedmont	Geoportale Piemonte (BDTRE via WFS), (EPSG:32632).	WFS to Shape file/ Vector Lines, 1:10000	1. WFS vector data extraction. 2. Topological geometry repair. 3. Spatial clip to study region.	Infrastructure exposure mapping and accessibility analysis in Piedmont.
Roads and Streets Aosta Valley	Geoportale SCT Valle d'Aosta (Uso suolo strade 2024), (EPSG:23032).	Shape file/ Vector Polygon, 1: 10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to study region.	Infrastructure exposure mapping and accessibility analysis in Aosta Valley.

5.5 Settlement Scale

5.5.5 Technical Metadata and Processing Workflow

Landcover Piedmont	Geoportale Piemonte (BDTRE via WFS), (EPSG:32632).	WFS to Shape file/ Vector Lines, 1:10000	1. WFS vector data extraction. 2. Topological geometry repair. 3. Spatial clip to study region. 4. Reclassification into 6 main categories.	Environmental baseline and surface roughness classification for Piedmont.
Landcover Aosta Valley	Geoportale SCT Valle d'Aosta (Uso suolo copertura), (EPSG:23032).	Shape file/ Vector Polygon, 1:10000	1. Reprojection to base CRS. 2. Topological geometry repair. 3. Spatial clip to study region. 4. Reclassification into 6 main categories.	Environmental baseline and surface roughness classification for Aosta Valley.
Contours (Curve 10) Piedmont	Geoportale Piemonte, BDTRE Municipal GeoPackage (EPSG:32632).	GeoPackage / Vector Lines to Raster TIF, 1:10000	1. GeoPackage extraction. 2. Topological geometry repair. 3. Spatial clip to settlement boundary. 4. TIN interpolation generation. 5. Aspect raster derivation. 6. Slope raster derivation and resampling. 7. 40m point sampling matrix generation. 8. Sample Raster Values tool: asp_1 and slp_1 fields appended.	Micro-topographic flow and aspect vector mapping for gravity-driven surface process visualization at settlement scale. Applied to Macugnaga and Elva.
Contours (Curve 10) Aosta Valley	Derived from territorial scale TIN model (EPSG:32632).	Shape file/ Vector Lines to Raster TIF, 1:10000	1. Spatial clip to settlement boundary. 2. Aspect raster derivation. 3. Slope raster resampling to settlement resolution. 4. 40m point sampling matrix generation. 5. Sample Raster Values tool: asp_1 and slp_1 fields appended.	Micro-topographic flow and aspect vector mapping for gravity-driven surface process visualization at settlement scale. Applied to Ollomont.

5.6 Data Use and Attribution

The spatial datasets incorporated in this thesis are sourced from multiple national and regional institutions, each operating under distinct licensing frameworks and legal conditions. All layers were imported, filtered, reprojected, or stylized within QGIS for visualization and analytical purposes. No modifications to the original datasets are validated or endorsed by the original data creators, and all derivative cartographic outputs are the sole work of the author.

Settlement boundary data, locality polygons, and Inner Areas classification layers sourced from ISTAT were geographically paired, layered, and styled within QGIS. The Borghi più belli d'Italia designation dataset and associated vector files were parsed and projected to align with local coordinate reference systems. These analytical adjustments are the work of the author and do not imply official validation by ISTAT or the Borghi più belli d'Italia association.

The landslide and flood hazard datasets sourced from the ISPRA IdroGEO platform (v4.0 2021, v5.0 2020) were layered, styled, and spatially intersected with other datasets in QGIS. All derivative works generated from these components are shared under the required Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) framework, consistent with the original licensing terms. ISPRA and persons acting on its behalf are not responsible for the use made of the information contained in the IdroGEO platform, nor for any direct or indirect damages arising from such use. ISPRA does not guarantee the completeness or updated status of the data. For full legal value, updated regional regulations, and land use constraints, reference must be made exclusively to the official cartography published by the competent River Basin District Authorities and Autonomous Provinces.

Regional and national boundary layers sourced from Eurostat and the GISCO geographic information service were used exclusively for contextual mapping at the national and European scales. Custom modifications, filtering, and localized map rendering within QGIS are the sole work of the author and are entirely independent of Eurostat.

Avalanche hazard data for the Macugnaga and Elva catchments was sourced from the ARPA Piemonte regional avalanche database (Banca dati valanghe). The intersection of this data with building footprints and road networks constitutes an analytical derivative produced by the author and does not represent an official assessment or regulatory determination by ARPA Piemonte or the Regione Piemonte.

Building cadastre, land cover, avalanche zoning, debris flow

5.6 Data Use and Attribution

polygons, and road network data for the Ollomont catchment were sourced from the Geoportale SCT della Regione Autonoma Valle d'Aosta under Creative Commons Attribution 4.0 International (CC BY 4.0) licensing. Building footprints, contour lines, land cover, and infrastructure data for the Macugnaga and Elva catchments were sourced from the Base Dati Territoriale di Riferimento degli Enti (BDTRE) through the Geoportale Piemonte, also under CC BY 4.0 licensing, accessed via both Web Feature Service and municipal GeoPackage downloads. Spatial intersections, reclassifications, and derivative cartographic outputs produced from all regional layers are the work of the author and do not imply validation by the respective regional administrations or their technical services.

All analytical outputs, classifications, and cartographic representations produced in this thesis are research outputs for academic purposes only and should not be used as a substitute for official regional or municipal planning documentation.

6 Results

This chapter presents the empirical findings of the multiscale spatial framework across four analytical scales, yielding the spatial results and layout configurations derived from the core methodology established in Chapter 5. At the national scale, 22,205 SMRS are identified across Italy, with 18.3% facing ghost or near-abandoned conditions. At the regional scale, Valle d'Aosta emerges as a near-universally hazard-exposed system with only 2.2% of SMRS recording zero hazard intersection. The territorial and settlement scale analyses confirm Ollomont and Macugnaga as maximum-constraint case studies, while Elva presents a structurally distinct low-constraint profile driven by institutional and demographic rather than physical barriers.

6.1 National Scale Results

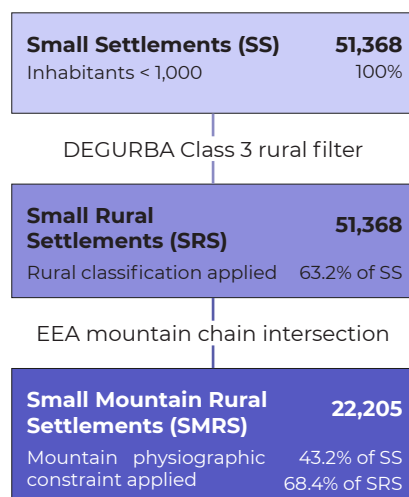


Figure 22. Progressive filtering from Small Settlements to Small Mountain Rural Settlements across Italy. (Source: Author's elaboration)

The application of the multiscale spatial framework to the national ISTAT locality dataset yields a structured inventory of small settlement typologies across Italy, providing the empirical foundation from which the three case study valleys are drawn. The full process, described in Chapter 5, progressively filters the national locality dataset through morphological, rural-urban, and physiographic criteria to isolate the target settlement population, as illustrated in Figure 22.

The settlement counts and population bracket distributions reported in this section were extracted from the ISTAT 2021 locality dataset through the QGIS Python processing across the national territory. This process identified 51,368 Small Settlements (SS), defined as localities with fewer than 1,000 inhabitants. Of these, 32,480 qualify as Small Rural Settlements (SRS) following the application of the DEGURBA Class 3 rural filter, representing 63.2% of the total SS universe. The further intersection with the European Environment Agency mountain chain polygon reduces this pool to 22,205 Small Mountain Rural Settlements (SMRS), corresponding to 43.2% of all SS and 68.4% of all SRS. This progressive reduction confirms the disproportionate concentration of small settlement fragility within the Alpine and Apennine mountain systems, where physiographic constraint compounds demographic contraction. Within the SMRS population, demographic fragility is acute. Table 19 presents the full population distribution across all three settlement tiers structured into seven demographic brackets ranging from total abandonment to the upper threshold of 999 inhabitants. The table reveals a consistent pattern of demographic compression across all three tiers: in every category, the largest single bracket is the marginal 10 to 49 range, which alone contains 9,978 SMRS or 44.9% of the total mountain settlement population. This concentration confirms that the modal condition of Italian mountain settlement is one of extreme demographic thinness rather than moderate decline. At the critical end of the spectrum, 455 SMRS record a population of zero, constituting ghost settlements where permanent residency has been entirely lost, while a further 3,615 fall in the nearly abandoned bracket of 1 to 9 inhabitants, representing communities where demographic viability is critically compromised.

Number of Inhabitant	Total	0	1-9	10-49	50-99	100-299	300-499	500-999
SS Count	51368	725	5575	23105	8071	8052	2694	3146
SRS Count	32480	537	4396	14996	4470	4551	1577	1953
SMRS Count	22205	455	3615	9978	2902	3021	1042	1192

Table 19. Population distribution of Settlements. (Source: Author's elaboration)

6.1 National Scale Results

The distribution of these figures across the SS and SRS tiers further confirms that demographic fragility intensifies with physiographic constraint, the mountain filter does not simply reduce the settlement count but concentrates the most severe abandonment conditions within it. Figure 23 visualizes the SMRS bracket distribution, highlighting the disproportionate weight of the critical categories against the rest of the population range.

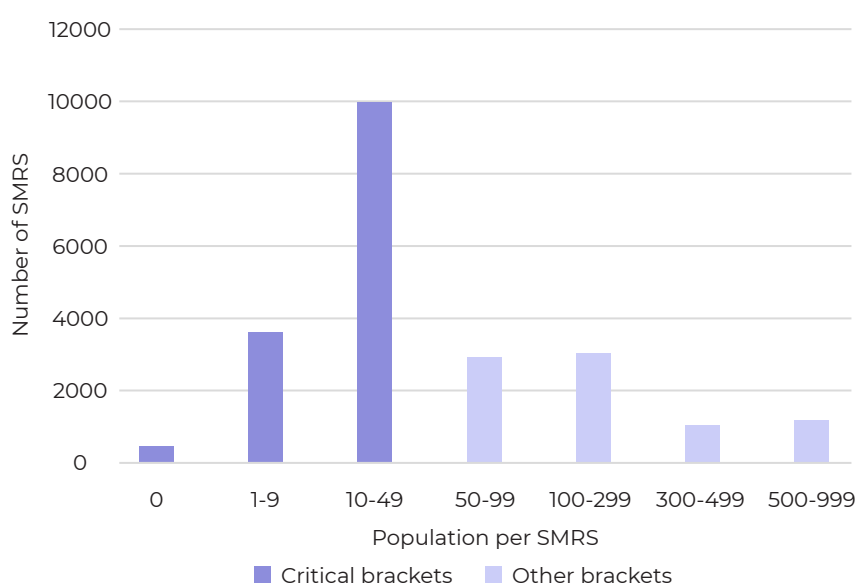


Figure 23. SMRS population bracket distribution showing concentration in marginal and abandoned categories. (Source: Author's elaboration)

The combined share of ghost and near-abandoned SMRS amounts to 18.3% of the national mountain settlement population, nearly one in five communities facing either total abandonment or imminent demographic collapse. Figure 24 maps this fragility against the Inner Areas institutional framework, illustrating how demographic decline and service peripheralization reinforce each other spatially across the national territory. Of the 22,205 SMRS, 836 fall in Zone F (ultra-peripheral) and 6,918 in Zone E (peripheral), summing to 35.8% of all SMRS, territories where service deprivation compounds physical isolation. A further 9,550 SMRS fall in Zone D (intermediate periphery), bringing the combined share of SMRS in the three most service-deprived SNAI categories to 78.8%. By contrast, only 63 SMRS fall in Zone A (urban poles) and 181 in Zone B (inter-municipal poles), confirming that the SMRS population is structurally concentrated in the margins of the Italian territorial system. The 23 SMRS recorded as falling outside the Inner Areas classification correspond to localities within the territory of San Marino, where the national SNAI framework does not apply. From the case studies, Elva and Macugnaga fall under Peripherral areas and Ollomont under outlaying areas.

6.1 National Scale Results

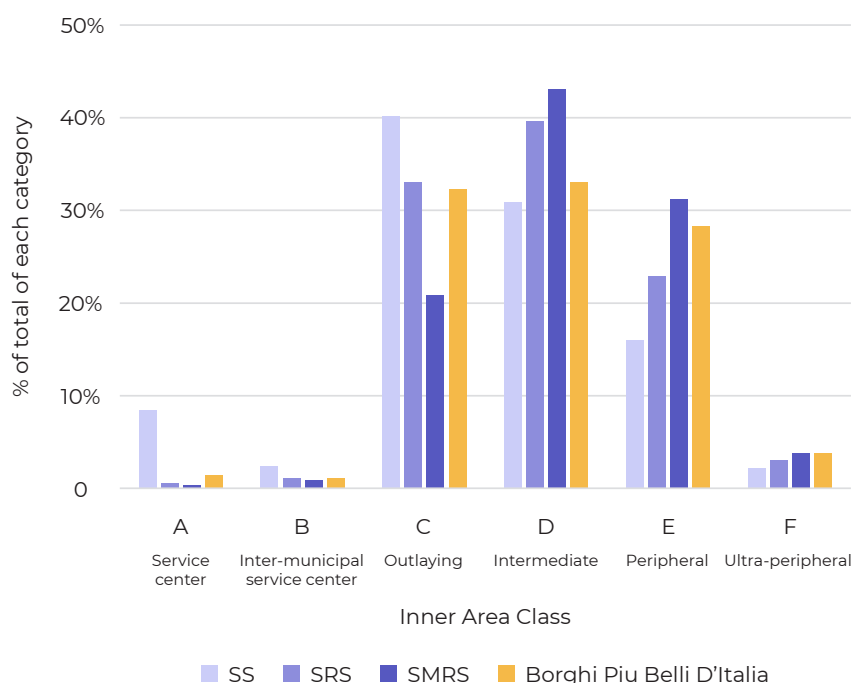


Figure 24. Inner Areas zone distribution comparing SS, SRS, SMRS and Borghi Più Belli. (Source: Author's elaboration)

The Borghi Più Belli d'Italia project identifies 375 certified heritage settlements across Italy. Unlike the SS, SRS, and SMRS classifications, which are derived from a consistent operational definition applied uniformly across the national locality dataset, the borghi designation follows a distinct selection logic based on heritage value, architectural integrity, and institutional nomination rather than population size or physiographic criteria. The population thresholds are not comparable, and the two classification systems cannot be directly equated.

The borghi dataset is included here not as a parallel tier of the settlement hierarchy but to expose a structural limitation of heritage-based identification frameworks: with only 14 certified borghi in Zone F and 106 in Zone E, the network's reach does not extend proportionally to the most peripheral communities, whether because documentation efforts have not reached them or because physical fabric has deteriorated beyond the threshold required for certification.

The distributional concentration of borghi in Zones C and D confirms that formal heritage certification tends to follow institutional accessibility rather than physical urgency, systematically under-representing the settlements most in need of reinhabitation support. This gap motivates the operational SMRS definition developed in Chapter 5 as a more territorially comprehensive and methodologically consistent instrument for identifying candidate reinhabitation sites.

6.2 Regional Scale Results

The regional scale analysis narrows the national SMRS inventory to the two administrative regions containing the three case study valleys: Piedmont and Valle d'Aosta. The settlement counts reported in this section were extracted from the ISTAT 2021 locality dataset through the QGIS Python processing across the Regional territory. Within these two regions, the SMRS population totals 3,799 settlements, distributed highly asymmetrically between the two administrative contexts: 3,338 SMRS in Piedmont (87.9%) and 461 in Valle d'Aosta (12.1%).

This asymmetry reflects the substantially larger territorial extent of Piedmont and its correspondingly greater number of small mountain localities, while Valle d'Aosta's compact alpine geography concentrates a smaller but proportionally more hazard-exposed settlement population. The settlement counts and hazard exposure figures reported in this section were extracted through the spatial intersection procedures described in Sections 5.3.2 through 5.3.5, with results summarized in Table 20.

Hazard Type	Degree	SMRS Piedmont	SMRS Aosta Valley
Flood	HPH	664	237
	MPH	135	37
	LPH	120	32
	Not Exposed	2419	155
Landslide	Very High	676	205
	High	336	141
	Medium	132	95
	Not Exposed	2194	20
Avalanche	Very High (V1 & Va)	-	35
	High (V2 & Vb)	-	34
	Low (V3)	-	25
	Administrative Hazard Zone Exposure	21	-
	Geomorphological Hazard Zone Exposure	150	-
	Not Exposed	3167	367
Total N of Settlements	-	3338	461

Table 20. Regional Hazard Exposure Summary.
(Source: Author's elaboration)

6.2 Regional Scale Results

Flood Hazard Exposure

The spatial intersection of the SMRS population with the ISPRA IdroGEO flood probability zones reveals that 1,225 settlements (32.2%) fall within at least one flood hazard class across the two regions. The distribution is dominated by the High Probability zone, with 901 SMRS (23.7%) intersecting HPH, the most severe classification associated with frequent and intense flooding events. Medium probability zones (MPH) affect a further 172 SMRS (4.5%) and Low probability zones (LPH) an additional 152 SMRS (4.0%). Flood exposure is substantially higher in Valle d'Aosta proportionally, where 306 of 461 SMRS (66.4%) fall within a flood zone, compared to 919 of 3,338 Piedmont SMRS (27.5%).

This disparity reflects the steeper hydraulic gradients and more confined valley geometries of the Aosta Valley system, where torrential discharge events are structurally more frequent and spatially concentrated than in the broader Piedmont catchments.

Landslide Hazard Exposure

Landslide susceptibility constitutes the most extensive single hazard affecting the SMRS population across both regions. 1,585 settlements (41.7%) intersect at least one PAI landslide hazard zone, making it the dominant environmental constraint on the two-region SMRS inventory. The severity distribution is concentrated at the upper end of the classification: 881 SMRS (23.2%) fall within Very High susceptibility zones (P4), 477 (12.6%) within High zones (P3), and 227 (6.0%) within Medium zones (P2).

