Deliverable Phase 2 – Climate risk assessment

Context specific climate risk assessment and adaptation strategies for the Valchiavenna Alpine territory (CMV4Clima)

Italy, Lombardy Region - Valchiavenna

Version 1.0 | July 2025

HORIZON-MISS-2021-CLIMA-02-01 - Development of climate change risk assessments in European regions and communities based on a transparent and harmonised Climate Risk Assessment approach

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101093864. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Document Information

Deliverable Title	Phase 2 – Climate risk assessment
Brief Description	
Project name	Context specific climate risk assessment and adaptation strategies for the Valchiavenna Alpine territory (CMV4Clima)
Country	Italy
Region/Municipality	Valchiavenna
Leading Institution	Comunità Montana della Valchiavenna
Author(s)	• Renato Dolci (Comunità Montana della Valchiavenna) • Maria Chiaravalli (Comunità Montana della Valchiavenna) • Monica Cribellati (Comunità Montana della Valchiavenna) • Alessandra Garolini (Comunità Montana della Valchiavenna) • Marco Pregnolato (Fondazione Lombardia per l'Ambiente- Ecometrics) • Luisa Battezzati (Fondazione Lombardia per l'Ambiente - Ecometrics)
Deliverable submission date	19/01/2026
Final version delivery date	19/01/2026
Nature of the Deliverable	R – Report
Dissemination Level	PU - Public

Version	Date	Change editors	Changes
1.0	19/01/2026	Comunità Montana della Valchiavenna	Deliverable submitted
2.0	…	CLIMAAX's FSTP team	Review completed
5.0	…		Final version to be submitted

Table of contents

Document Information ... 3
Table of contents ... 4
List of figures ... 5
List of tables ... 6
Abbreviations and acronyms ... 7
Executive summary ... 8
1 Introduction ... 9
1.1 Background ... 9
Demography and social impact ... 9
Economic sectors ... 9
Infrastructure ... 10
Environment and Biodiversity ... 10
1.2 Main objectives of the project ... 10
1.3 Project team ... 11
1.4 Outline of the document's structure ... 12
2 Climate risk assessment – phase 2 ... 12
2.1 Scoping ... 12
2.1.1 Objectives ... 12
2.1.2 Context (update) ... 12
2.1.3 Participation and risk ownership ... 14
2.1.4 Application of principles ... 15
2.1.5 Stakeholder engagement ... 15
2.2 Risk Exploration ... 19
2.2.2 Screen risks (selection of main hazards) ... 19
2.2.3 Choose Scenario ... 19
2.3 Regionalized Risk Analysis ... 19
2.3.1 Heavy Rainfall risk - fine-tuning to local context ... 19
2.3.2 River flooding risk - finetuning to local context ... 36
2.3.3 Additional assessments based on local models and data ... 46
2.4 Key Risk Assessment Findings ... 47
2.4.1 Mode of engagement for participation ... 47
2.4.2 Gather output from Risk Analysis step ... 48

2.4.3 Assess Severity 49
2.4.4 Assess Urgency 49
2.4.5 Understand Resilience Capacity 50
2.4.6 Decide on Risk Priority 50
2.5 Monitoring and Evaluation 51
2.6 Work plan Phase 3 52
3 Conclusions Phase 2- Climate risk assessment 53
4 Progress evaluation 55
5 Supporting documentation 58
6 References 59

List of figures

Figure 1. Source: Local Forest Fire Prevention Plan (DRE.AM Italia)
Figure 2. Homogenous alert zones of Valchiavenna from the regional Civil Protection system of Lombardy Region
Figure 3. Percentage of municipal area in high and very high PAI hazard classes (P3–P4)
Figure 4. Map of the hydrogeological hazard levels (PAI) on the territory of Valchiavenna
Figure 5. Graph of the time period for the datasets used in the analysis
Figure 6. Mean monthly accumulated total precipitation and •mean daily maximum for the month in the ARPA observed data
Figure 7. Sample of CERRA gridded data over the AOI of Valchiavenna IM-01 (red star represents the position of Chiavenna Cerletti ARPA weather station)
Figure 8. Comparison between AOI averages and point-based monthly climatologies (monthly accumulation)
Figure 9. Comparison of Mean monthly accumulated total precipitation and mean daily maximum (R1day) between the ARPA and CERRA dataset
Figure 10. Representation of the CERRA and CORDEX respective grids and cells included in the AOI
Figure 11. Representation of the metrics utilized in the comparative evaluation of CERRA and different CORDEX datasets
Figure 12. Representation of the test metrics for the bias-correction process of the CORDEX datasets
Figure 13. Temporal evolution of threshold exceedances (Equivalent Rainfall method – CERRA and CORDEX annual counts) (the shaded area in the figure highlights the future period (2041–2070), while the dashed line marks the end of the historical period (2025))
Figure 14. Bounding box of the area of Mera river basin, Valchiavenna
Figure 15. Percentage of municipal area in high, medium and low hydraulic (flood) hazard classes (P1–P3)
Figure 16. Map of the hydraulic (flood) hazard levels (PGRA) on the territory of Valchiavenna
Figure 17. JRC Flood depth map for the Mera river basin with 200-years return period
Figure 18. Risk data layer for the territory of Valchiavenna, based on data provided by Lombardy Region