The concentration of SMRS in P4 zones is particularly significant, as these zones carry direct regulatory constraints on development and reconstruction under Italian hydrogeological planning law. Valle d'Aosta again shows proportionally higher exposure: 441 of 461 SMRS (95.7%) intersect a landslide zone of some severity, compared to 1,144 of 3,338 Piedmont SMRS (34.3%), confirming that the compact alpine morphology of the Aosta Valley subjects virtually its entire small settlement population to mass movement probability.

Avalanche Hazard Exposure

Avalanche hazard exposure affects a smaller but analytically significant share of the SMRS population, with 265 settlements (7.0%) intersecting at least one avalanche hazard zone across the two regions. As discussed in Section 5.3.4, the two regional datasets encode avalanche hazard through structurally distinct classification systems

6.2 Regional Scale Results

and require separate interpretation, which is reflected in Table 20 through the use of region-specific category rows. In Piedmont, where avalanche data is sourced from the ARPA Banca dati valanghe, 171 SMRS (5.1% of Piedmont SMRS) fall within a mapped avalanche zone. Of these, 150 intersect Geomorphological Hazard Zones and 21 fall within Administrative Hazard Zones, which carry binding land use planning implications under the PRGC framework. In Valle d'Aosta, where the regional classification uses the standardized V1 through V3 zonal hierarchy, 94 of 461 SMRS (20.4%) intersect an avalanche zone: 35 in the Very High category (V1/Va), 34 in the High category (V2/Vb), and 25 in the Low category (V3). The proportionally higher avalanche exposure in Valle d'Aosta reflects the more extensive glaciated high-alpine terrain of the Aosta Valley and its greater concentration of steep north-facing couloirs above settled valley floors.

Multi-Hazard Synthesis

The synthesis layer generated from the cumulative intersection of all three hazard datasets, visualized in Figure 25, reveals the compound exposure profile of the two-region SMRS population. Across both regions, 1,776 SMRS (46.7%) record no intersection with any hazard zone, representing settlements where reinhabitation constraints are primarily demographic and infrastructural rather than geomorphological. 1,144 SMRS (30.1%) are exposed to a single hazard type, indicating a manageable degree of environmental constraint where targeted mitigation measures could in principle address the primary source of physical vulnerability. 706 SMRS (18.6%) face two concurrent hazard types, where the compounding of independent geomorphological processes significantly complicates any reinhabitation or conservation intervention.

At the most severe end of the spectrum, 173 SMRS (4.6%) intersect all three hazard types simultaneously, representing settlements where the convergence of flood, landslide, and avalanche exposure creates structural constraints that may render conventional reinhabitation approaches insufficient without substantial civil engineering intervention. The contrast between the two regions on this synthesis measure is the most analytically significant finding at the regional scale. In Piedmont, 1,766 SMRS (52.9%) record zero hazard exposure, and only 90 (2.7%) face triple-hazard convergence, confirming that across the broader Piedmont mountain system the majority of small settlements operate under conditions where environmental constraint is not the primary driver of abandonment. In Valle d'Aosta, the distribution is dramatically inverted: only 10 SMRS (2.2%) record zero hazard exposure, while 224 (48.6%) face dual-hazard exposure and 83 (18.0%) face triple-

6.2 Regional Scale Results

hazard convergence. In this context, environmental constraint and demographic decline are not independent processes but mutually reinforcing ones, the physical inaccessibility and geomorphological instability of Valle d'Aosta's mountain corridors actively compounds the socioeconomic pressures driving depopulation, creating a feedback dynamic in which hazard exposure accelerates abandonment and abandonment in turn reduces the maintenance capacity that might otherwise mitigate hazard impacts. This structural difference, made visually explicit in Figure 25, confirms that the Valle d'Aosta SMRS population operates under a fundamentally more constrained environmental regime than its Piedmont counterpart, with compound hazard exposure as the modal condition rather than the exception. It is within this context of near-universal hazard exposure that the Ollomont catchment, examined at territorial and settlement scale in the following sections, represents a characteristic rather than an outlying case of Alpine settlement vulnerability.

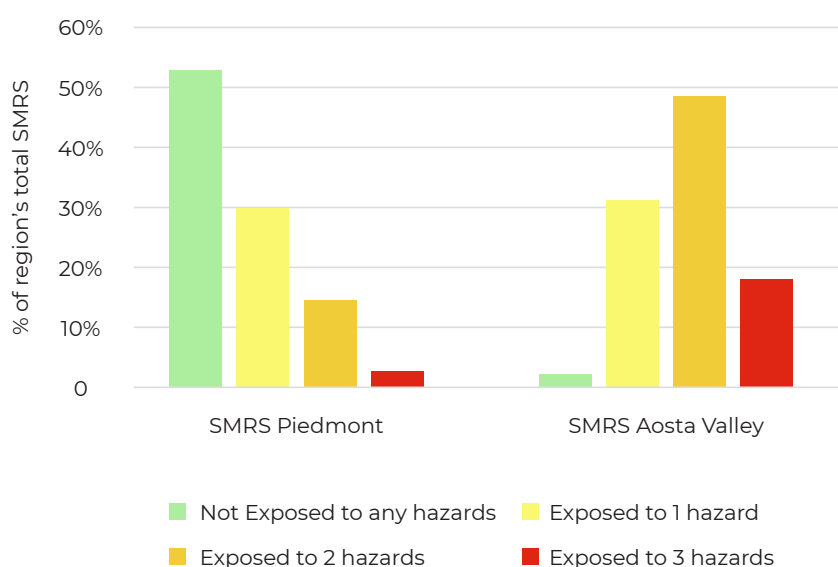


Figure 25. Regional multi-hazard exposure comparison between Piedmont and Valle d'Aosta SMRS. (Source: Author's elaboration)

The regional scale analysis thus establishes a differentiation between the study regions: while Piedmont's mountain settlement system presents a heterogeneous hazard exposure profile in which zero-constraint conditions remain the majority condition, Valle d'Aosta's alpine geography subjects virtually its entire SMRS population to compound multi-hazard exposure. This regional contrast provides the institutional and geomorphological context within which the territorial and settlement scale findings presented in the following sections must be interpreted.

6.3 Territorial Scale Results

The territorial scale analysis applies the multiscale spatial framework to the three case study valley catchments, intersecting land cover, hazard zones, slope gradient, and road network accessibility to produce a composite Hazard Constraint Score (HCS) for each SMRS within the three corridors. The HCS combines the internal hazard exposure count (0 to 3) derived from the regional scale analysis with the access corridor blockage count (0 to 3) generated through the road network intersection described in Section 5.4.3, e yielding an integer score from 0 to 6 where higher values indicate greater compound constraint on reinhabitation feasibility.

6.3.1 Valpelline Corridor (Ollomont)

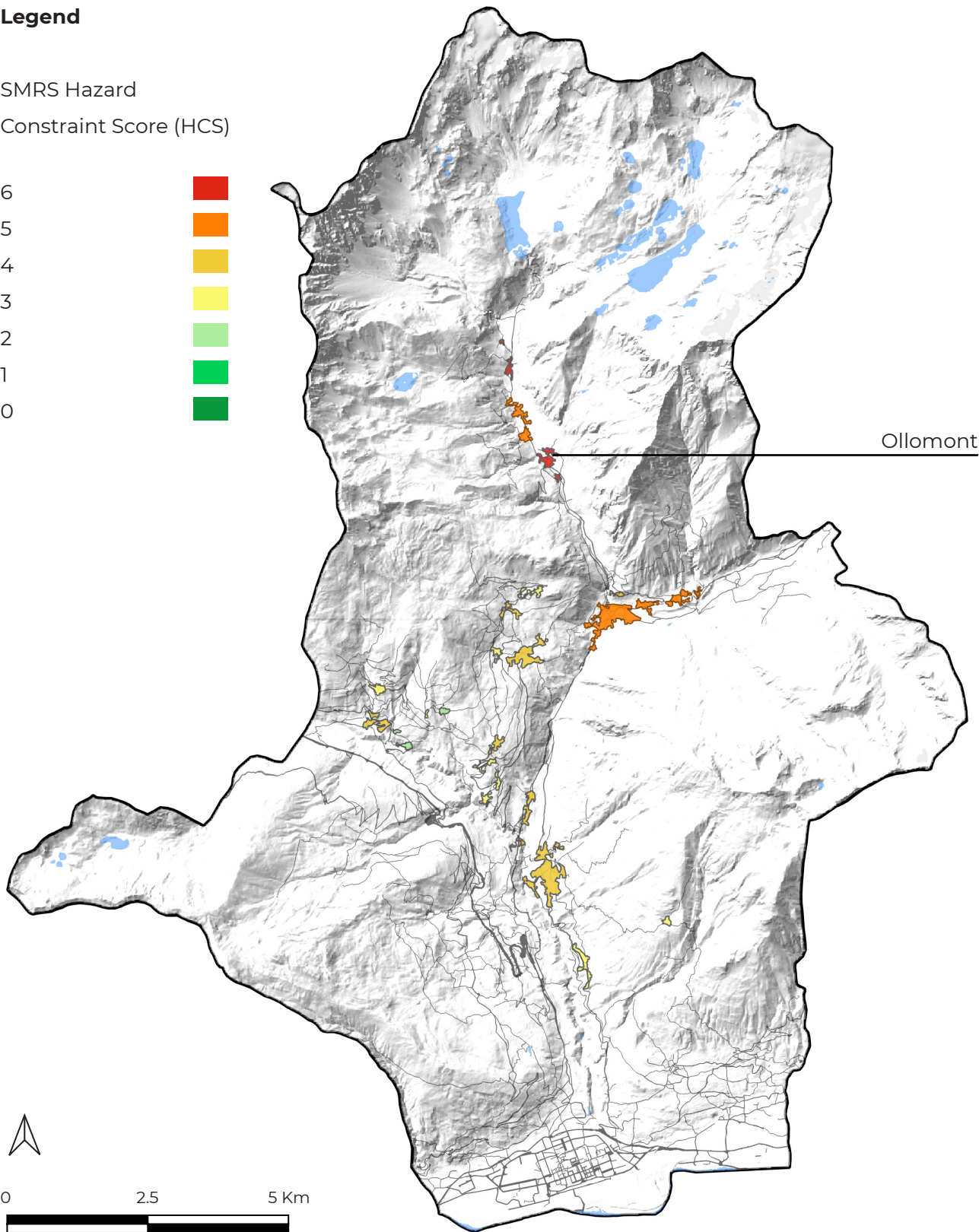
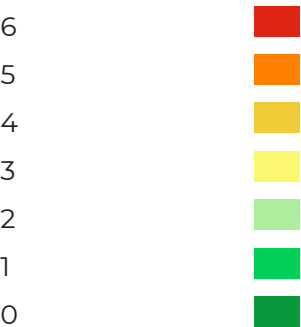
The Valpelline corridor contains 36 SMRS, of which the Ollomont settlement itself records the maximum possible HCS of 6, indicating simultaneous intersection with all three hazard types at the territorial level and compound blockage of its access corridor by multiple hazard processes. As visualized in Map E1, the HCS distribution across the corridor is notably severe: no settlement scores 0 or 1, confirming that every SMRS in the Valpelline catchment faces at least some degree of compound environmental constraint. The modal score is 4, recorded by 12 settlements (33.3%), while 10 settlements (27.8%) score 5 or 6 and represent the most critically constrained reinhabitation candidates in the corridor.

The spatial pattern visible in Map E1 reveals a clear altitudinal gradient in hazard constraint: settlements scoring 5 and 6 cluster in the upper valley where the confluence of steep slopes, confined torrent channels, and avalanche release terrain creates the densest hazard convergence. Settlements scoring 2 and 3 tend to occupy lower valley positions with wider floodplain buffers and more accessible road connections. The access corridor analysis underlying the HCS confirms that the primary blockage drivers in the Valpelline corridor are flood and landslide rather than avalanche, consistent with the confined hydraulic geometry of the valley and the extensive P4 Very High landslide susceptibility zones documented in Map C2. The slope gradient analysis shows that 25% of the Valpelline catchment exceeds 35°, the threshold above which shallow soil cover is structurally compromised and avalanche release becomes probable. A further 23% falls in the 27–35° bracket, associated with active landslide source zones. Together, terrain exceeding 27° accounts for nearly half the valley catchment, providing the geomorphological foundation for the hazard pattern documented in Maps C1 through C4.

E1. Hazard Constraint Score Map Of Ollomont

Legend

SMRS Hazard
Constraint Score (HCS)



6.3 Territorial Scale Results

6.3.2 Anzasca Valley (Macugnaga)

The Anzasca Valley contains 33 SMRS, of which the Macugnaga settlement records the maximum possible HCS of 6, matching Ollomont as the most severely constrained case study in the analytical framework. The corridor HCS distribution is more varied than Ollomont, with 6 settlements scoring 0 and 4 scoring 1, indicating that a meaningful subset of Anzasca Valley SMRS operate under minimal compound constraint. At the upper end, 8 settlements (24.2%) score 5 or 6, representing a proportionally smaller but still notable critically constrained population compared to the Valpelline corridor. The moderate scores concentrated in the central valley reflect the broader and more developed valley floor of the lower Anzasca system, where hazard zones tend to be less spatially concentrated than in the upper reaches of the catchment.

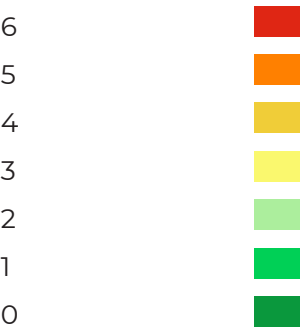
The spatial pattern in Map E2 shows a pronounced concentration of high-HCS settlements in the upper Anzasca corridor toward the Monte Rosa massif, where the convergence of glacial meltwater channels, steep lateral moraines, and avalanche couloirs creates the densest hazard convergence across the three study corridors. The access corridor analysis confirms that for Macugnaga specifically, blockage is driven by the combination of flood and landslide hazard along the sole provincial road connecting the settlement to the valley floor. The absence of alternative access routes means that any concurrent blockage event on this corridor would result in the complete physical isolation of the upper settlement cluster.

The slope gradient distribution for the Anzasca Valley is the most pronounced of the three case studies: 50% of the catchment exceeds 35°, more than double the equivalent figure for Elva and substantially higher than Ollomont's 25%. This reflects the direct proximity of the Monte Rosa massif, whose near-vertical granite faces dominate the northern and eastern catchment boundary and generate some of the most extreme relief differentials in the entire Alpine arc. A further 26% falls in the 27–35° bracket, meaning that 76% of the Anzasca catchment operates at gradients associated with active mass movement processes. The limited share of terrain below 17°, which corresponds to the narrow valley floor and lower terrace system where the majority of built settlement is concentrated, underscores the degree to which the Macugnaga building stock is compressed into a geomorphologically constrained corridor with very limited lateral expansion capacity. This geomorphological profile provides the structural context for why Macugnaga reaches the maximum HCS despite having a more varied corridor-level distribution than Ollomont, as the settlement itself occupies the most topographically constrained section of the valley where hazard convergence and access constraint are simultaneously at their most acute.

E2. Hazard Constraint Score Map Of Macugnaga

Legend

SMRS Hazard
Constraint Score (HCS)



Macugnaga



6.3 Territorial Scale Results

6.3.3 Maira Valley (Elva)

The Maira Valley contains 64 SMRS, the largest of the three corridor populations, and presents a fundamentally different hazard constraint profile from both alpine case studies. The Elva settlement records an HCS of 2, the near-minimum of the possible range, indicating that while some environmental constraint exists, the compound multi-hazard convergence characterizing Ollomont and Macugnaga is absent. As shown in Map E3, the corridor HCS distribution is concentrated in the low to moderate range: 5 settlements score 0, 18 score 1, and 16 score 2, meaning that 60.9% of Maira Valley SMRS operate under minimal or low compound constraint.

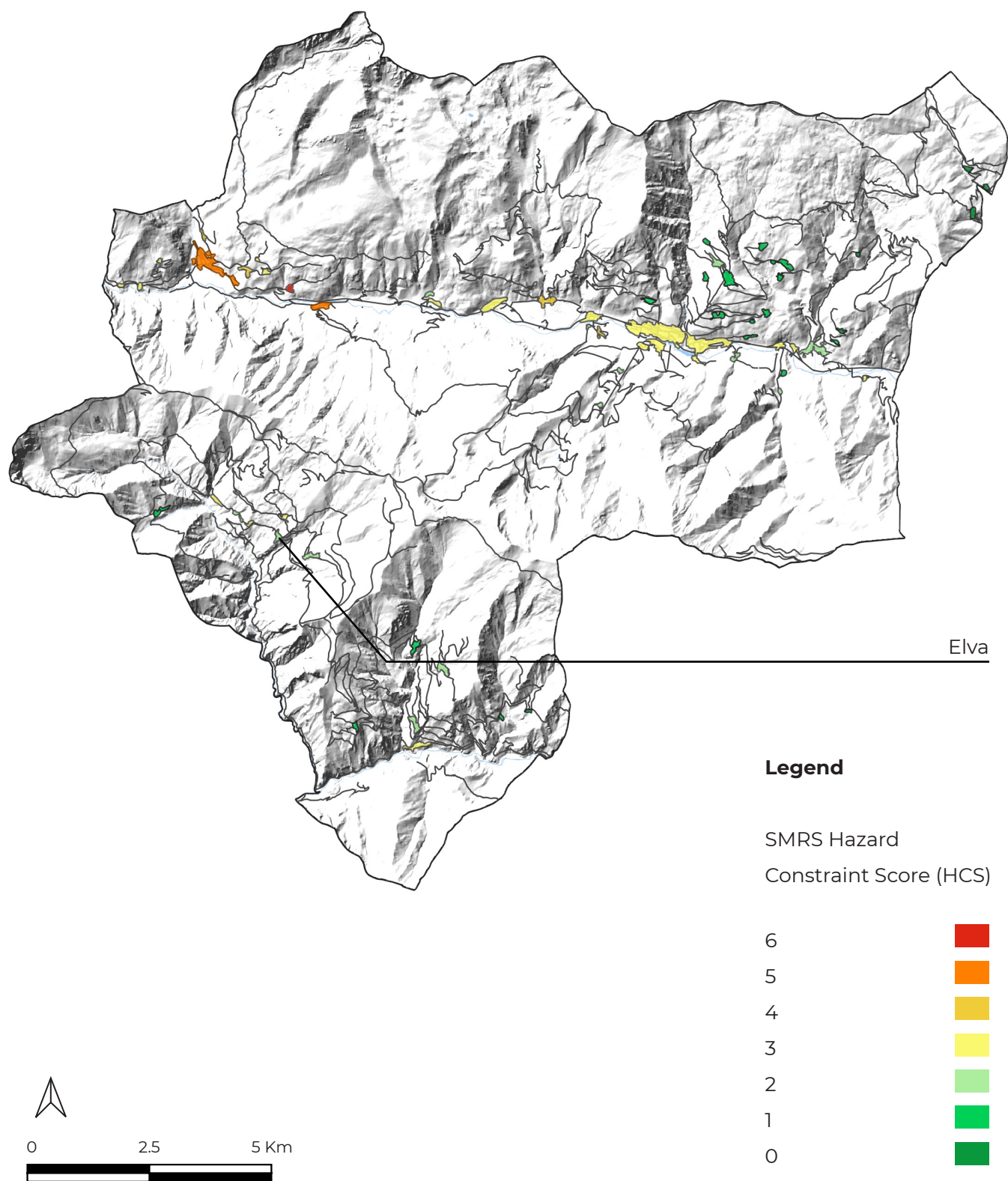
Only 1 settlement reaches HCS 6 and 2 reach HCS 5, confirming that extreme compound constraint is an isolated rather than systemic condition in this corridor. The spatial pattern in Map E3 is visually striking in its contrast with E1 and E2: the predominantly green and yellow-green palette across the valley reflects the lower hazard convergence, with the isolated orange and red cluster appearing in the upper left of the catchment where terrain steepens toward the Cottian Alps divide. The access corridor analysis confirms that flood hazard is the primary blockage driver in the Maira Valley, with landslide playing a secondary role and avalanche exposure largely absent from the road network at this corridor's elevation and orientation.

The slope gradient profile of the Maira Valley confirms its more moderate geomorphological character relative to the alpine case studies: only 23% of the catchment exceeds 35° and 30% falls in the 27–35° bracket. The largest single bracket is 17–27° at 30%, associated with moderate mass movement susceptibility rather than active source zone conditions. This distribution reflects the Maira Valley's position within the pre-alpine rather than high-alpine morphological system, where relief is substantial but does not reach the extreme gradients of the Monte Rosa or Monte Viso massifs.

The Maira Valley case therefore represents a methodologically important counterpoint within the three-valley comparative framework. Its low HCS profile demonstrates that the compound hazard constraint documented in the Valpelline and Anzasca corridors is not a universal condition of Alpine small settlement systems, but rather a function of specific high-alpine geomorphological configurations that not all mountain valleys share.

For Elva and the broader Maira corridor, the primary obstacles to reinhabitation are not physical but structural, rooted in decades of outmigration, the erosion of local service provision, and the loss of the agricultural and pastoral economies that historically sustained these communities.

E3. Hazard Constraint Score Map Of Elva



6.3 Territorial Scale Results

6.3.4 Comparative Synthesis

Table 21 summarizes the full Hazard Constraint Score (HCS) distribution, detailed in 6.3, across all three corridors, allowing direct comparison of the settlement-level hazard constraint profiles produced by the territorial scale analysis. Table 22 presents the slope gradient breakdown for each catchment, providing the geomorphological foundation underlying the HCS distributions.

HCS	Ollomont	Macugnaga	Elva
6	4	3	1
5	6	2	2
4	12	6	4
3	11	5	18
2	3	7	16
1	0	4	18
0	0	6	5
Total	36	33	64

Table 21. HCS Distribution Across Three Valley Corridors.
(Source: Author's elaboration)

Slope Bracket	Percentage of Territorial Area		
Territory	Ollomont	Macugnaga	Elva
≤ 9°	10	3	5
9° – 17°	13	5	12
17° - 27°	28	16	30
27° - 35°	23	26	30
> 35°	25	50	23

Table 22. Slope Gradient Distribution Across Three Valley Catchments.
(Source: Author's elaboration)

The three-valley comparison reveals two structurally distinct hazard constraint regimes within the study area. The Valpelline and Anzasca corridors share a high-constraint profile driven by high-alpine geomorphology, confined valley geometry, and singular road access corridors that concentrate multi-hazard blockage onto a single infrastructure spine. In both valleys the case study settlement itself scores at the maximum HCS, confirming that Ollomont and Macugnaga were not selected as exceptional cases but as representative examples of the most constrained class of SMRS within their respective regional systems.

The Maira Valley and Elva present a contrasting low-constraint profile in which demographic decline and cultural marginalization, rather than physical hazard convergence, constitute the primary reinhabitation barrier. With 60.9% of

6.3 Territorial Scale Results

6.3.4 Comparative Synthesis

SMRS scoring HCS 0 or 1 and Elva itself scoring only 2, the Maira corridor demonstrates that severe abandonment can occur in the relative absence of multi-hazard compound constraint. This finding is analytically significant: it confirms that the HCS does not predict abandonment but rather characterizes the physical conditions under which reinhabitation must be attempted, and that different valleys require fundamentally different intervention logics. Where Ollomont and Macugnaga demand hazard mitigation and infrastructure resilience as preconditions for reinhabitation, Elva's primary constraints are institutional, economic, and demographic, a distinction that carries direct implications for the policy recommendations developed in Chapter 7.

6.4 Settlement Scale Results

The settlement scale analysis descends to the highest spatial resolution of the analytical framework, intersecting individual building footprints with the hazard datasets active at each case study location to produce a building-level hazard exposure inventory. At this scale, the analysis is enriched by demographic and dwelling occupancy data drawn from the ISTAT 2021 Permanent Census, enabling a composite picture of physical hazard exposure, population structure, and building vacancy that together constitute the empirical foundation for reinhabitation feasibility assessment. Results are organized by settlement and presented through a series of figures and tables that move from building-level hazard intersection to dwelling occupancy patterns.

6.4.1 Ollomont

The Ollomont settlement cluster encompasses four distinct hamlets, Ollomont, Vouece, Le Clapey, and Le Morion, containing a combined total of 249 buildings and a permanent resident population of 128 people distributed across 70 occupied dwellings. The ratio of buildings to residents immediately signals the structural condition of the settlement: with an average of fewer than 0.6 permanent residents per structure, the Ollomont cluster operates under conditions of advanced demographic thinning in which much of the built fabric is seasonally occupied or entirely vacant.

6.4 Settlement Scale Results

6.4.1 Ollomont

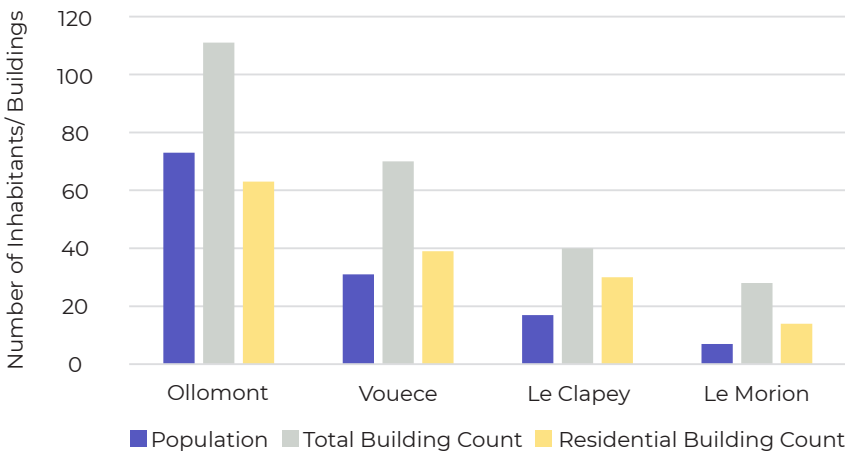


Figure 26. Population and Building Stock Distribution by Hamlet, Ollomont.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census available at : <https://www.istat.it/en/statistical-themes/censuses/permanent-census-of-population-and-housing>)

As shown in Figure 26, the main hamlet of Ollomont accounts for the majority of both the building stock (111 buildings) and the permanent population (73 residents), while Le Morion records the most extreme imbalance with only 7 residents across 28 structures. The building-to-population ratio worsens progressively from the main hamlet toward the dependent hamlets, confirming that demographic contraction has been most severe in the most isolated and topographically constrained portions of the settlement system.

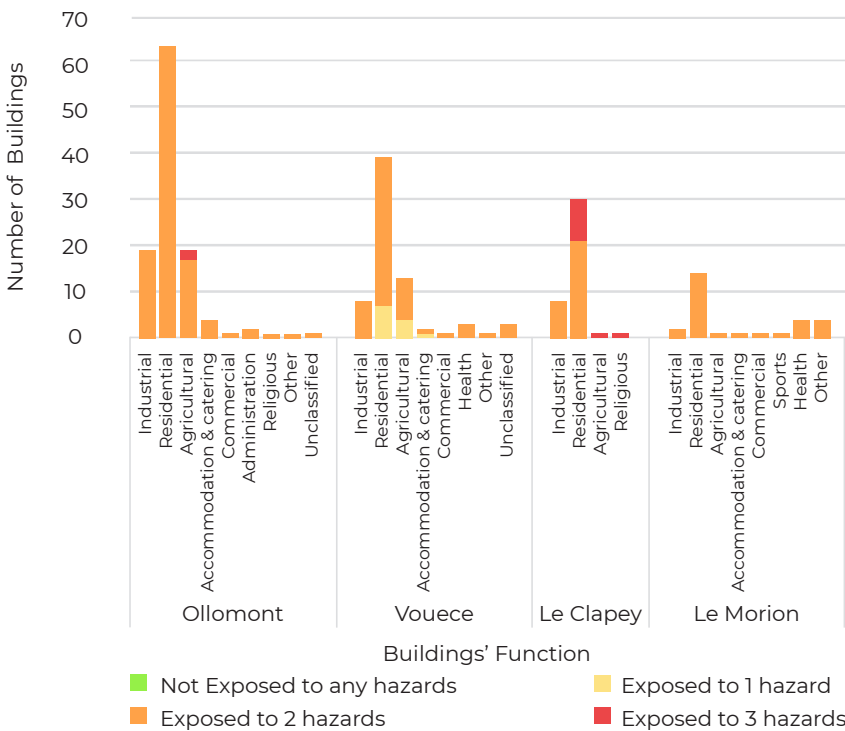


Figure 27. Building Hazard Exposure by Functional Type and Hamlet, Ollomont.
(Source: Author's elaboration)

6.4 Settlement Scale Results

6.4.1 Ollomont

The building-level hazard intersection, visualized in Figure 27 and summarized in Table 23, reveals that not a single building across all four hamlets records zero hazard exposure, the most absolute physical constraint profile in the three-case-study dataset. The main hamlet of Ollomont contains 111 buildings, of which 109 (98.2%) are exposed to two concurrent hazard types and 2 (1.8%) to all three simultaneously. The functional breakdown shows that all 63 residential buildings in the main hamlet are exposed to dual hazard, alongside all 19 industrial structures and all 15 agricultural infrastructure buildings, of which 2 record triple-hazard exposure. This universal exposure pattern means that no functional category within Ollomont offers a hazard-free reinhabitation option, a condition with direct implications for the prioritization of structural intervention in any future reinhabitation strategy.

Le Clapey presents the proportionally most severe profile within the cluster: of its 40 buildings, 11 (27.5%) record triple-hazard exposure, the highest concentration of structures exposed to all three hazard types in the entire three-case-study dataset. Critically, 9 of these 11 triple-hazard buildings are residential, meaning that the inhabited core of Le Clapey, not its peripheral or ancillary structures, faces the most acute compound physical constraint.

The convergence of avalanche, flood, and landslide zones over this small hamlet makes it the most constrained reinhabitation candidate within the Ollomont municipal boundary. Vouece records 70 buildings, of which 12 (17.1%) are exposed to a single hazard and 58 (82.9%) to two concurrent hazards, a slightly more moderate but still severely constrained profile. Le Morion, with 28 buildings all exposed to dual hazard, presents an additional dimension through the overlap of the mine park boundary with 2 mining structures, as documented in Table 23.

Settlement Name	Total Buildings	Not Exposed (0)	Exposed to 1 Hazard (1)	Exposed to 2 Hazards (2)	Exposed to 3 Hazards (3)	HCS
Ollomont	111	0	0	109	2	6
Vouece	70	0	12	58	0	5
Le Clapey	40	0	0	29	11	6
Le Morion	28	0	0	28	0	5
	Total Mines					
Le Morion	2	0	2	0	0	-

Table 23. Building and Mine Hazard Exposure by Settlement, Ollomont. (Source: Author's elaboration)

6.4 Settlement Scale Results

6.4.1 Ollomont

The demographic profile of the Ollomont cluster, shown in Figure 28, confirms a deeply aged population structure. Across all four hamlets, the 50–59 age bracket is the largest single cohort, with 29 residents, followed by the over-70 group with 23 residents. By contrast, the combined 0–19 population across the entire cluster totals only 17 individuals, representing 13.3% of the permanent population. This severe age compression means that the current resident population cannot sustain natural demographic renewal and that reinhabitation would require attracting working-age residents from outside the existing community rather than relying on internal generational succession.

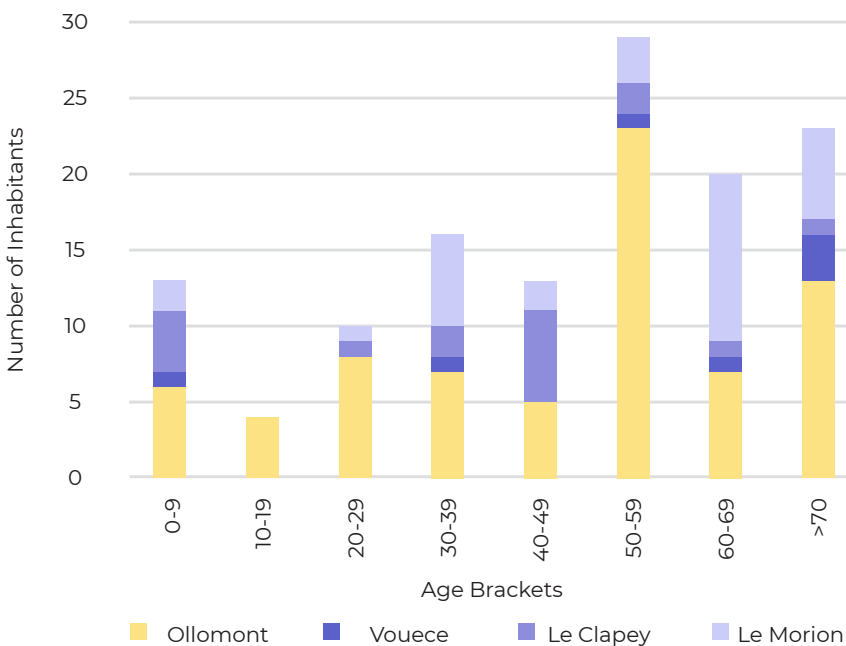


Figure 28. Age Structure by Hamlet, Ollomont.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The household composition and dwelling occupancy data, presented in Figure 29, deepen this picture further. Single-person households constitute the largest household category across the cluster with approximately 38 units, consistent with an elderly population in advanced stages of household dissolution following spousal bereavement or family outmigration. The dwelling occupancy data, summarized in Table 24, reveals significant vacancy rates across all four hamlets: Le Clapey records the most extreme condition with only 9 occupied dwellings against 21 unoccupied, a vacancy rate of 70%. Le Morion records 64% vacancy (5 occupied, 9 unoccupied), while Ollomont and Vouece show more moderate but still substantial

6.4 Settlement Scale Results

6.4.1 Ollomont

vacancy at 46% and 44% respectively. These vacancy figures confirm that the building stock documented in the hazard intersection analysis substantially overstates the number of permanently inhabited structures, and that the effective reinhabitation challenge involves not only hazard mitigation but the reactivation of a largely dormant building stock.

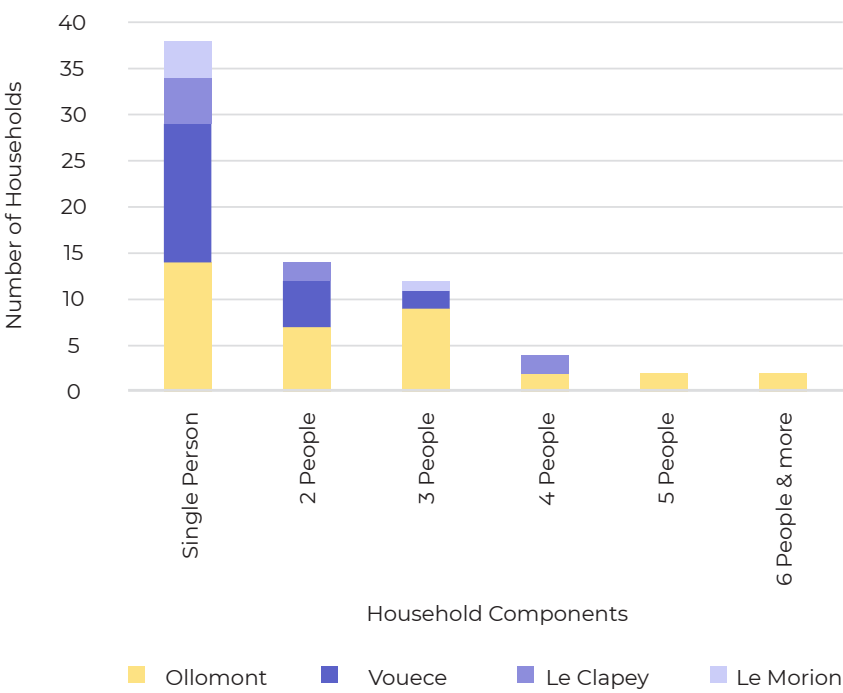


Figure 29. Household Composition and Dwelling Occupancy, Ollomont. (Source: Author's elaboration based on ISTAT 2021 Permanent Census)

Settlement	Occupied Dwellings	Unocupied Dwellings
Ollomont	34	29
Vouece	22	17
Le Clapey	9	21
Le Morion	5	9

Table 24. Dwelling Occupancy by Hamlet, Ollomont. (Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The foreign and stateless resident population across the Ollomont cluster is negligible, with only 2 foreign residents in the main hamlet and 3 in Le Morion, confirming that unlike some Italian inner areas where foreign immigration has partially offset native depopulation, the Ollomont cluster has not experienced this form of demographic stabilization.