Figure 19. Population density (GHS-POP) for year 2030 – area of Chiavenna
Figure 20. Population density (GHS-POP) for year 2030 – area of Piuro
Figure 21. Curves of the Estimated damage to buildings for Chiavenna and Piuro – comparison between OSM and DBT data
Figure 22. Critical infrastructures mapped over the territory of Chiavenna according to OSM data
Figure 23. Critical infrastructures mapped over the territory of Chiavenna according to DBT data
Figure 24. Example of the ranking of buildings according to their heights (red buildings are lower ones) – area of Chiavenna

List of tables

Table 2-1. Regional stakeholders involved in Phase 2 (denominations and roles)
Table 2-2. Metrics for the evaluation of the CERRA reanalysis data with respect to the ARPA observations
Table 2-3. Relative ranking for the analysed CORDEX datasets (lower values indicate closer agreement with CERRA)
Table 2-4. Parameters characterizing the interpretation of the results in the application of the Equivalent Rainfall method
Table 2-5. Population and buildings exposed to risk (P3 and P4 areas) according to the PAI
Table 2-6. Cultural heritage sites and local business units in P3 and P4 hydrogeological hazard areas in Valchiavenna
Table 2-7. Area of territory prone to flood risk according to the Flood Risk Management Plan classification (P1-P3)
Table 2-8. People exposed to flood risk (municipalities)
Table 2-9. Buildings exposed to flood risk
Table 2-10. People exposed to flood risk (Mountain Community)
Table 2-11. Cultural Heritage sites and business units exposed to flood risk (Mountain Community)
Table 2-12 Data overview workflow Flood-related building damage and exposed population
Table 2-13. Estimated annual damage to buildings for Chiavenna and Piuro – comparison between OSM and DBT data
Table 2-14. Key Risk Dashboard for Valchiavenna

Abbreviations and acronyms

Abbreviation / acronym	Description
ADBPO	Autorità di Bacino del Fiume Po (Po River Basin Authority)
AIB	Anti-incendio Boschivo (Forest fire prevention and fighting)
ARPA	Agenzia Regionale per la Protezione dell'Ambiente (Regional Environmental Agency)
CMV	Comunità Montana Valchiavenna (Mountain Community Valchiavenna)
EAD	Estimated Average Damage
ENCORE	Environmental Conference of the Regions of Europe
EWS	Early Warning System
FLA	Fondazione Lombardia per l'Ambiente (Lombardy Foundation for the Enviroment)
FWS	Flood Warning System
GCMs	Global Climate Models
ISTAT	Istituto Nazionale di Statistica (National Institute for Statistics)
PAI	Piano Stralcio di Assetto Idrogeologico (Hydrogeological Asset Management Plan)
PGRA	Piano di Gestione del Rischio Alluvionale (Flood Risk Management Plan)
RCMs	Regional Climate Models
RT	Rainfall Threshold

Executive summary

This deliverable presents the results of Phase 2 of the CMV4Clima project, which aims to strengthen climate risk knowledge for the Valchiavenna Alpine territory and to support local and regional decision-making within the CLIMAAX framework. The focus of this phase is on translating climate information into risk-relevant evidence for civil protection and territorial planning.