6.4 Settlement Scale Results

6.4.2 Macugnaga

The Macugnaga settlement cluster encompasses two primary hamlets, Staffa and Pecetto, containing a combined total of 562 buildings and a permanent resident population of 289 people distributed across 157 occupied dwellings.

Unlike Ollomont, where the entire building stock is exposed to hazard, the Macugnaga cluster presents a more internally differentiated profile in which the majority of buildings sit outside active hazard zones but a concentrated subset faces extreme compound exposure. The ratio of buildings to residents, at approximately 1.9 buildings per permanent resident, reflects the well-documented seasonal occupation pattern of Alpine tourism settlements where a large share of the building stock functions as second homes or holiday accommodation rather than permanent residences.

As shown in Figure 30, Staffa contains 408 buildings with 219 permanent residents, while Pecetto contains 154 buildings with 70 residents. The size asymmetry between the two hamlets is pronounced, yet both record similarly elevated building-to-population ratios that confirm the dominance of non-permanent occupation across the cluster.

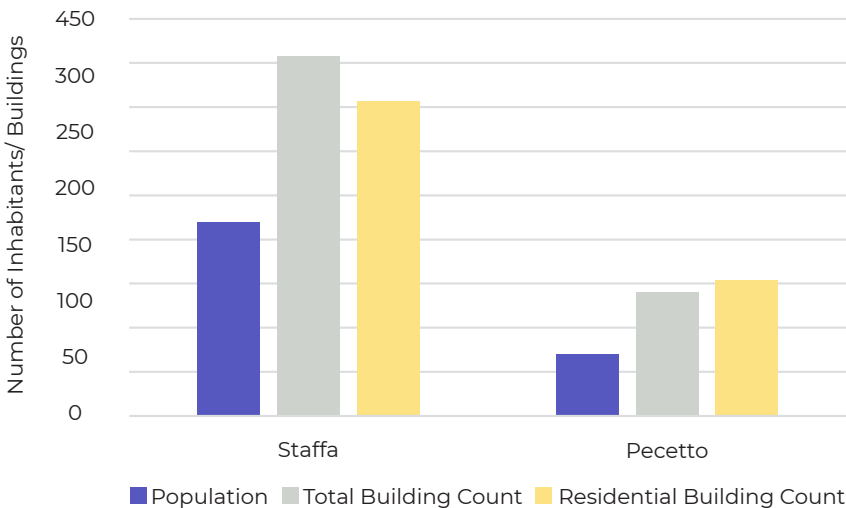


Figure 30. Population and Building Stock Distribution by Hamlet, Macugnaga.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The building-level hazard intersection, visualized in Figure 31 and summarized in Table 25, reveals that Staffa's exposure is concentrated in its residential core. Of 408 total buildings, 301 (73.8%) record no hazard intersection, confirming that the majority of the Staffa building stock occupies terrain outside the active hazard zone boundaries.

6.4 Settlement Scale Results

6.4.2 Macugnaga

However, 61 buildings (15.0%) are exposed to two concurrent hazard types and 44 (10.8%) to all three simultaneously. The functional breakdown shows that 39 of these 44 triple-hazard buildings are residential, alongside 2 public administration buildings and isolated religious and commercial structures. This concentration of triple-hazard exposure within the inhabited residential core of upper Staffa, visible in Map D7, constitutes the most acute building-level reinhabitation constraint in the Macugnaga cluster. Pecetto records 154 buildings, of which 114 (74.0%) are not exposed, 29 (18.8%) are exposed to two hazard types, and 10 (6.5%) to three, with exposed buildings concentrating along its northern edge where avalanche and flood zones extend onto the lower moraine terrace.

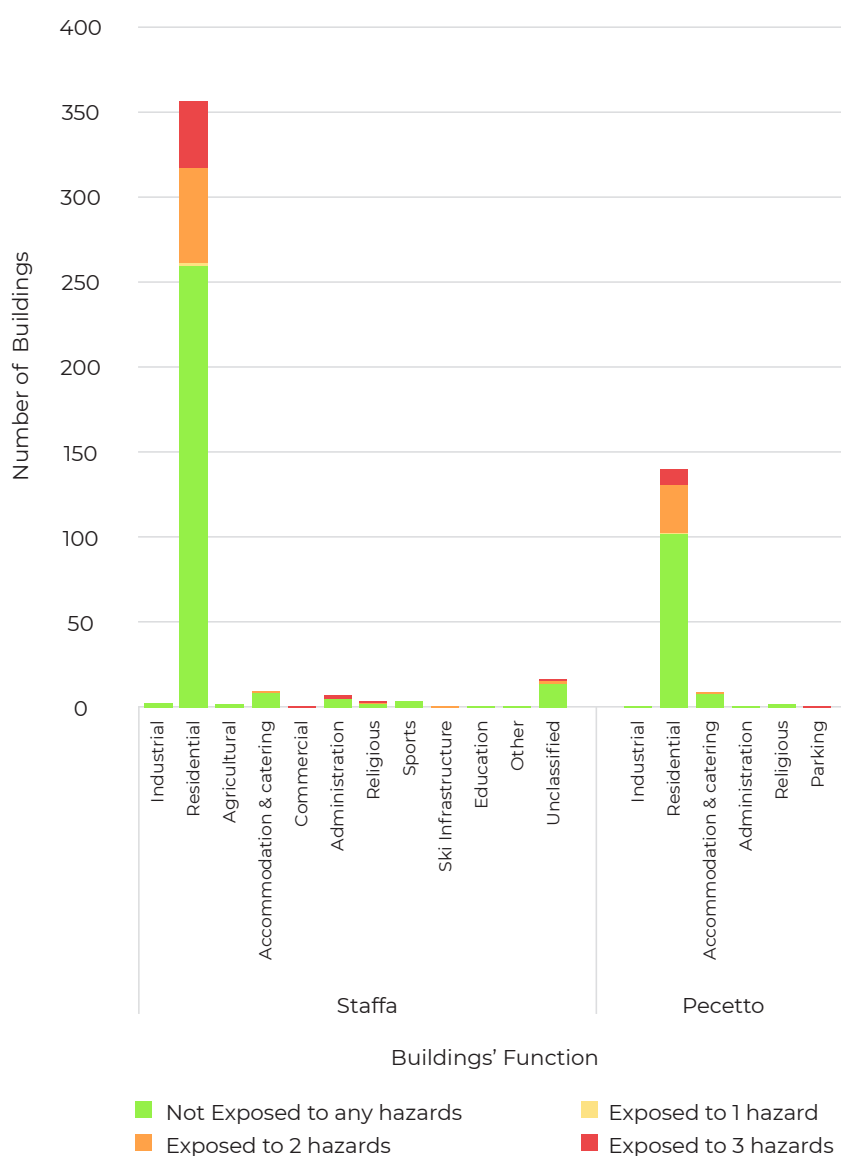


Figure 31. Building Hazard Exposure by Functional Type and Hamlet, Macugnaga.
(Source: Author's elaboration)

6.4 Settlement Scale Results

6.4.2 Macugnaga

The mining asset analysis documented in Table 25 reveals an additional layer of complexity. Staffa contains 14 mining buildings, of which 7 are not exposed, 5 are exposed to two hazards, and 2 to three hazards.

Pecetto contains 2 mining structures, one not exposed and one exposed to three hazards. Unlike the Ollomont mine park, which represents formally repurposed heritage tourism infrastructure, the Macugnaga mining buildings correspond to the former Pestarena gold mine complex, currently under inactive concession. Their hazard exposure profile confirms that any future adaptive reuse would require addressing compound natural hazard constraints alongside the regulatory complexities of the mining concession boundary.

Settlement Name	Total Buildings	Not Exposed (0)	Exposed to 1 Hazard (1)	Exposed to 2 Hazards (2)	Exposed to 3 Hazards (3)	HCS
Staffa	408	301	2	61	44	6
Pecetto	154	114	1	29	10	6
	Total Mines					
Staffa	14	7	0	5	2	-
Pecetto	2	1	0	0	1	-

Table 25. Building and Mine Hazard Exposure by Settlement, Macugnaga. (Source: Author's elaboration)

The demographic profile shown in Figure 32 reveals an aging population structure broadly consistent with the Ollomont pattern. It is also worth noting that the population trends in both Staffa and Pecetto follow the same trends.

The dominant cohort reveals that most of the population in these settlements are older than 60 with 96 residents over 60 years old in Staffa and 26 in Pecetto which account for 43% and 37% of their population respectively. The combined working-age population (20–49) is proportionally larger than in Ollomont, consistent with seasonal employment in the ski and hospitality sector, counting up to around 28% in each locality.

However permanent young residents (0–19) remain a small minority of the population with only 5% aging between 0–9 in both settlements, confirming that natural demographic renewal is not occurring within the existing resident population.

6.4 Settlement Scale Results

6.4.2 Macugnaga

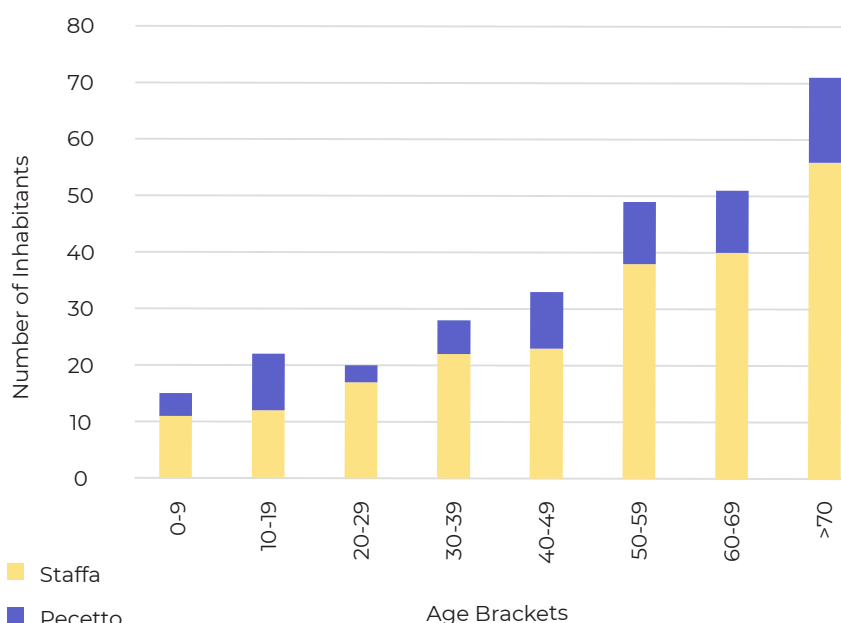


Figure 32. Age Structure by Hamlet, Macugnaga.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The household composition and dwelling occupancy data, presented in Figure 33 and summarized in Table 26, confirm the dominant role of single-person households, with 73 single-person units in Staffa, the largest single household category by a considerable margin. The overwhelming predominance of single-person and two-person households across both hamlets is consistent with an elderly resident population in advanced stages of household dissolution, compounded by the outmigration of younger family members.

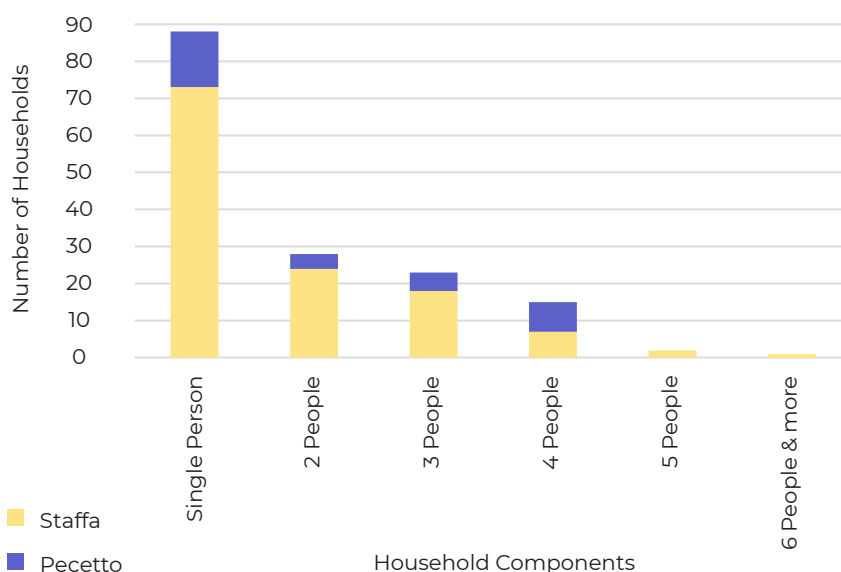


Figure 33. Household Composition and Dwelling Occupancy, Macugnaga.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

6.4 Settlement Scale Results

6.4.2 Macugnaga

Settlement	Occupied Dwellings	Unoccupied Dwellings
Staffa	125	232
Pecetto	32	108

Table 26. Dwelling Occupancy by Hamlet, Macugnaga.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The dwelling occupancy data in Table 26 confirms significant vacancy across both hamlets: Staffa records 232 unoccupied dwellings against 125 occupied, a vacancy rate of 65%, while Pecetto records 108 unoccupied against 32 occupied, a rate of 77%. The foreign resident population is minimal with 4 foreign residents in Staffa and 3 in Pecetto, confirming that foreign immigration has not compensated for native demographic decline in the Anzasca Valley context.

6.4.3 Elva

The Elva settlement cluster encompasses six dispersed hamlets, Serre, Gorla, Martini, Villar, Clari, and Rinaud, containing a combined total of 158 buildings and a permanent resident population of only 40 people distributed across 23 occupied dwellings. These figures represent the most extreme demographic-to-building ratio in the three-case-study dataset, with an average of fewer than 0.25 permanent residents per structure, meaning that three out of every four buildings in the Elva cluster have no permanent resident. This single statistic encapsulates the depth of demographic collapse in the Maira Valley more than any hazard metric.

As shown in Figure 34, Gorla presents the most extreme individual hamlet profile with 49 buildings and only 7 permanent residents, a building-to-population ratio of 7:1. Serre, the largest hamlet with 46 buildings, records 11 residents, while Martini (33 buildings, 7 residents), Villar (12 buildings, 6 residents), Clari (9 buildings, 2 residents), and Rinaud (9 buildings, 7 residents) all show the same pattern of substantial building stock supporting minimal permanent occupation. The significant volume of building stock relative to the tiny permanent population also reflects the historical legacy of traditional, multi-functional alpine architecture that has outlived its original socio-economic context. Consequently, these hamlets face a critical governance challenge where a massive architectural heritage must be maintained by an almost non-existent local tax and labor base.

6.4 Settlement Scale Results

6.4.3 Elva

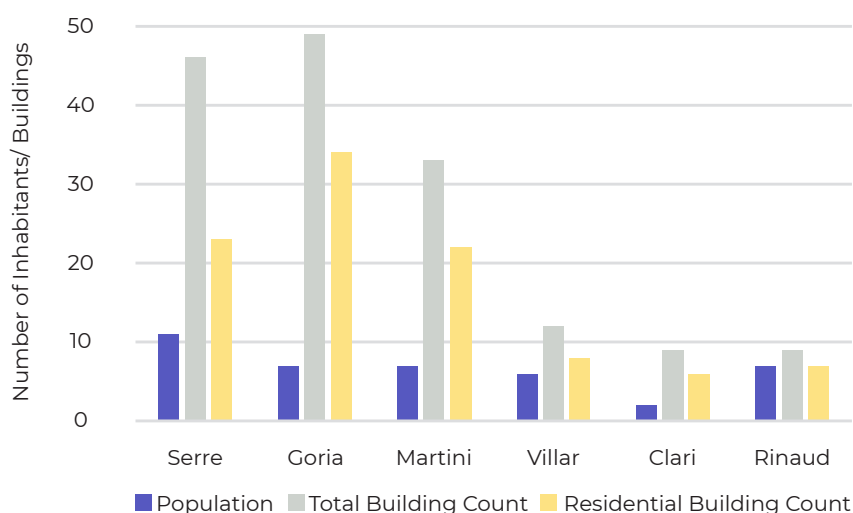


Figure 34. Population and Building Stock Distribution by Hamlet, Elva.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The building-level hazard intersection, visualized in Figure 35 and summarized in Table 27, presents a fundamentally different picture. As shown in Figure 35, 126 of 158 buildings (79.7%) record zero hazard exposure, confirming that the compound multi-hazard convergence characterizing Ollomont and Macugnaga is largely absent from this settlement system. Serre, Gorìa, Villar, Clari, and Rinaud record complete non-exposure across their entire building stocks. The sole anomaly is the Martini hamlet, where 32 of 33 buildings (97.0%) are exposed to a single hazard type, a localized landslide susceptibility zone extending across the hamlet's eastern slope, visible in Map D9. While meaningful, this single-hazard exposure does not approach the compound multi-hazard convergence of the alpine case studies. The functional composition across all six hamlets reflects the predominantly residential and agricultural character of the settlement, with rural buildings and minor ancillary structures comprising a significant share of the inventory alongside the residential core.