Phase 2 builds on the outcomes of Phase 1 and addresses the need for a more operational and impact-oriented climate risk assessment. Readers will find an integrated overview of how climate data, risk analysis workflows and stakeholder input were combined to deepen understanding of the regional Early Warning System and to improve the quality of the established risk analysis and mapping for the territory for flood and hydrogeological hazards. In continuity with Phase 1, also Phase 2 focuses on Heavy Rainfall and River Flood hazard and risks.

With respect of the Heavy Rainfall workflow Phase 2 explored the application of the Equivalent Rainfall Method, currently used within the regional early warning system, to assess hydrogeological and flood-related risk conditions under current and future climate scenarios.

A central component of the work is the systematic evaluation of climate datasets, including observed precipitation data from ARPA, the CERRA reanalysis and CORDEX regional climate model simulations. The comparison between observations and reanalysis confirmed the suitability of CERRA as a reference dataset for impact-oriented applications. Based on a multi-criteria evaluation, a subset of CORDEX simulations was selected and bias-corrected to ensure consistency with the reference climatology while preserving the projected climate change signal.

While no statistically robust trends in rainfall threshold exceedances were detected over the analysed periods, the results provide promising outputs and meaningful insights on the application of the method for future scenarios. A strong collaborative approach with the technical offices of the regional Civil Protection and the Environmental Agency has been established thanks to the process and will be of use during phase 3.

For river flooding, the assessment combined regional flood hazard maps with population, building and infrastructure data to refine the understanding of exposure and potential impacts. The application of the CLIMAAX flood-related building damage and exposed population workflow highlighted the concentration of exposed assets along the Mera River corridor and demonstrated the added value of integrating locally detailed datasets, while also identifying important data gaps, particularly regarding flood water depth and vulnerability characteristics.

The Key Risk Assessment synthesised the analytical results by evaluating severity, urgency and resilience capacity. Heavy rainfall was identified as a very high priority risk, while river flooding was classified as a high priority risk for the Valchiavenna territory. This prioritisation provides a clear and transparent basis for focusing future efforts on the most critical climate risks.

In summary, Phase 2 delivers a robust, transparent and decision-relevant climate risk assessment, although still limited in its scope (limited number of risks) and depth (better data could dramatically improve the outcomes). It strengthens the link between climate science and local risk management, clarifies priorities, and explicitly acknowledges data and methodological limitations. These outcomes provide a solid foundation for the final phase of the project.

Phase 3 will focus on refining impact assessments using local-scale data, integrating climate risk information into planning and civil protection instruments, and supporting a stronger understanding of the Early Warning and Civil Protection system, also through risk awareness and education initiatives.

1 Introduction

1.1 Background

Valchiavenna is a **rural Alpine area** located in northern Italy, in the Lombardy region, bordering Switzerland to the north. It covers a territory of 57,681 ha and has a population of 24,440 inhabitants. The region has a north-south vertical orientation, with an altitude range from 199 m to 3279 m asl. It features a main valley (Piano di Chiavenna) and two lateral valleys branching off from the main valley after Chiavenna: the Valle Spluga, oriented north-south, and the Val Bregaglia, oriented east-west. The territory is administratively divided into **twelve municipalities**. In addition to the more populated centres, the valley is characterized by **numerous scattered villages** (at least 76 permanently inhabited) which have remained unchanged over time and represent an essential element of local identity.

Demography and social impact

The distribution of the population across the territory is heavily influenced by its geomorphology: The main valley, characterized by a wide valley floor, hosts nearly the 80% of the total population, while each of the two side valleys, marked by narrow floors, steep slopes, and increasing altitude, hosts approximately the 10%. A slow but steady **migration from the side valleys to the main valley** is occurring due to their isolation, the gradual decline of essential services and commercial activities, and **frequent hydrogeological disruptions** that impact the internal road network, with social and ecological consequences for these areas.

From a social perspective, the analysis of demographic indicators, such as birth rates, average age, and emigration rates, clearly pointed out an aging population. This demographic shift is reshaping the social structure, increasing social-welfare spending, and potentially weakening the community's resilience. A **decreasing and aging population** can reduce the region's ability to respond effectively to disasters and adapt to change.

Economic sectors

Economically, Valchiavenna relies mainly on **agriculture, tourism, and small-scale industries sectors** highly vulnerable to climate variability and extreme weather events. Tourism, in particular, is strongly related to the region's natural attractions and is expected to be significantly impacted by climate change, posing a major challenge to local economic stability.