Settlement Name	Total Buildings	Not Exposed (0)	Exposed to 1 Hazard (1)	Exposed to 2 Hazards (2)	Exposed to 3 Hazards (3)	HCS
Serre	43	43	0	0	0	2
Gorìa	49	49	0	0	0	2
Martini	33	1	32	0	0	3
Villar	12	12	0	0	0	3
Clari	9	9	0	0	0	2
Rinaud	9	9	0	0	0	2

Table 27. Building and Mine Hazard Exposure by Settlement, Elva.
(Source: Author's elaboration)

6.4 Settlement Scale Results

6.4.3 Elva

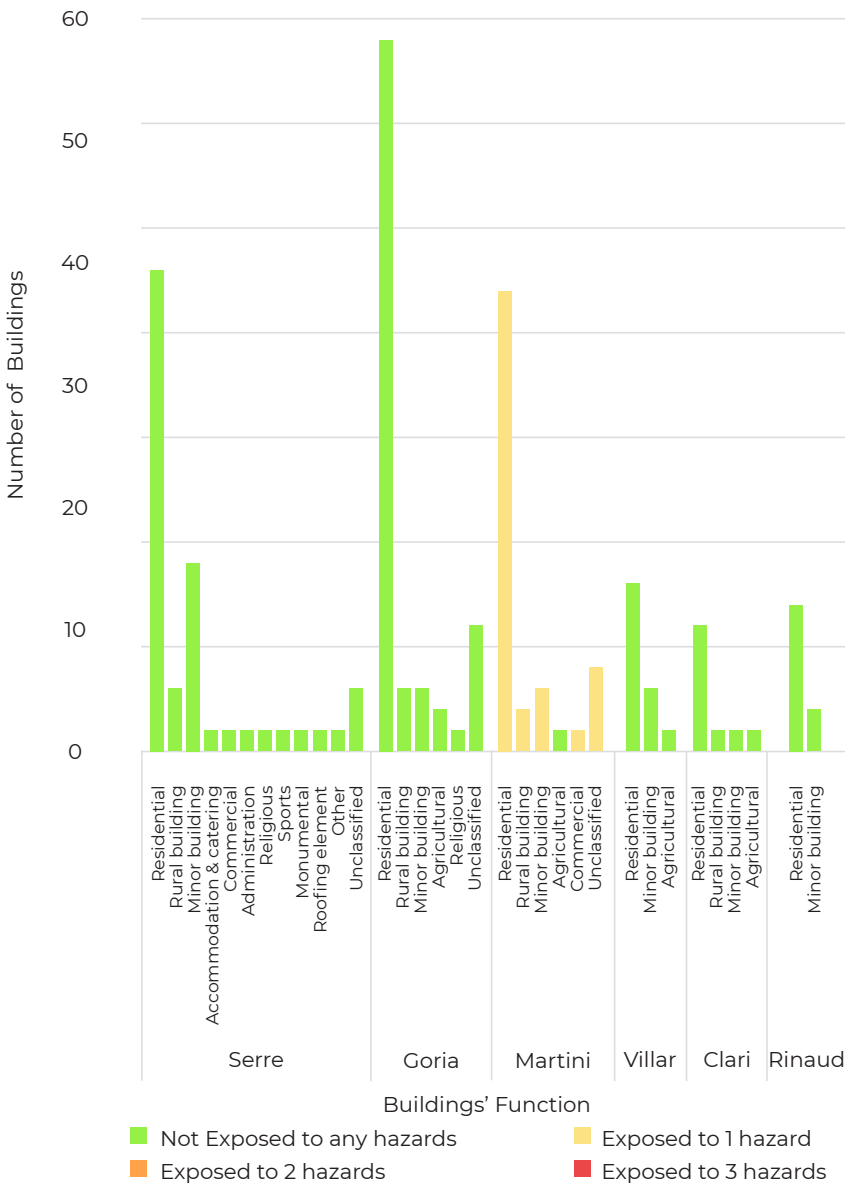


Figure 35. Building Hazard Exposure by Functional Type and Hamlet, Elva. (Source: Author's elaboration)

The demographic profile shown in Figure 36 reveals the most acute aging structure in the dataset. With a total permanent population of only 40 residents across six hamlets, the over-50 population represents the overwhelming majority of permanent residents, while the combined 0–19 population across the entire Elva cluster is negligible. The foreign resident population is zero across all six hamlets, distinguishing Elva even from Ollomont and Macugnaga where small numbers of foreign residents are present, and confirming that the demographic stabilization mechanism observed in some Italian inner areas has not operated in the Maira Valley at the hamlet scale.

6.4 Settlement Scale Results

6.4.3 Elva

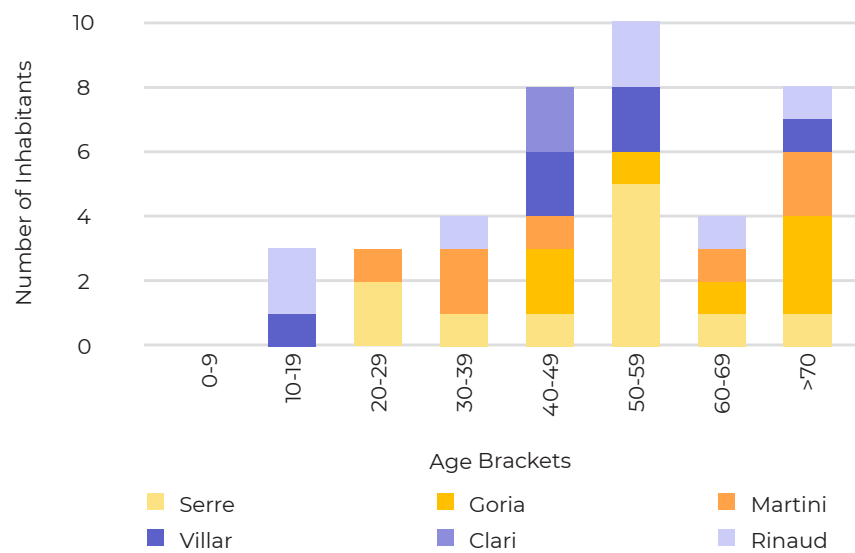


Figure 36. Age Structure by Hamlet, Elva.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The household composition and dwelling occupancy data, presented in Figure 37 and summarized in Table 28, show single-person households as the dominant category across the cluster, consistent with the extreme elderly skew of the population. The near-total absence of households with four or more members confirms that family-unit occupation, which might support building maintenance and intergenerational property succession, has effectively ceased across most of the Elva hamlet system.

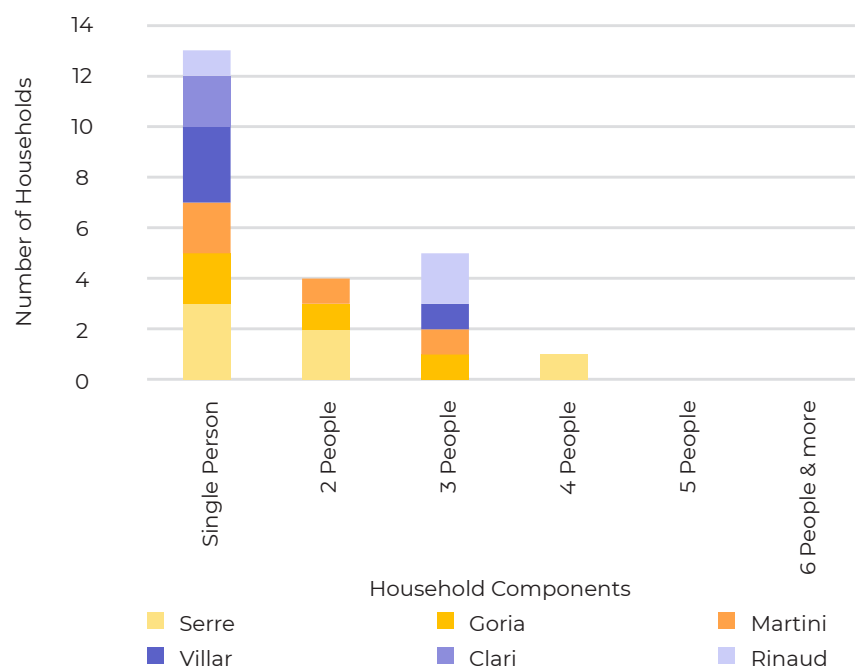


Figure 37. Household Composition and Dwelling Occupancy, Elva.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

6.4 Settlement Scale Results

6.4.3 Elva

Settlement	Occupied Dwellings	Unocupied Dwellings
Serre	6	17
Goria	4	30
Martini	4	18
Villar	4	4
Clari	2	4
Rinaud	3	4

Table 28. Dwelling Occupancy by Hamlet, Elva.
(Source: Author's elaboration based on ISTAT 2021 Permanent Census)

The vacancy data in Table 28 confirms the most extreme occupancy conditions in the dataset: Goria records 30 unoccupied dwellings against only 4 occupied, a vacancy rate of 88%. Serre records 17 unoccupied against 6 occupied (74% vacant), while Martini records 18 unoccupied against 4 occupied (82% vacant). The absence of mining assets and debris flow data from the Elva analysis reflects both the distinct economic history of the Maira Valley and the data availability constraints discussed in Section 5.5.3.

6.4.4 Comparative Synthesis

The three settlements present three distinct reinhabitation profiles that cannot be reduced to a single constraint axis. Ollomont combines universal building-level hazard exposure with advanced demographic aging and moderate vacancy, making physical hazard mitigation one of the main preconditions for any reinhabitation strategy. Macugnaga presents a spatially differentiated profile where hazard exposure is severe but localized, vacancy is driven by seasonal tourism patterns rather than pure abandonment, and heritage mining infrastructure adds institutional complexity to the physical constraint picture. Elva, with 82.9% of buildings unexposed and a vacancy rate reaching 88% in Goria, confronts a condition where the building stock has effectively outlasted its resident population, a challenge that no amount of hazard mitigation can resolve without first addressing the demographic and institutional barriers to permanent reoccupation. Taken together, the three case studies confirm that reinhabitation feasibility is the product of compound interactions between geomorphological constraint, building vacancy, demographic aging, and heritage complexity, interactions that demand differentiated intervention logics and that can only be fully documented at the settlement scale.

7 Discussion and Conclusions

7.1 From Questions to Findings

This thesis set out to investigate whether hazard-aware, data-driven spatial documentation, integrating multiscale geospatial datasets and MHC-inspired documentation methods, could support the evaluation of conditions under which viable, safe, and strategic pathways for the reinhabitation of small mountain villages and historical centers can be identified. The empirical findings presented in Chapters 5 and 6 confirm that this is possible and the four-scale framework developed, produces analytically meaningful and operationally usable differentiation between reinhabitation contexts that a single-scale approach might not be able to achieve.

The question of which multiscale spatial datasets are most relevant for documenting settlement structure, accessibility, and environmental hazard in alpine contexts is answered directly by the methodology developed in Chapter 5. The national ISTAT locality dataset, filtered through DEGURBA and EEA mountain chain criteria, provides the demographic and settlement boundary foundation. The ISPRA IdroGEO platform, the regional PAI landslide datasets, and the ARPA Piemonte and SCT Valle d'Aosta avalanche inventories provide the hazard evidence base. The BDTRE and uso suolo fabbricato cadastral layers provide the building-level physical inventory. Together, these datasets, all publicly available through institutional geoportals, constitute a sufficient and replicable data architecture for hazard-aware settlement documentation at the scales required for reinhabitation assessment. The principal constraint is not data availability but data harmonization: the structural asymmetry between Piedmont and Valle d'Aosta datasets, documented throughout Chapter 5, reflects a persistent interoperability deficit in Italian regional environmental information systems that currently prevents fully standardized cross-regional analysis.

The question of how different spatial scales can be integrated within a unified GIS-based workflow is answered by the framework itself. The four-scale progression from national settlement inventory through regional hazard exposure to territorial corridor analysis and building-level intersection constitutes a coherent analytical hierarchy in which each scale conditions the interpretation of the next. The national scale establishes the population of candidate settlements and their institutional positioning within the Inner Areas framework. The regional scale identifies which corridors face compound multi-hazard constraint and which operate under more moderate conditions. The territorial scale disaggregates corridor-level findings into settlement-specific accessibility and land cover profiles, producing the Hazard Constraint Score as a composite measure of compound environmental constraint. The settlement scale descends to the building footprint, producing the granular physical, demographic, and occupancy inventory

7.1 From Questions to Findings

that constitutes the direct input for reinhabitation planning decisions. No single scale is sufficient in isolation, the Martini anomaly in Elva, where 32 of 33 buildings are exposed to a single landslide zone despite the valley's overall low-constraint profile, illustrates precisely how corridor-level scores can mask localized conditions that only building-level intersection reveals.

The question of how environmental hazards spatially correlate with demographic decline, service accessibility, and infrastructural fragility is answered by the regional scale findings. In Valle d'Aosta, where 97.8% of SMRS face at least one hazard intersection and 18.0% face triple-hazard convergence, environmental constraint and demographic decline operate as mutually reinforcing processes rather than independent variables. The physical inaccessibility and geomorphological instability of Valle d'Aosta's mountain corridors actively compounds the socioeconomic pressures driving depopulation, creating a feedback dynamic in which hazard exposure accelerates abandonment and abandonment in turn reduces the maintenance capacity that might otherwise mitigate hazard impacts. The three case studies confirm this relationship at the settlement scale: in Ollomont, where not a single building is unexposed, the 70% vacancy rate in Le Clapey and the 13.3% share of residents under 19 years old confirm that physical constraint and demographic depletion have advanced in tandem over decades. Macugnaga, where the triple-hazard cluster in upper Staffa coincides with the most historically significant portion of the settlement fabric, shows how hazard exposure has selectively concentrated precisely where heritage value is highest, a pattern with direct implications for the prioritization of conservation investment. However, it is worth mentioning that hazards alone, are not the single reason for depopulation, but a contributor that shouldn't be overlooked.

The question of which hazard indicators most strongly constrain reinhabitation potential is answered differently across the three case studies. In the Valpelline and Anzasca corridors, the convergence of PAI P4 Very High landslide susceptibility with flood HPH zones on the sole access road constitutes the primary reinhabitation constraint, with avalanche playing a secondary but significant role in the upper settlement clusters. In the Maira Valley, flood hazard along the river corridor is the primary access constraint, but its impact is substantially lower than in the other cases due to the valley's broader morphological geometry and more ramified road network. This finding confirms that hazard constraint is not a uniform condition across alpine Italy but a geomorphologically specific outcome of each valley's terrain configuration, hydraulic geometry, and access infrastructure, a conclusion that could not have been reached without the territorial scale corridor analysis.

7.2 The Multiscale Framework as a Decision-Support Tool

The framework developed in this thesis constitutes a functional prototype of the decision-support tool proposed in the thesis objective. By integrating national statistical boundaries, regional hazard inventories, territorial slope and accessibility analysis, and settlement-level building intersection into a single GIS workflow, it produces a structured and replicable evidence base that local administrations, regional planners, and heritage conservation bodies can use to evaluate reinhabitation potential in a systematic and hazard-aware manner.

The Hazard Constraint Score, combining internal hazard exposure with access corridor blockage into a composite integer measure from 0 to 6, represents the most operationally direct output of the territorial scale analysis. Its value as a decision-support metric lies not in its numerical precision but in its capacity to differentiate between settlement profiles that aggregate statistics obscure: the contrast between Ollomont's maximum HCS of 6 and Elva's score of 2 encodes a fundamentally different reinhabitation logic that no single hazard layer or demographic indicator alone could communicate. At the same time, the HCS is explicitly presented as a constraint characterization tool rather than a feasibility verdict, it documents the conditions under which reinhabitation must be attempted, not whether reinhabitation should be pursued. That determination requires the integration of social, economic, institutional, and heritage value dimensions that the current framework does not yet capture, and that constitute the primary direction for future development discussed in Section 7.4.

The framework's replicability is confirmed by its data architecture. Every dataset used in this analysis is publicly available through institutional geoportals operating under open licensing frameworks, and the GIS operations documented in Tables 15 through 28 are executable in open-source QGIS without proprietary software dependencies. This means the framework can in principle be applied to any SMRS population in the Italian Alpine arc where equivalent regional hazard data exists, and can be extended to other mountain regions in Europe where comparable institutional data infrastructures operate. The Ollomont debris flow intersection demonstrated in Map D3 illustrates the methodology's scalability to additional hazard process types wherever certified regional datasets are available. The same intersection logic applied to debris flow zones could equally be extended to seismic vulnerability maps, wind hazard classifications, wildfire risk perimeters, or any other formally certified hazard dataset published by regional environmental authorities, making the settlement scale framework adaptable to the specific geomorphological and climatic hazard profile of any target region rather than limited to the flood, landslide, and avalanche triad examined here.

7.3 Differentiated Reinhabitation Logics

One of the most significant analytical contributions of the three-case-study comparison is the confirmation that reinhabitation feasibility is not a spectrum with a single worst-case and best-case end but a multi-dimensional space in which different settlements face fundamentally incommensurable constraint profiles requiring different intervention logics.

For Ollomont, where the entire building stock of 249 structures is exposed to at least two concurrent hazard types, where Le Clapey records 27.5% triple-hazard building exposure, and where the resident population of 128 people is aging rapidly with only 13.3% under 19 years old, reinhabitation is physically preconditioned on hazard mitigation at the infrastructure and building scale. No demographic attraction strategy, heritage certification initiative, or fiscal incentive can be effective without first addressing the structural conditions that make the settlement physically unsafe for permanent occupation. The primary intervention axis for Ollomont is therefore engineering and risk governance: torrent channelization, slope stabilization, road reinforcement against flood and landslide blockage, and the formal integration of the mine park heritage infrastructure into a hazard-managed tourism and community reuse framework.

For Macugnaga, where 73.8% of Staffa's building stock is not exposed and the settlement retains an active if seasonally concentrated economic life through ski and mountain tourism, the reinhabitation challenge is more spatially targeted. The 44 triple-hazard residential buildings in upper Staffa represent a critical vulnerability node that requires selective intervention, potentially relocation of the most severely exposed residential cluster, engineering protection for the access corridor along the provincial road, and formal hazard assessment of the former Pestarena mine complex before any adaptive reuse can proceed. The majority of the building stock, however, occupies relatively safe terrain and could in principle support permanent reinhabitation through targeted incentive policies, second-home conversion programs, and the development of year-round economic alternatives to seasonal ski tourism, which faces increasing uncertainty under climate change projections for Alpine snowpack.

For Elva, where 82.9% of buildings are unexposed and the primary constraint is the near-total collapse of the resident population to 40 people distributed across 158 buildings, the intervention logic is entirely different. Hazard mitigation is not the limiting factor, the Maira Valley's more moderate geomorphological profile means that the physical conditions for reinhabitation are substantially present. What is missing is the demographic and institutional foundation for sustainable

7.3 Differentiated Reinhabitation Logics

reoccupation: a resident community capable of maintaining common infrastructure, accessing services, and sustaining the social fabric that makes rural life viable over the long term. The functional building inventory makes this service deficit concrete: across all six hamlets, only a single public administration building exists in Serre, alongside one sports facility, two commercial service structures in Serre and Martini respectively, and a single accommodation building in Serre. No health facilities and no educational infrastructure are present anywhere in the settlement cluster. This near-total absence of public service infrastructure within the built fabric is itself a reinhabitation barrier, independent of and compounding the demographic collapse documented in Chapter 6.

Elva is nonetheless already the subject of one of Italy's most significant reinhabitation investment experiments. In 2022 Elva won the Linea A competition of the Piano Nazionale Borghi, a PNRR-funded program supporting the regeneration of settlements at risk of abandonment, receiving 20 million euros, one of 21 Italian borghi selected nationally. The funding supports eleven projects including university partnerships with the University of Turin, the University of Gastronomic Sciences of Pollenzo, and the Politecnico di Torino, alongside an astronomical observatory, a mountain forestry facility, and a museum dedicated to the Flemish painter Hans Clemer, author of the frescoed altarpiece in Elva's church.

However, the case of Elva has become emblematic of the structural difficulties of the Piano Nazionale Borghi: the administrative architecture of the program, with its complex reporting requirements and urban-oriented procurement procedures, has placed extraordinary demands on a municipality that before the PNRR award did not have a strong administrative system (Bongioanni, 2025).

The Elva case therefore illustrates both the opportunity and the limitation of top-down reinhabitation funding. The 20 million euro investment was allocated on the basis of heritage value and project quality. A framework such as the one developed here, had it been available and consulted during the candidacy process, could have informed the spatial targeting of the eleven project interventions, directing investment toward the hamlets and building typologies where reinhabitation potential is highest and service infrastructure gaps are most acute. The Borghi Più Belli d'Italia certification framework, which has not yet reached Elva despite the PNRR recognition of its heritage value, could further amplify the long-term institutional visibility of the settlement beyond the PNRR funding cycle, which is scheduled to end in 2026.

7.4 Data Gaps and the Building Vulnerability and Heritage Index

The settlement scale analysis documented in Chapter 6 reveals a structural limitation that no amount of methodological refinement within the current framework can resolve: the building footprint intersection captures what hazard zones overlap with each structure, but it cannot capture the condition of the structure itself, its social and heritage significance, the cost of bringing it to habitability standards, the history of hazard damage it has sustained, or whether it is legally available for reoccupation. These dimensions, physical condition, heritage value, economic feasibility, and legal status, are precisely the variables that a planner or local administrator needs to prioritize reinhabitation investment at the building scale, and they are currently absent from any unified publicly available dataset in the Italian context.

To address this gap, this thesis proposes the development of a Building Vulnerability and Heritage Index (BVHI), a standardized attribute field extension to the existing building footprint layer that would transform the current hazard count output into a full reinhabitation feasibility score per structure. This would be structured around five attribute domains, each populated from a combination of existing institutional sources and targeted field survey:

Physical Condition: encoded as a five-class conservation status equivalent to *ottimo*, *buono*, *mediocre*, *pessimo*, *rovina* consistent with the ISTAT E-series building quality fields, and upgraded to individual building resolution through regional cadastral records and targeted visual survey.

Hazard Damage History: an ordinal field recording whether the structure has sustained documented damage from flood, landslide, avalanche, debris flow events or any other hazards, sourceable from ISPRA event databases, regional civil protection records, and municipal damage registers maintained under the EU Floods Directive reporting obligations.

Heritage and Cultural Value: a categorical field encoding the structure's heritage classification status, including whether it falls within a *Borghi Più Belli d'Italia* designated area, a UNESCO buffer zone, a regional landscape protection perimeter, or carries individual architectural significance as recorded in the ICCD MiC national heritage catalog.

Renovation Cost Estimate: a parametric cost band (low, medium, high, prohibitive) derived from regional construction cost indices applied to building footprint area and conservation status, providing a first-order economic filter for reinhabitation feasibility assessment without requiring individual structural surveys.

7.4 Data Gaps and the Building Vulnerability and Heritage Index

Legal and Ownership Status: a field recording whether the building is privately owned with an identifiable owner, held by a deceased estate, municipally owned, or subject to ownership dispute, sourceable from the Agenzia delle Entrate cadastral database and municipal registry records. This dimension is frequently the most operationally decisive factor in reinhabitation feasibility, a structurally sound and hazard-safe building with disputed or untraceable ownership is effectively inaccessible to reinhabitation programs regardless of its physical condition.

These five domains are detailed in Table 29. Each column represents an independent attribute domain with five possible classification values. A building receives one value per domain, producing a five-field BVHI profile.

The integration of these five attribute domains with the existing hazard count output would produce a composite BVHI score per building footprint that encodes physical constraint, heritage significance, economic feasibility, and legal accessibility within a single spatial layer. This layer would constitute a genuinely operational decision-support tool for planners, enabling evidence-based prioritization of reinhabitation investment at the building scale, a resolution that no existing Italian planning instrument currently achieves.

Physical Condition	Hazard Damage History	Heritage and Cultural Value	Renovation Cost Estimate	Legal and Ownership Status
Excellent	No recorded damage	UNESCO Buffer Zone	Low	Privately owned with identifiable owner
Good	Minor recorded damage	Regional Landscape Protection Perimeter	Medium	Municipally owned
Mediocre	Significant recorded damage	ICCD MiC Heritage Catalog	High	Deceased estate
Very Poor	Severe or repeated damage	Borghi Più Belli d'Italia	Prohibitive	Ownership dispute
Ruined	Unknown	No formal designation	Not assessable	Untraceable ownership
Unknown	-	-	-	-

Table 29. Proposed Building Vulnerability and Heritage Index (BVHI) Attribute Framework. (Source: Author’s elaboration)

7.5 Policy Implications and Recommendations

The findings of this thesis carry three direct policy implications for the governance of Italian mountain settlement reinhabitation.

First, the harmonization deficit in Italian regional environmental information systems requires urgent structural attention. The documentation of avalanche hazard through fundamentally different classification systems in Piedmont and Valle d'Aosta, the absence of certified hazard polygons data for Piedmont at cadastral resolution, and the different building functional classification frameworks between the BDTRE and the SCT Valle d'Aosta cadastre collectively demonstrate that the data infrastructure required for systematic cross-regional reinhabitation assessment does not yet exist in a harmonized form. The INSPIRE Directive provides the legislative mandate for this harmonization, but implementation across Italian regional administrations remains inconsistent. A national harmonization protocol for alpine hazard datasets, developed jointly by ISPRA, ARPA regional agencies, and the regional geoportal operators under the coordination of the Ministry of the Environment, would substantially reduce the methodological friction documented throughout this thesis and enable the kind of comparative cross-regional analysis that reinhabitation policy currently lacks.

Second, the accessibility and usability of regional geoportal data requires substantive improvement if spatial research and planning practice are to make effective use of publicly available datasets. The practical experience of data collection for this thesis revealed significant structural obstacles that go beyond the question of which datasets exist and extend to whether those datasets can be found, understood, and used by researchers and planners without specialized insider knowledge of each regional system. The ISTAT national data infrastructure, while imperfect, offers a comparatively coherent and navigable catalog structure. Regional geoportals present a more varied and frequently frustrating picture.

The Geoportale Piemonte in particular presented systematic usability challenges: many datasets are available for download only at the municipal scale, making them operationally unusable for regional or territorial analysis without individual downloads for each of the hundreds of municipalities in the study area. Where Web Feature Service access was available, it partially compensated for this limitation, but WFS availability was itself inconsistent across dataset types. More fundamentally, the BDTRE data architecture encodes each category as a separate spatial layer rather than as attribute values within a unified layer, producing a catalog of approximately 80 layers with abbreviated technical names requiring cross-reference with a separate codebook to interpret. This structure transforms what should be a straightforward data retrieval task into a time-intensive

7.5 Policy Implications and Recommendations

decoding exercise that places the burden of harmonization entirely on the end user rather than the data producer. The contrast with the Valle d'Aosta SCT geoportal, where the classification is encoded directly in the attribute table of a single layer, illustrates that more user-oriented data architectures are achievable within the Italian regional institutional context. A national standard for geoportal data architecture, specifying attribute-based rather than layer-based functional classification, consistent layer naming conventions, and regional-scale as well as municipal-scale download options, would substantially reduce the barrier to evidence-based spatial planning practice for researchers, local administrators, and planners working across regional boundaries.

Third, the Borghi Più Belli d'Italia certification framework should incorporate an explicit peripherality weighting in its admission criteria. The finding that only 14 certified borghi fall in SNAI Zone F and 106 in Zone E, the two most peripheral and service-deprived categories, while the SMRS population in these zones numbers in the thousands, confirms a systematic misalignment between heritage certification reach and reinhabitation urgency. The current admission process, which requires municipalities to submit formal applications demonstrating architectural quality and community engagement capacity, structurally disadvantages the most isolated and administratively fragile settlements, precisely those where heritage certification could have the greatest catalytic effect on institutional attention and investment. Introducing a peripherality adjustment that lowers the administrative threshold for Zone E and F settlements, combined with proactive outreach to municipalities that have not applied, would substantially extend the network's coverage into the territories where it is most needed. It must be acknowledged, however, that the Borghi Più Belli d'Italia network is primarily oriented toward promoting Italian villages through cultural tourism rather than facilitating permanent reinhabitation, and that heritage visibility and demographic recovery are not equivalent outcomes. A tourism influx can generate seasonal economic activity without producing the permanent resident population that sustains schools, healthcare, and local governance over the long term. Extending the network's reach into Zones E and F is therefore a necessary but not sufficient condition for reinhabitation, and must be accompanied by the fiscal, administrative, and service provision interventions discussed in Section 7.3 if certification is to translate into durable community regeneration rather than seasonal visitor attraction.

Fourth, building-level hazard intersection should become a mandatory component of reinhabitation feasibility assessments under the SNAI and PNRR frameworks. Current SNAI area

7.5 Policy Implications and Recommendations

strategies and PNRR investments in inner area regeneration are evaluated against demographic and service accessibility indicators but rarely incorporate systematic building-level physical constraint data. The settlement scale methodology demonstrated in this thesis, executable in open-source GIS using publicly available institutional datasets, provides a replicable template for this integration. Requiring building-level hazard intersection as a standard component of documentation would ensure that reinhabitation is achievable.

7.6 WebGIS Implementation and Features

To translate the multiscale framework into an accessible, non-specialist tool, the spatial outputs of this thesis were packaged into an interactive WebGIS platform. While the core spatial analysis and data preparation utilize open-source pipelines via QGIS, the final web deployment was built using Esri's ArcGIS Pro and ArcGIS Experience Builder ecosystem. This software choice was facilitated by an institutional license provided by Politecnico di Torino. While the author acknowledges that fully open-source alternatives exist for web publishing (e.g., Lizmap, QGIS Server, GeoServer), the integrated cloud capabilities and responsive widget design of the Esri environment were selected to ensure maximum stability, performance, and user accessibility.

The platform consolidates the hazard, settlement, and other layers developed across the National, Regional, Territorial, and Settlement scales into a single interactive interface, allowing users to explore exposure and reinhabitation indicators without requiring desktop GIS software. As a proof of concept, the platform features were fully configured for the Ollomont case study. However, the architecture is designed as a template; the exact same operational workflows and visualization structures can be dynamically replicated for any other small mountain rural settlement (SMRS) within the study area.

The platform is accessible at: <https://arcg.is/1Tyzqi2>. or by scanning the QR code in Figure 38.

Multi-Scale Interface Navigation

Upon accessing the platform, users are presented with an intuitive dashboard that abstracts complex desktop GIS layers



Figure 38. WebGIS access QR code.
(Source: Author's elaboration)

7.6 WebGIS Implementation and Features

into clear visualization panels as shown in Figure 39. The primary interface includes quick-access cards at the bottom to toggle between the project's conceptual scales (National to Settlement scales), allowing users to seamlessly transition from broad macroeconomic patterns down to local administrative realities.

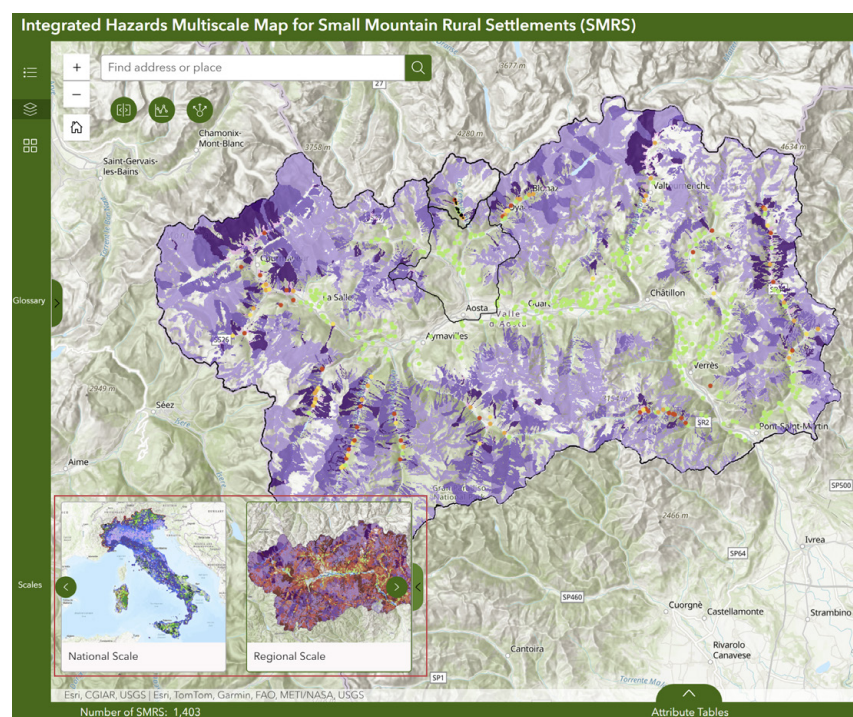


Figure 39. General interface of WebGIS and the scales' access bar.
(Source: Author's elaboration)

Accessible Conceptual Glossary

Because the target audience includes planners, local administrators, and community stakeholders who may lack specialized geospatial training, and because the taxonomy developed in this thesis (such as SMRS) is unique to this research, a dedicated Glossary widget has been integrated into the sidebar. This ensures that users who are completely unfamiliar with the text of the thesis can still immediately understand the specific settlement classifications and spatial indicators.

When activated, the panel in Figure 40 displays definitions for specialized institutional and analytical terms utilized throughout the project, such as Small Mountain Rural Settlements (SMRS), Hazard Count Score (HCS), Road Blockage (RB) Count, etc. This ensures that the underlying spatial evidence remains clear and actionable for any external user exploring the platform.

7.6 WebGIS Implementation and Features

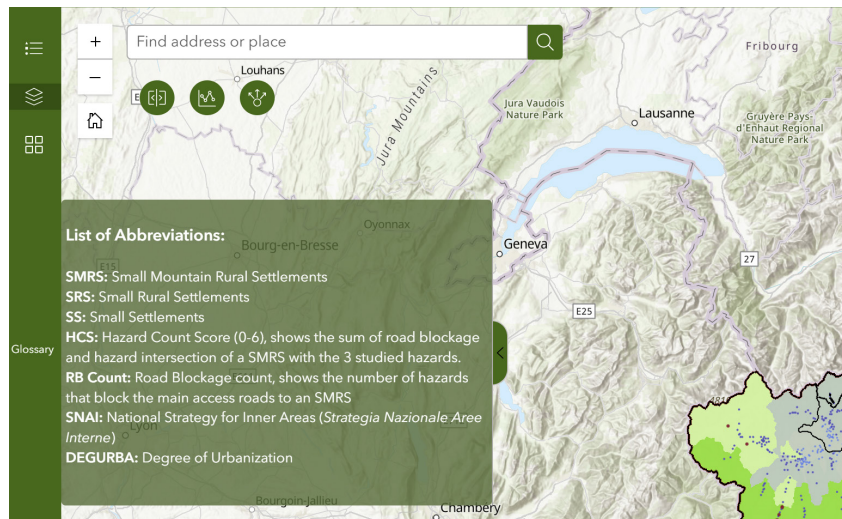


Figure 40. Interactive glossary panel detailing the spatial and planning abbreviations used across the indicators.
(Source: Author's elaboration)

National Scale Layer Interactions and Swipe Tool

At the macro level, understanding how rural centers interact with isolated peripheral areas is essential. To visually demonstrate this, the National Scale view includes an interactive Swipe tool widget.

This feature, Shown in Figure 41 allows users to dynamically slide between the Degree of Urbanization (DEGURBA) classification layers and the Inner Areas (SNAI) perimeters, seeing how the SMRS intersect with each. The swipe functionality makes it immediately evident how spatial isolation correlates with urbanization levels across Italy, offering a direct visual argument for targeted structural interventions.