Water is a vital resource for valley ecosystems, increasingly affected by climate change. In dry years, water availability may become limited, creating competition between ecosystems and the numerous reservoirs used for hydroelectric power production. Conversely, in rainy years with intense precipitation events, these reservoirs can serve as a crucial resource, acting as a water storage system. They help regulate water availability by retaining excess water during heavy rainfall to prevent flooding and releasing stored water during droughts to sustain the flow of downstream watercourses.

Infrastructure

Access to the valley is primarily dependent on the state route 36, the main road running through the central valley up to Chiavenna, where it splits into two routes leading to the Swiss border. A railway line runs alongside the road up to Chiavenna, providing additional, though limited, connectivity. However, frequent hydrogeological issues threaten to isolate Valchiavenna, as no alternative transport routes exist.

The region also faces critical infrastructure challenges. Many protective measures against natural hazards are outdated and inadequate given the current level of risk. Limited financial resources make it difficult to maintain and upgrade infrastructure to withstand increasingly severe weather events, placing additional strain on the community's long-term sustainability.

Environment and Biodiversity

Valchiavenna has a rich environmental and cultural heritage territory. It includes **protected areas** regulated by the Directive 2009/147/EC on the conservation of wild birds which covers the protection, management and control of wild birds and lays down rules for their exploitation. There are also areas regulated by the Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora.

Biodiversity is one of Valchiavenna's greatest treasures. Several factors contribute to the richness in both plant and animal biodiversity, including the vast extent of the territory, the significant difference in elevation, from 199 meters to 3,279 meters at its highest peak and the presence of Lake Mezzola at the valley's mouth, which helps moderate the climate in the lower areas. The geological, geomorphological, and pedological diversity further enhances the variety of vegetation types found here. Valchiavenna is rich in **environmental resources** such as water, wood and pastures, which, depending on how they are managed, can contribute to increasing or limit the problems linked to climate change. Valchiavenna has an extensive network of aquatic ecosystems, including **two main rivers, Mera and Liro**, which merge after Chiavenna in the main valley, as well as numerous streams, creeks, brooks, alpine lakes, and reservoirs.

1.2 Main objectives of the project

Phase 1 enabled an in-depth reflection on the methods used by the Regional Civil Protection system to define meteorological and hydrogeological warning conditions within the territory of the Mountain Community, through the analysis of the thresholds adopted by the Early Warning System for the homogeneous zone corresponding to the Valchiavenna area.

It also laid the groundwork for a characterization of exposure and vulnerability in flood-prone areas within the main urbanized zones of the Mera sub-basin, one of the two main watercourses in the valley and the one affecting the areas with the highest population density.

Phase 2 aims to:

- further investigate the threshold-based methodology used in the Early Warning System ("Equivalent Rainfall method") and assess whether trends can be identified in the scenario data;

- further refine the characterization of exposure and vulnerability to hydrogeological and river flood hazard by adapting the approaches proposed by the CLIMAAX project to local conditions;
- integrate and systematize risk assessment elements derived from different sources (Civil Protection Plans, AIB Plans, natural hazard projects), which have recently been implemented across the territory of the Mountain Community.

Phase 2 builds on the achievements of Phase 1, pursuing the same overarching objectives of enhancing resilience and reducing vulnerability to climate change in the Valchiavenna region.

The expected benefits include:

- Establish the foundations for an approach that can subsequently be reused and further refined—also in cooperation with regional authorities—to monitor trends in the number of threshold exceedances and activations of the local Civil Protection system (including, in a forward-looking perspective, an assessment of the associated costs).
- Identify the most relevant vulnerability factors in determining flood-related risk, determine which of these factors can effectively be addressed, and define how interventions can be implemented.
- Develop an overall risk framework for the territory of the Mountain Community, by proposing a gap analysis and outlining future developments to complete a comprehensive risk assessment for the area.

1.3 Project team

Name	***Description***	***Role in the project***
Comunità Montana Valchiavenna (CMV)	A **public local authority** representing the union of 12 municipalities in Valchiavenna, dedicated to protecting and enhancing the mountain territory. It serves as a socio-economic and territorial-urban planning body, as well as a coordinating entity that manages functions and services, either directly or on behalf of the municipalities.	- **Project beneficiary** - **Main interlocutor** with European institutions and CLIMAAX project coordinators - Coordinating project activities - Engaging stakeholder - Dissemination, communication, and presentation of project results - Providing FLA with scientific data collected directly by the Mountain Community or through other relevant entities, institutions, or authorities
Fondazione Lombardia per l'Ambiente (FLA)/Ecometrics ltd	A **non-profit legal entity** engaged in research activities on environmental protection and pollution prevention. Its main mission is to conduct and disseminate studies, research, projects, and information to enhance awareness and understanding of environmental issues.	- **Technical experts** - Guiding CMV in the development and achievement of the project's objectives and the technical analysis

1.4 Outline of the document's structure

This deliverable is structured into five main sections.