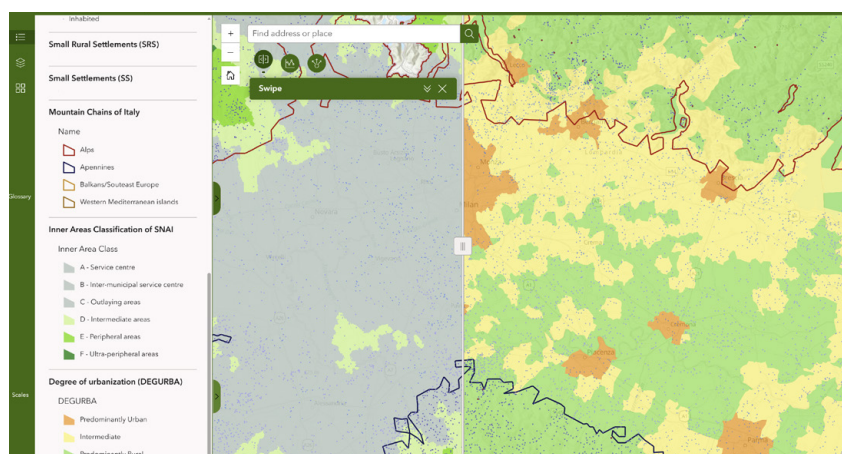


Figure 41. Interactive Swipe widget comparing the Degree of Urbanization (DEGURBA) layer with the National Strategy for Inner Areas (SNAI) perimeters.
(Source: Author's elaboration)

7.6 WebGIS Implementation and Features

Integrated Indicators and Research Documentation

The interface continuously processes and displays macro-level metrics in the header and footer bars, such as the total Number of SMRS by extent (Figure 42).

Figure 42. The “Number of SMRS” widget dynamically counts the total quantity of classified SMRS by extent. (Source: Author’s elaboration)

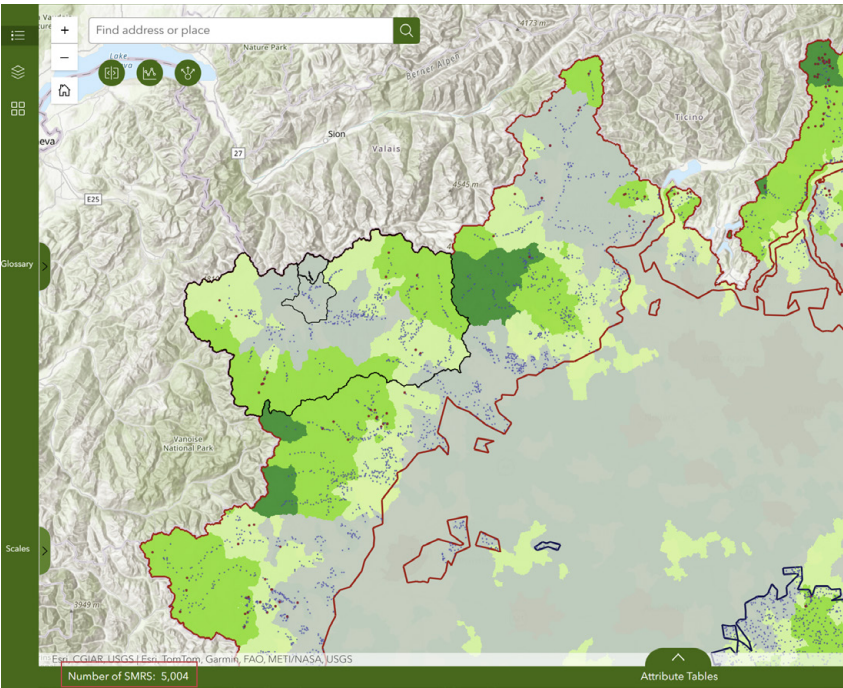
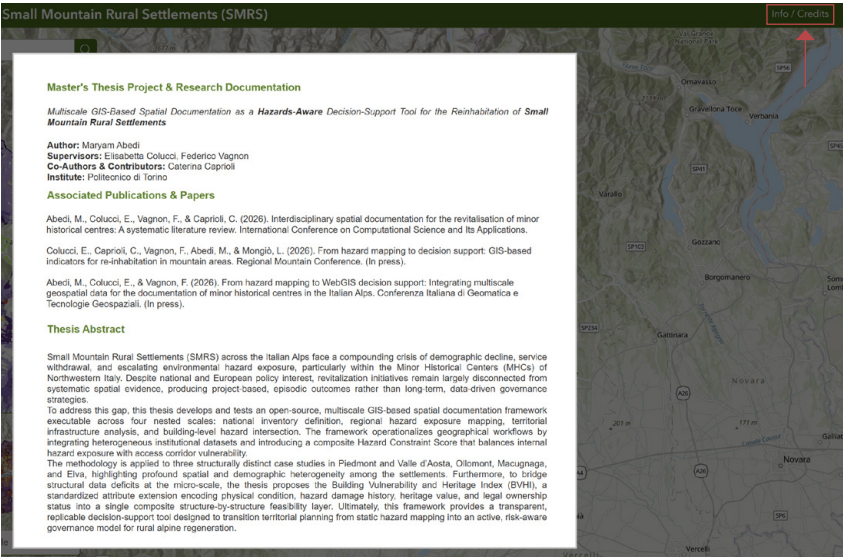


Figure 43. Integrated WebGIS research panel embedding the master’s thesis metadata, academic credits, and associated publications for immediate user reference. (Source: Author’s elaboration)



7.6 WebGIS Implementation and Features

Furthermore, an integrated information/documentation panel embeds the master's thesis abstract, academic supervisors, and associated peer-reviewed publications directly within the application environment (Figure 43). This bridges the gap between scientific methodology and user execution, providing immediate context on how the data was calculated and how it should be interpreted for territory-wide decision support.

7.7 Future Research Perspectives

The framework developed in this thesis opens several directions for future research that extend its analytical scope and operational applicability. The most immediate priority is the development and pilot testing of the Building Vulnerability and Heritage Index proposed in Section 7.4. The five attribute domains outlined there require a coordinated data collection effort involving regional cadastral authorities, civil protection agencies, heritage institutions, and municipal administrations, a cross-institutional collaboration that would benefit from a dedicated research project within the Italian PNRR research funding stream, where inner area regeneration constitutes an explicit thematic priority.

The temporal dimension of settlement abandonment represents a second significant research opportunity. The current framework captures a snapshot of hazard exposure and demographic condition as of the 2021 Census, but reinhabitation feasibility is inherently a dynamic assessment that changes as climate projections alter hazard frequencies, as demographic trajectories continue, and as infrastructure conditions evolve. Integrating repeat satellite-based land cover change detection, ground motion monitoring from Copernicus InSAR services, and longitudinal demographic tracking into a dynamic version of the framework would transform it from a static documentation tool into a living monitoring system capable of tracking reinhabitation conditions over time. The extension of the framework to other Italian mountain regions, the Apennines, the Eastern Alps, the Calabrian highlands, represents a third research direction with significant policy relevance. The three Northwest Italian case studies examined here represent a specific geomorphological and institutional context that may not be fully representative of the broader Italian inner area condition. A comparative application of the

7.7 Future Research Perspectives

multiscale framework across multiple mountain systems would test its transferability, identify regional modifications required by different hazard process regimes and data infrastructures, and produce the national-scale comparative evidence base that reinhabitation policy currently lacks.

Finally, the social and cultural dimensions of reinhabitation feasibility deserve dedicated research attention that the spatial framework developed here cannot provide. The BVHI attribute domains proposed in Section 7.4 include heritage value and legal ownership status, but they do not capture community attachment, cultural identity, and the social infrastructure of belonging that determine whether returning residents can form viable communities rather than simply occupying buildings. The Occitan cultural identity of the Maira Valley, the Walser heritage of Macugnaga, and the mining community memory of Ollomont represent distinct cultural assets whose preservation and activation are as central to reinhabitation feasibility as any physical or hazard metric. Future research combining the spatial framework developed here with ethnographic, oral history, and community participation methods would produce a genuinely integrated reinhabitation assessment methodology capable of addressing the full complexity of mountain settlement regeneration.

To build upon the structural GIS workflow established in this study, future research perspectives should look toward integrating participatory mapping methodologies. Incorporating localized community knowledge, qualitative stakeholder questionnaires, and crowdsourced geospatial data from local actors would provide an essential bottom-up validation layer to complement the institutional hazard models utilized herein.

7.8 Conclusions

Italian mountain settlements are experiencing a slow and cumulative process of demographic and physical decline. The losses accumulate quietly: a family that does not return after winter, a building left unrepaired after a landslide, a school that closes when enrollment falls below the minimum threshold, a road that is not maintained because the community it serves has become too small to justify the cost. Understanding and potentially addressing these processes requires, as a necessary first step, a clear and systematic account of their spatial

7.8 Conclusions

dimensions, at the right scales, with the right data, and with the right analytical tools. The multiscale GIS framework and the WebGIS platform developed in this thesis does not resolve the problem of mountain abandonment. No spatial analysis framework can. What it provides is something that has been largely absent from both academic research and planning practice in this field: a systematic, replicable, and operationally grounded method for characterizing what kind of problem each settlement faces, and therefore what kind of response it requires. The 22,205 SMRS identified across Italy are not a homogeneous population of villages awaiting a single policy intervention. They represent a profoundly heterogeneous set of physical, demographic, heritage, and institutional conditions, and the tendency to treat them as a uniform category is one of the reasons why many regeneration initiatives have produced inconsistent or short-lived outcomes.

The three case studies of Ollomont, Macugnaga, and Elva demonstrate this heterogeneity in concrete terms. A settlement where every building intersects at least two concurrent hazard types, and where the most historically significant hamlet faces triple-hazard convergence across the majority of its residential stock, presents a fundamentally different challenge from a settlement where most buildings are physically unconstrained but three quarters stand vacant because the population that once inhabited them has not been replaced. Both face abandonment. Both are losing built heritage. Both fall outside the effective reach of existing policy instruments. But the conditions driving their decline are distinct, and the interventions required to address them are correspondingly different. The framework developed here makes those distinctions visible, measurable, and communicable to the planners, administrators, and communities who must act on them.

The built fabric of Italian mountain settlements encodes centuries of accumulated knowledge about inhabiting difficult terrain, managing water on steep slopes, building with local materials, and sustaining collective life in conditions of geographic isolation. That knowledge is embodied in the spatial organization of hamlets, in construction techniques adapted to specific geologies, and in the landscape management practices that shaped the valleys over generations. Whether this accumulated heritage can be preserved, reactivated, and adapted to contemporary conditions is a question of political will, community agency, and institutional coordination that lies beyond the scope of spatial analysis. What this thesis has attempted to demonstrate is that the spatial analysis required to inform those decisions exists, that it is accessible using publicly available data and open-source tools, and that it is ready to be applied.

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A Appendix

Appendix A

This Appendix presents the complete literature matrix produced through the Systematic Literature Review documented in Chapter 2 and the coding matrix of the included references. Each source is assigned a unique identifier corresponding to its retrieval method: S (academic database search), SE (excluded from academic database search), W (web search), WE (excluded from web search), SN (snowballing), and G (gray literature). Inclusion and exclusion decisions are recorded alongside the thematic pillars addressed by each source, coded as follows: (1) Spatial documentation and GIS methodology, (2) Natural hazard classification and assessment, (3) Demographic decline and inner areas, (4) Heritage conservation and minor historical centers, (5) Planning and policy frameworks, (6) Reinhabitation and regeneration strategies, (7) Governance and institutional frameworks.

Table A1. Systematic Literature Review Matrix

Source	Code	Title	Status	Relevant pillars or Ex. reason
Academic database - String (i)	S1	Grecchi, M.; Colucci, A.; Malighetti, L.E.; Speciale, F..Reinventing Mountain and Rural Villages Strategies for Regeneration in the Perspective of a Circular Economy,2025	In.	(3), (4),
	S2	Barrile, V.; Bibbò, L.; Bilotta, G.; Meduri, G.M.; Genovese, E..Geomatics Innovation and Simulation for Landslide Risk Management: The Use of Cellular Automata and Random Forest Automation,2024	In.	(1), (2),
	S3	Ardizzone, F.; Esposito, G.; Cavalli, M.; Crema, S.; Fiorucci, F..Sediment connectivity as a key to understand geomorphic effects of the Storm Alex in two mountain catchments of the Mediterranean Alps (Italy),2024	In.	(2), (3),
	S4	Colucci, E.; Lingua, A.M.; Kokla, M.; Spanò, A..Minor historical centres ontology enrichment and population: An Hamlet case study,2022	In.	(1), (3),

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	S5	Colucci, E..Mountain Hamlet Heritage Between Risk and Enhancement,2022	In.	(2), (3),
	S6	Nappo, N.; Peduto, D.; Polcari, M.; Stramondo, S.; Michetti, A.M..Subsidence in Como historic centre (northern Italy): Assessment of building vulnerability combining hydrogeological and stratigraphic features, Cosmo-SkyMed InSAR and damage data,2021	In.	(1), (2),
	S7	Buseti, A.; Calligaris, C.; Forte, E.; Mocnik, A.; Zini, L..Non-invasive methodological approach to detect and characterize high-risk sinkholes in urban cover evaporite karst: Integrated reflection seismics, PS-INSAR, leveling, 3D-GPR and ancillary data.,2020	In.	(2), (1), (3),
	S8	Pérez-Rey, I.; Riquelme, A.. A multi-approach rockfall hazard assessment on a weathered granite natural rock slope,2019	In.	(2),
	S9	Onitsuka, K.; Ninomiya, K.; Hoshino, S..Potential of 3D visualization for collaborative rural landscape planning with remote participants,2018	In.	(1), (3), (6),
	S10	Trigila, A.; Iadanza, C.; Esposito, C.; Scarascia-Mugnozza, G..Comparison of Logistic Regression and Random Forests techniques for shallow landslide susceptibility assessment in Giampilieri (NE Sicily, Italy),2015	In.	(2),
	S11	Pirlone, F.; Sotgia, Z.; Spadaro, I..Sustainability in the Safety Measures of the Historical-Cultural Heritage against Hydraulic Risks,2012	In.	(2),
	S12	Fusco Girard, L.; De Toro, P..Integrated spatial assessment: A multicriteria approach to sustainable development of cultural and environmental heritage in San Marco dei Cavoti, Italy,2007	In.	(5), (7),

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	SE1	Terrone, M.; Mandarino, A.; Piana, P.; Faccini, F..Identification, computation, and mapping of anthropogenic landforms in urban areas: Case studies in the historical centre of Genoa, Italy (UNESCO World Heritage),2024	Ex.	Genoa Large scale
	SE2	Hussain, A.; Schmidt, S.; Nüsser, M..Dynamics of Mountain Urbanisation: Evidence from the Trans-Himalayan Town of Kargil, Ladakh, India,2023	Ex.	India outside Eu
	SE3	Zhuang, Q.; Hussein, M.K.; Mohd Ariffin, N.F.; Mohd. Yunus, M.Y.; Chen, S..Rural landscape characterization from the perspective of the tourist using online reviews: A case study of Yayou Gou Village in Shandong, China,2022	Ex.	China outside Eu
	SE4	Jiménez-Espada, M.; Cuartero, A.; Le Breton, M..Sustainability Assessment through Urban Accessibility Indicators and GIS in a Middle-Sized World Heritage City: The Case of Cáceres, Spain,2022	Ex.	Middle-Sized City.
	SE5	Petrosino, P.; Claudia Angrisani, A.; Barra, D.; Jicha, B.R.; Calcaterra, D..Multi-proxy approach to urban geology of the historical center of Naples, Italy,2021	Ex.	Naples large scale
	SE6	Faccini, F.; Giardino, M.; Paliaga, G.; Perotti, L.; Brandolini, P..Urban geomorphology of Genoa old city (Italy),2021	Ex.	Genoa large scale
	SE7	Martinát, S.; Cowell, R.; Navrátil, J..Rich or poor? Who actually lives in proximity to AD plants in Wales?,2020	Ex.	Unrelated
	SE8	Vallis, S.; Gálvez, F.; Swidan, M.; Orcheston, C.; Ingham, J..Classical Temples and Industrial Stores: Survey Analysis of Historic Unreinforced Masonry (URM) Precincts to Inform Urban Seismic Risk Mitigation,2018	Ex.	Unrelated
	SE9	Morelli, S.; Battistini, A.; Catani, F..Rapid assessment of flood susceptibility in urbanized rivers using digital terrain data: Application to the arno river case study (Firenze, northern Italy),2014	Ex.	Firenze large scale

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	SE10	Deng, Y.C.; Tsai, F.; Hwang, J.H..Landslide characteristics in the area of Xiaolin Village during Morakot typhoon,2016	Ex.	Taiwan outside Eu
	SE11	Caserta, A.; Martino, S.; Bozzano, F.; Govoni, A.; Marra, F..Dynamic properties of low velocity alluvial deposits influencing seismically-induced shear strains: The Grottaperfetta valley test-site (Rome, Italy),2012	Ex.	Unrelated
Academic database -String (ii)	S13	Pilogallo, A.; Saganeiti, L.; Fiorini, L..Deep Dive into the Recovery Fund: A (Real) Chance for Inner Areas? The Abruzzo Region Study Case, Italy,2025	In.	(3), (5),
	S14	Oteri, A.M..Perspectives in the Debate on the Future of Abandoned Heritage in Inner Areas. The Contribution of Architectural Preservation in the Post-Pandemic Era,2025	In.	(4),
	S15	Trovato, M.R.; Sanzaro, D..A Knowledge and Evaluation Model to Support the Conservation of Abandoned Historical Centres in Inner Areas,2024	In.	(4),
	S16	Limongi, G.; Napolitano, A.; Galderisi, A..What Future for Small Historical Centres in Inner Areas? The Case Study of Guardia Sanframondi in the Campania Region,2024	In.	(3), (5),
	S17	Sanzaro, D.; Trovato, M.R.; Circo, C..An Interpretive Ruination Model of the Built Heritage in Inner Areas: The Case Study of the Neighbourhood Granfonte in Leonforte,2023	In.	(1),
	S18	Magnini, L.; Bettineschi, C..Object-based predictive modeling (Obpm) for archaeology: Finding control places in mountainous environments,2021	In.	(1),
	SE12	Colucci, E.; Lingua, A.M.; Kokla, M.; Spanò, A..Minor historical centres on-tology enrichment and population: An Hamlet case study,2022	Ex.	Duplicated
	SE13	Bell, B.A.; Fletcher, W.J.; Hughes, P.D.; Fink, D.; Rhoujjati, A..Palynological evidence from a sub-alpine marsh of enhanced Little Ice Age snowpack in the Marrakech High Atlas, North Africa,2022	Ex.	Unrelated

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Academic data-base - String(iii)	S19	Rossitti, M.; Torrieri, F..Territorial Inequalities in Adaptive Reuse Opportunities: Evidence from Lombardy Region ,2026	In.	(3), (4), (5),
	S20	Tsamou, G.; Vlami, A.; Sarantakou, E.; Christidou, A..Heritage Hospitality and Sustainable Tourism in Mountain Cultural Landscapes: The Case of Zagori Within the UNESCO Framework,2025	In.	(3),
	S21	Barelles-Vicente, E.; Torner-Feltrer, M.E.; Llinares Millán, J.; Aparicio-Fernández, C..From Ruin to Resource: The Role of Heritage and Structural Rehabilitation in the Economic and Territorial Regeneration of Rural Areas,2025	In.	(4), (7),
	SE14	Çakan, M.R.; Kishal, E.; Yaman, A..The Morphology of Continuity: An Analytical Documentation of Vernacular Architecture in Phoenix Rural Settlements,2026	Ex.	Turkey outside Eu.
	SE15	Zhang, Z.; Hu, X.; Liu, W.; Bao, R..Data-driven heritage revitalisation: Exploring the paradigm of Lifan adaptive renovation evaluation based on space syntax,2025	Ex.	Relevant China.
	SE16	Zhao, T.; Zhang, W.; Zhou, J.; Chen, Y.; Jiang, J..Niche divergence of evolutionarily significant units with implications for repopulation programs of the world's largest amphibians,2020	Ex.	Unrelated
Web search	W1	ISPRA / ISTAT (within MASE framework). Demographic scenarios, residential mobility and impacts of climate change in the Alps. Intermediate Report focusing on the Italian and partly Austrian Alps,2025	In.	(2) (3) (5), (6),
	W2	Colucci, E..Geospatial Ontology to Support the Documentation of Minor Historical Centres. PhD Thesis,2022	In.	(1), (3), (4),
	W3	Agnoletti, M.; Errico, A.; Santoro, A.; Dani, A.; Preti, F..Terraced Landscapes and Hydrogeological Risk.,2019	In.	(2), (3),
	W4	Nunes, A.N.; Coelho, C.O.A.; De Almeida, A.C.; Figueiredo, A..Soil Erosion and Hydrological Response to Land Abandonment.,2010	In.	(2), (3),

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	W5	Picarelli, L.; Lacasse, S.; Ho, K..The Impact of Climate Change on Landslide Hazard and Risk,2020	In.	(2), (3),
	W6	Benedini, D..Borghi Abbandonati: Censimento di un'Italia che Scompare.,2018	In.	(3), (4), (6),
	W7	Amodio, T..Territories at risk of abandonment in Italy and hypothesis of repopulation,2022	In.	(4), (5), (6), (7),
	W8	publicarchitecture@polimi. 2009.. Geografie dell'Abbandono. La dismissione dei borghi in Italia,2009	In.	(3), (4), (6),
	W9	Cotella, G..Territorialising EU Cohesion Policy in Inner Peripheries.,2024	In.	(3), (5), (7),
	W10	De Rossi, A.; Crotti, M.; Dini, R..Viaggio in Otto Borghi.,2015	In.	(3), (4), (6),
	W11	Delon, M., & Graziano, T. .L'iniziativa "case a un euro" contro la marginalità territoriale in Italia: mercificazione o rivitalizzazione?,2023	In.	(4), (6), (7),
	W12	De Luca, G..I borghi come monumento, questo l'intento del bando nazionale sulla rigenerazione,2023	In.	(4), (5),
	W13	Kim, H.; Lee, D.; Park, C.; Kil, S.; Son, Y.; Park, J..Evaluating Landslide Hazard Using RCP 4.5 and 8.5.,2015	In.	(2),
	W14	MacDonald, D.; Crabtree, J. R.; Wiesinger, G.; Dax, T.; Stamou, N.; Fleury, P.; Gutierrez Lazpita, J.; Gibon, A..Agricultural Abandonment in Mountain Areas of Europe.,2000	In.	(3), (5), (7),
	W15	Cassar, M. & Pender, R. .Climate Change and the Historic Environment.,2003	In.	(2), (4), (5),
	W16	Rolli, G. L. .Salvare i centri storici minori. Proposte per un atlante urbanistico dei centri d'Abruzzo,2005	In.	(2), (5), (6),
	W17	Colucci, E.; Kokla, M.; Noardo, F..Ontology-Based Data Mapping to Support Planning in Historical Urban Centres.,2021a	In.	(1),

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	W18	Colucci, E.; Xing, X.; Kokla, M.; Mostafavi, M.A.; Noardo, F.; Spanò, A..Ontology-Based Semantic Conceptualisation of Historical Built Heritage from Point Clouds.,2021b	In.	(1), (2),
	W19	Colucci, E.; Kokla, M.; Mostafavi, M.A.; Noardo, F.; Spanò, A..Semantically Describing Urban Historical Buildings Across Different Levels of Granularity.,2020	In.	(2), (3), (4), (6),
	W20	Mercalli, L..Salire in Montagna: Prendere Quota per Sfuggire al Riscaldamento Globale.,2020	In.	(1), (3), (4),
	W21	Jeong, J. S.; García-Moruno, L.; Hernández-Blanco, J.; Sánchez-Ríos, A.; Ramírez-Gómez, Á..Identifying priority areas for rural housing development using the participatory multi-criteria and contingent valuation methods in Alange reservoir area, Central Extremadura (Spain),2017	In.	(1), (4), (7),
	W22	Fantechi, F.; Urso, G.; Modica, M..Can extreme events be an opportunity? Depopulation and resilience of rural communities in Central Italy after the 1997 earthquake,2020	In.	(2), (4), (5), (6),
	W23	De Montis, A.; Ledda, A.; Ganciu, A.; Serra, V.; De Montis, S..Recovery of rural centres and “albergo diffuso”: A case study in Sardinia, Italy,2015	In.	(2), (3), (4), (5), (6),
	W24	Jovanović, R.; Almeida; García, F.; Cortés-Macías, R; Parzych, K..Assessment of wine tourism potential in the countries of the former Yugoslavia,2025	In.	(4), (7),
	WE1	Colucci, E.; Lingua, A.M.; Kokla, M.; Spanò, A..Minor Historical Centres Ontology Enrichment and Population.,2022	Ex.	Duplicate
	WE2	Cross, J. A..Megacities and Small Towns: Different Perspectives on Hazard Vulnerability.,2011	Ex.	Not open access
	WE3	Predieri, A. .Report for the VI Convegno A.N.C.S.A.,1971	Ex.	Not open access

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	WE4	Rosenzweig, C.; Solecki, W.; Hammer, S.; Mehrotra, S. .Urbanisation of climate change: Responding to a new global challenge.,2013	Ex.	Not open access
	WE5	Greco, F.; Clemente, L.; Bifulco, F.. Tourism Start-ups: A Systematic Review., 2024.	Ex.	Not relevant
Snowballing	SN1	Horton, P.; Jaboyedoff, M.; Zimmermann, M.; Mazotti, B.; Longchamp, C..Flow-R Model for Debris-Flow Susceptibility.,2013	In.	(3),
	SN2	Bacci, E.; Cotella, G.; Staricco, L.; Vitale Brovarone, E.V..Quale accessibilità per le aree interne? Temi, sfide e prospettive per le politiche,2020	In.	(3), (7),
	SN3	Prezioso, M..Quale territorial impact assessment della coesione territoriale nelle regioni italiane,2018	In.	(1), (5),
	SN4	D'Alessandro, S.; Salvatore, R.; Bortoletto, N..Ripartire dai borghi per cambiare le città.,2020	In.	(3), (6),
	SN5	De Rubertis, S..Dinamiche insediative in Italia: spopolamento dei comuni rurali,2019	In.	(3), (6),
	SN6	Covino, R..Aree interne: una marginalità che parla al futuro.,2017	In.	(3), (6),
	SN7	Battisti, G..Le aree interne: un'interpretazione geopolitica.,2017	In.	(3), (6),
	SN8	Onni, G. & Pittaluga, P..Territori dell'abbandono. Strategie di rigenerazione per contesti spaziali e sociali in crisi demografica,2021	In.	(2), (3), (4),
	SN9	Canonaco, B. & Molezzi, F..The Recovery of The Beauty of Minor Historical Centers The Albergo Diffuso As A Means Of Reviving What Has Been Built,2016	In.	(3), (4), (7),
	SN10	Randazzo, G.; Italiano, F.; Micallef, A..WebGIS Implementation for Dynamic Mapping and Visualization of Coastal Geospatial Data: A Case Study of BESS Project,2022	In.	(1),
	SN11	Sau, A..La rivitalizzazione dei borghi e dei centri storici minori come strumento per il rilancio delle aree interne,2018	In.	(3), (4),

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	SN12	Ginzarly, M.; Houbart, C.; Teller, J..The Historic Urban Landscape approach to urban management: a systematic review,2021	In.	(5),
	SN13	Pirlone, F..I borghi antichi abbandonati. Patrimonio da riscoprire e mettere in sicurezza,2016	In.	(3), (4),
	SN14	Morena, M.; Truppi, T.; Del Gatto, M. L.. Sustainable tourism and development: the model of the Albergo Diffuso,2017	In.	(3), (4), (7),
	SN15	Vallone, C. & Veglio, V.. "Albergo Diffuso" and Customer Satisfaction: A Quality Services Analysis,2013	In.	(4), (7),
	SNE1	Carrosio, G..I margini al centro. L'Italia delle aree interne tra fragilità e innovazione,2019	Ex.	Not open access
	SNE2	Paoletta, A..Il riuso dei borghi abbandonati. Esperienze di comunità,2019	Ex.	Not open access
	SNE3	Corrado, F.; Dematteis, G.; Di Gioia, A..Nuovi montanari. Abitare le Alpi nel XXI secolo.,2014	Ex.	Not open access
	SNE4	Bertinotti, L. .Da borghi abbandonati a borghi ritrovati.,2020	Ex.	Not open access
	SNE5	Silvestrelli, P..Hospitality innovation through historic sites requalification in Italy: evidences from Marche Region,2012	Ex.	Not open access
Gray literature	G1	ISTAT. La demografia delle aree interne.,2024	In.	(3), (5),
	G2	ISTAT.The Geography of Inner Areas in 2020.,2022	In.	(3), (5),
	G3	European Commission.Annex to the Communication: Long-Term Vision for Rural Areas.,2021	In.	(3), (5), (7),
	G4	McEldowney, J..Long-Term Vision for Rural Areas: European Commission Communication.,2021	In.	(3), (5),
	G5	Government of Italy.Adaptation Communication of Italy (UNFCCC Submission).,2023	In.	(3), (5),
	G6	Alpine Convention.Transport and Mobility in the Alps (State Of the Alpes Report 1).,2007	In.	(3), (5),

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	G7	Alpine Convention.Water Management in the Alps (State Of the Alpes Report 2),2009	In.	(3), (5),
	G8	Alpine Convention.Sustainable Rural Development & Innovation (State Of the Alpes Report 3),2011	In.	(3), (5),
	G9	Alpine Convention.Sustainable Tourism in the Alps (State Of the Alpes Report 4),2013	In.	(3), (5), (7),
	G10	Alpine Convention.Demographic Changes in the Alps (State Of the Alpes Report 5),2015	In.	(3), (5), (7),
	G11	Alpine Convention.Greening the Economy in the Alpine Region (State Of the Alpes Report 6),2017	In.	(3), (5),
	G12	Alpine Convention.Risk Governance in Natural Hazards (State Of the Alpes Report 7),2019	In.	(3), (5), (7),
	G13	Alpine Convention.Air Quality in the Alps (State Of the Alpes Report 8),2020	In.	(3), (5),
	G14	Alpine Convention.Alpine Towns (State Of the Alpes Report 9),2022	In.	(2), (3), (5),
	G15	Alpine Convention.Background Study for State Of the Alpes Report 10,2023	In.	(2), (3), (5),
	G16	Alpine Convention.Workplan 2023–2025 — Action Group 6,2023	In.	(3), (5),
	G17	Alpine Convention.Workplan 2023–2025 — Action Group 6,2023	In.	(3), (5),
	G18	Veith (ed.).Why Invest in Sustainable Mountain Development? (FAO),2011	In.	(3),
	G19	ISTAT.Forme e livelli dell'urbanizzazione in Italia.,2017	In.	(5),
	G20	Delmonaco, G.; Guarneri, E. M.; Moretti, P.; Nisio, S.; Pompili, R.; Pistocchi, L.; Puzzilli, L. M.; Traversa, F..Le Ghost Cities d'Italia, l'inventario ISPRA (national project summary) ,2023	In.	(5),

	G21	UNESCO.Recommendation on the Historic Urban Landscape (HUL),2011	In.	(3), (4),
	G22	UNESCO.HUL Guidance Notes.,2016	In.	(3), (5),

Table A2. Included References Coding Matrix

Code	Author, Year.	GIS-based multiscale documentation	hazard and climate exposure	rural and alpine contexts	Reinhabitation Strategies	Policy Frameworks
S1	Grecchi et al., 2025.	1	2	4	4	3
S2	Barrile et al., 2024.	4	4	3	1	1
S3	Ardizzone et al., 2024.	3	4	4	1	1
S4	Colucci et al., 2022.	4	2	4	3	2
S5	Colucci, 2022a.	3	4	4	3	2
S6	Nappo et al., 2021.	4	4	1	0	0
S7	Busetti et al., 2020.	4	4	4	1	0
S8	Pérez-Rey et al., 2019.	2	4	3	0	0
S9	Onitsuka et al., 2018.	4	0	4	3	1
S10	Trigila et al., 2015.	3	4	2	0	1
S11	Pirlone et al., 2012.	2	4	3	2	3
S12	Fusco & De Toro, 2007.	3	1	2	3	4
S13	Pilogallo et al., 2025.	1	0	4	2	4
S14	Oteri, 2025.	2	0	3	4	2
S15	Trovato & Sanzaro, 2024.	3	1	3	4	2
S16	Limongi et al., 2024.	2	1	4	3	4
S17	Sanzaro et al., 2023.	4	3	2	1	0
S18	Magnini & Bettineschi, 2021.	4	3	3	1	0
S19	Rossitti & Torrieri, 2026.	3	1	4	4	4
S20	Tsamos et al., 2025.	1	0	4	3	2

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S21	Barelles-Vicente et al., 2025.	2	1	3	4	2
W1	ISPRA, ISTAT, 2025.	0	4	3	2	1
W2	Colucci, 2022b.	4	1	0	1	1
W3	Agnoletti et al., 2019.	1	1	3	1	1
W4	Nunes et al., 2010.	0	1	3	1	1
W5	Picarelli et al., 2020.	0	1	4	0	1
W6	Benedini, 2018.	1	3	0	1	1
W7	Amodio, 2022.	0	3	1	3	1
W8	publicarchitecture@polimi, 2009.	1	3	1	1	1
W9	Cotella & Vitale Brovarone, 2024.	0	1	0	1	4
W10	De Rossi et al., 2015.	1	4	1	3	1
W11	Delon & Graziano, 2023.	0	1	0	3	1
W12	De Luca, 2023.	0	1	0	1	3
W13	Kim et al., 2015.	0	1	4	0	0
W14	MacDonald et al., 2000.	0	1	4	1	1
W15	Cassar & Pender, 2003.	1	1	3	1	1
W16	Rolli, 2005.	1	4	0	1	1
W17	Colucci et al., 2021a.	4	1	0	1	0
W18	Colucci et al., 2021b.	4	0	0	0	0
W19	Colucci et al., 2020a.	4	1	0	0	0
W20	Mercalli, 2020.	0	3	4	3	2
W21	Jeong et al., 2017.	4	1	3	4	3
W22	Fantechi et al., 2020.	3	4	3	4	4
W23	De Montis, 2015.	2	4	4	4	4
W24	Jovanović, 2025.	2	0	2	4	2

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SN1	Horton et al., 2013.	1	1	4	0	0
SN2	Bacci et al., 2020.	0	3	4	3	1
SN3	Prezioso, 2018.	4	1	0	0	4
SN4	D'Alessandro et al., 2020.	1	3	4	3	1
SN5	De Rubertis, 2019.	0	3	4	1	1
SN6	Covino, 2017.	0	1	4	1	1
SN7	Battisti, 2017.	0	1	4	1	1
SN8	Onni & Pittaluga, 2021.	1	4	4	4	1
SN9	Canonaco & Molezzi, 2015.	1	1	4	4	1
SN10	Randazzo et al., 2022.	4	0	1	0	0
SN11	Sau, 2018.	1	3	4	4	1
SN12	Ginzarly et al., 2021.	1	0	1	1	4
SN13	Pirlone, 2016.	1	3	4	4	1
SN14	Morena et al., 2017.	1	3	4	4	1
SN15	Vallone & Veglio, 2013.	0	1	0	4	1
G1	ISTAT, 2024.	0	3	4	1	4
G2	ISTAT, 2022.	0	3	4	1	4
G3	European Commission, 2021a.	0	3	4	1	4
G4	European Commission, 2021b.	0	3	4	1	4
G5	McEldowney, 2021.	0	3	4	1	4
G6	Gov. of Italy, 2023.	0	1	4	0	4
G7	Alpine Conv., 2007.	0	3	4	0	4
G8	Alpine Conv., 2009.	0	3	4	0	4
G9	Alpine Conv., 2011.	0	3	4	1	4

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G10	Alpine Conv., 2013.	0	3	4	1	4
G11	Alpine Conv., 2015.	0	3	4	1	4
G12	Alpine Conv., 2017.	0	3	4	1	4
G13	Alpine Conv., 2019.	0	4	4	0	4
G14	Alpine Conv., 2020.	0	4	4	0	4
G15	Alpine Conv., 2022.	0	1	4	1	4
G16	Alpine Conv., 2023a.	0	1	4	1	4
G17	Alpine Conv., 2023b.	0	1	4	1	3
G18	Veith, FAO, 2011.	0	3	1	1	4
G19	ISTAT, 2017.	0	1	0	1	4
G20	ISPRA, 2020.	1	3	4	4	1
G21	UNESCO, 2011.	1	0	4	1	4
G22	UNESCO, 2016.	1	0	4	1	4