Section 1 – Introduction provides the contextual background of the Valchiavenna territory, including its demographic, environmental, infrastructural and socio-economic characteristics. It outlines the objectives of the CMV4Clima project, introduces the project partners and describes the overall structure of the document.

Section 2 – Climate risk assessment – Phase 2 presents the core analytical work of the deliverable. It describes the scoping and risk exploration activities, the selection of climate scenarios, and the regionalised risk analysis for heavy rainfall and river flooding. The section also includes the Key Risk Assessment, monitoring and evaluation, and the work plan for Phase 3.

Section 3 – Conclusions Phase 2 summarises the main findings, achievements and limitations of the climate risk assessment carried out in Phase 2, highlighting its added value compared to Phase 1 and its relevance for future actions.

Section 4 – Progress evaluation assesses the progress achieved against the project's objectives and key performance indicators, and reflects on the contribution of Phase 2 to the overall CMV4Clima project and to the subsequent phases.

Section 5 – Supporting documentation lists the main outputs produced during this project phase, including reports, visual materials and datasets, and provides references to supporting material.

2 Climate risk assessment – phase 2

2.1 Scoping

2.1.1 Objectives

The projects objectives, as well as the context, have been defined as formulated in the Deliverable of phase 1. No major changes need to be communicated at this time.

2.1.2 Context (update)

The Mountain Community of Valchiavenna is currently updating its territorial planning and risk management instruments, recognizing the importance of effectively addressing climate-related and natural hazards affecting the area.

The **Civil Protection Plan** is developed at different administrative levels; in this case, it is developed at a supra-municipal scale, corresponding to the Mountain Community of Valchiavenna. In Italy, the municipal Civil Protection Plan represents the primary operational instrument for emergency preparedness and response. It defines territorial risk scenarios, the organizational structure, roles and responsibilities of authorities, emergency procedures, and alert and communication mechanisms aimed at protecting the population and critical assets in the event of natural or anthropogenic hazards. The first step in the development of a Civil Protection Plan consists of the analysis of natural hazards affecting the territory and the exposed population and the definition of risk scenarios and the definition of procedure for the safeguarding of population in the first place. This phase shows strong points of convergence with the development of the CLIMAAX project and is expected to generate significant synergies in Phase 3, particularly about the integration of climate risk assessment results into risk management planning and the active involvement of the local population.

Furthermore, the Valchiavenna Mountain Community has recently developed the **Forest Fire Prevention Plan (AIB)** in accordance with the regional guidelines of Lombardy Region, with a prevention-oriented and integrated approach to wildfire risk management. The Plan is based on territorial analyses, historical data, predictive models, and operational tools to identify the most exposed areas and to plan targeted interventions such as preventive forest management, strategic infrastructure and protection of wildland–urban interfaces. Fully aligned with the Valchiavenna Mountain Community's planning framework, the AIB Plan supports the transition from reactive emergency response to a proactive system aimed at reducing territorial vulnerability and enhancing local resilience.

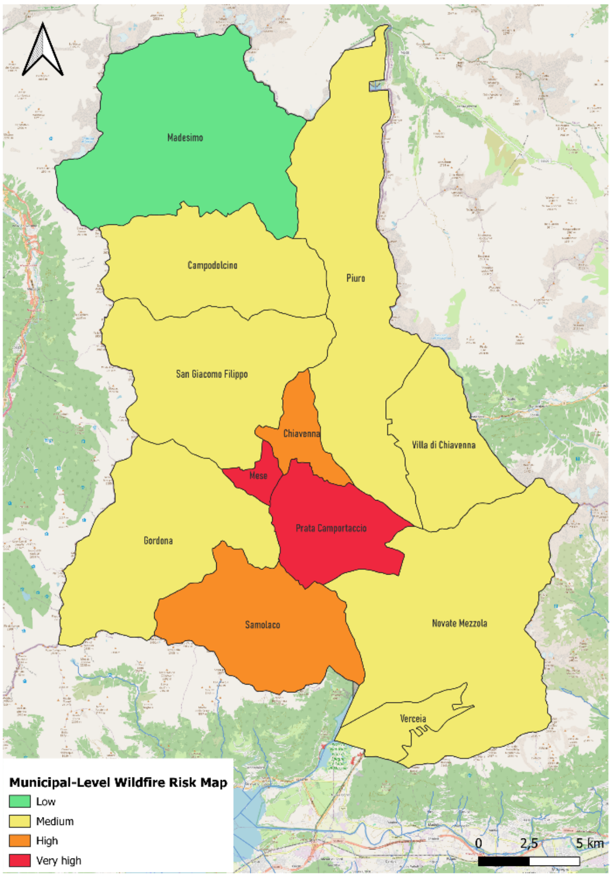

Figure 1. Source: Local Forest Fire Prevention Plan (DRE.AM Italia)

Wildfire risk results from the combination of hazard and vulnerability and is classified into five classes, ranging from Very Low to Very High. Wildfire hazard is defined as the probability that a fire will occur with a given fire-front intensity (kW/m). Wildfire vulnerability depends on ecosystem characteristics and land use. Within the territory of the Valchiavenna Mountain Community, most municipalities fall into the Medium risk class. In the lower and middle valley, there are two municipalities at High risk, Chiavenna and Samolaco, and two at Very High risk, Mese and Prata Camportaccio. The following figure shows in detail the risk class for each municipality.

At the European level, the Mountain Community of Valchiavenna is actively involved in the **AMALPI More** project, which promote the implementation of a monitoring network for slope movements (rockfalls, rockslides, landslides, movements related to the permafrost creep) and for key hydro-meteorological parameters (precipitations, temperatures, snow, humidity, water quality) that will allow to assess and quantify climate change impacts on high mountain territories in an integrated way. By analysing climate change impacts at both regional and local scales, the initiative will enhance natural hazard prevention and strengthen the resilience of affected territories by improving adaptation strategies.

In addition, the Mountain Community of Valchiavenna has applied to the Pathways to Resilience call, a European initiative supporting regions and communities in the development of long-term climate resilience pathways.

2.1.3 Participation and risk ownership

Starting in April–May 2025, institutional exchanges between the Mountain Community and the relevant regional departments took shape through a series of meetings—initially strategic in nature and subsequently more operational—aimed at refining the specific objectives of Phase 2 for all risk typologies addressed by the CMV4Clima pilot project: intense precipitation (and associated hydrogeological risk) and flood risk.

A series of meetings and exchanges have been arranged along the process, involving the following offices and roles within the Lombardy Regional administration:

Table 2-1. Regional stakeholders involved in Phase 2 (denominations and roles)

Denomination (I)	*Denomination (II)*	*Role*
Directorate-General for Security and Civil Protection		
	Head of **Civil Protection Organizational Unit**	Strategic consulting and specific goal setting (phase 2 and 3), terms of cooperation on the application of the regional EWS approach
	Organizational Unit for **Regulation and Promotion of Civil Protection Culture**	Strategic consulting and specific goal setting (phase 2 and 3), with respect of risk culture and awareness raising activities to be developed in the scope of the project
	Head of the Regional Civil Protection Department's Functional **Centre for Risk Monitoring, Natural Hazards and Early Warning System**	Guidance on the application of the regional EWS approach and the "Equivalent Rainfall" method
	Coordination Unit **for the Civil Protection Volunteering System and Emergency Planning**	Strategic consulting and specific goal setting (phase 2 and 3), with respect of the economic aspects of the Civil Protection management system
Directorate-General for Territory and Green Systems		
	Unit for the Implementation of Regional Soil Protection Measures	Strategic consulting and specific goal setting (phase 2 and 3), with respect of the implementation of the Flood Risk Management Plan on the territory of Valchiavenna, risk mitigation measures planned and in place, characterization of the exposed assets on the territory

The **Po River Basin Authority** (ADBPO) was involved as well, as the reference authority on the matter of river flood risk for the region, to provide both hazard and risk data and user recommendations.

Moreover, the **Regional Environmental Agency** (ARPA) has been directly involved, providing both data and guidance on the use of the same, as well as on reanalysis and scenario data.

In parallel, structured engagement was initiated with the **University of Milan** (particularly with the Head of the Engineering Geology Laboratory and of the Valchiavenna Alpine Environment Research Station), which has been actively involved for several decades in the territory of the Mountain Community through geological, hydrological and hydraulic research activities, as well as broader risk-related studies.

This collaboration aims to further refine the objectives and specific activities of the CMV4Clima project in Phase 2 (and subsequently in Phase 3), to support the acquisition of baseline climatic, hydrological and geological data required for the implementation of the project workflows, and to strengthen the transferability, scalability and long-term legacy of the project through the integration of its results into future research initiatives and project developments.

Further contacts and exchanges were established with:

- the external consultants responsible for drafting the updates of the Municipal Civil Protection Plans for the Valchiavenna area (currently under development)
- the update of the Forest Fire Prevention Plan (recently completed in 2025)

The process was mainly conducted by the technical experts for the operational aspects, supervised by the Technical Office of the Mountain Community and by the coordinators of the Mountain Community as for the strategy and agenda setting aspects.

The project set the goal of involving the same actors in a review process of the outcomes of phase 2 and the facilitation of the uptake of the same outcome for further analysis and for awareness-raising and risk mitigation initiatives on the territory to be developed in phase 3. This will likely need to broaden furtherly the number and spectrum of involved stakeholders.

2.1.4 Application of principles

In line with the CLIMAAX Framework, the analysis systematically integrates the principles of social justice, equity and inclusivity by explicitly accounting for differentiated climate impacts across territories, socio-economic groups and sectors. Vulnerability assessments incorporate disaggregated socio-economic indicators to identify disproportionate risks and to ensure that adaptation priorities do not exacerbate existing inequalities. Quality, rigour and transparency are ensured through the application of scientifically robust methodologies, the use of harmonised and traceable data sources, and the clear documentation of assumptions, limitations and uncertainty ranges. The analysis follows a reproducible workflow aligned with established EU climate risk assessment standards. The precautionary approach is applied by considering multiple climate scenarios and time horizons, including high-impact, low-probability events, and by adopting conservative risk thresholds to support informed decision-making under conditions of uncertainty.

2.1.5 Stakeholder engagement

Throughout the Phase 2 of the CLIMAAX project, the Mountain Community of Valchiavenna (CMV) carried out a broad and diverse set of stakeholder engagement activities to support the CLIMAAX – CMV4CLIMA project. These actions aimed to raise awareness, share preliminary findings, collect feedback, and build a stronger local and transnational network around climate adaptation challenges.

Engagement efforts targeted a wide spectrum of actors, including local authorities, thematic experts, educational institutions, community organisations, and citizens, reflecting the multi-level approach required for climate resilience processes

The main activities are summarized in the following section, focusing on the key meetings, presentations and workshops in which CMV introduced or discussed the CLIMAAX project. The description highlights the audiences involved, the communication approaches adopted, and the feedback and outcomes generated. Taken together, these activities significantly contributed to enhancing knowledge exchange and strengthening stakeholders' ownership and participation in the project.

Overall, the combination of public events, targeted meetings, and ongoing communication activities contributed to expanding the project's visibility, strengthening stakeholder engagement, and fostering a shared understanding of climate-related risks and opportunities for the Valchiavenna territory.

2.1.5.1 Public events open to all stakeholders

2.1.5.1.1 "Biodiversity loss resulting from climate change" – Conference – April 2025

The conference featured a series of presentations addressing key aspects of climate risk and adaptation at both project and territorial levels, strengthening the understanding of local climate risks, promoting the role of monitoring and agrobiodiversity in resilience building, and informing adaptation strategies for the agricultural sector in the context of climate change. The first contribution presented the results of the activities carried out during the initial phase of the CLIMAAX project, providing an overview of the methodological approach and preliminary findings.

Residents and municipal authorities engaged with or impacted by the CLIMAAX initiatives demonstrated keen interest and valued the opportunity to gain deeper insights into CMV's climate-focused efforts. The event overall provided an important platform to foster dialogue among stakeholders, raise awareness of climate-related challenges, and stimulate wider participation in sustainability-driven actions to support the long-term resilience of the mountain region

2.1.5.1.2 "Rapporto Montagne Italia 2025" – Meeting - November 2025

The Mountain Community of Valchiavenna hosted a public event at its headquarters to present UNCEM's Montagne Italia 2025 report, inviting local institutions, associations, and citizens from municipalities across the valley. Since the report focuses on the future of mountain territories, the event offered a fitting opportunity for CMV to illustrate its ongoing efforts to support sustainable mountain development.

In this context, CMV introduced the CLIMAAX – CMV4CLIMA project, presenting the project's objectives, its approach to context-specific climate risk assessment, and the initial findings emerging for the Valchiavenna area.

Local citizens and authorities—directly involved in or affected by the CLIMAAX studies—showed strong interest and expressed appreciation for learning more about CMV's climate-related activities. Representatives from UNCEM also reacted positively, noting how the work carried out in Valchiavenna aligns with and enriches the themes explored in their research.

Overall, the event served as a valuable occasion to promote dialogue among local stakeholders, strengthen awareness of climate challenges, and encourage broader engagement in sustainability-oriented actions for the future of the mountain territory

2.1.5.2 Communication with public authority

2.1.5.2.1 Conference of mayor of Valchiavenna – July 2025

The Conference of Mayors serves as a consultative and coordinating body bringing together the mayors of municipalities within the mountain territory. The main purpose of the Conference is to support the alignment of local policies, promote joint strategies to address shared challenges—such as sustainable development, environmental protection, climate adaptation, and local economic growth—and facilitate the exchange of experiences and best practices among municipal administrations. During the Conference, the results of the first phase of the CMV4Clima project were presented, providing insights into climate-related activities, preliminary findings, and ongoing initiatives.

2.1.5.3 Workshop dedicated to the educational system

2.1.5.3.1 High school students, workshop at "Istituto Leonardo da Vinci" - 01/04/2025

The meeting at the educational institution focused on the project goals and intermediate results which were communicated through a structured presentation, using visual tools such as slides and charts to make key concepts easier to understand. The objectives of the project were outlined, emphasizing the importance of assessing climate risks and how these risks might impact the local community and environment. We aimed to make the information easily digestible by adapting the language to the school audience and encouraged questions to foster active participation.

2.1.5.3.2 Teachers and public authority from Poland - Meeting – September 2025

As part of a study visit organised for a group of Polish teachers and representatives of local public authorities, the Mountain Community of Valchiavenna hosted a meeting at its institutional headquarters. The session introduced the role and functions of the CMV, with a dedicated focus on its work on climate-related issues.

The CLIMAAX – CMV4Clima project was presented in an accessible and simplified way, tailored to an audience not specifically specialised in climate adaptation. Participants expressed strong interest in understanding how a local authority integrates climate considerations into its planning and territorial policies, and appreciated the practical approach adopted in Valchiavenna.

The discussion required adapting both language and content to ensure clarity, but no major difficulties emerged. The meeting represented an opportunity to raise awareness of climate challenges among education professionals and institutional representatives, and to showcase how the CLIMAAX project contributes to building local resilience.

2.1.5.4 Dissemination in other project in which Mountain Community is partner and partecipation in events organized by European projects or network

2.1.5.4.1 Interreg Europe EURADAPT - Kick-off meeting – June 2025

During the kick-off meeting of the Interreg Europe EURADAPT project, attended by project managers and representatives of the partner organisations, the Mountain Community of Valchiavenna introduced the CLIMAAX – CMV4CLIMA project during the opening session. The presentation focused on the project's objectives, the main climate-related challenges of the Valchiavenna area, and the approach adopted for the climate risk assessment.

The information shared raised interest among participants and prompted informal discussions during the breaks. Feedback was positive, in particular regarding the specific needs of the alpine territory of Valchiavenna. The main difficulty encountered was the limited knowledge of the Valchiavenna territory among international participants, which required additional contextual explanations. Nevertheless, the meeting offered a useful opportunity to introduce the area and its climate adaptation needs within a wider European exchange.

2.1.5.4.2 ENCORE Network - conference in Gothenburg – September 2025

The Mountain Community of Valchiavenna took part in the ENCORE Conference held in Gothenburg. ENCORE (Environmental Conference of the Regions of Europe) is a long-standing network bringing together European regional authorities committed to environmental protection and climate action. The event gathered policymakers, regional institutions and technical experts with a high level of knowledge on climate-related issues from European countries.

CMV was invited to present its experience as a local authority implementing concrete adaptation actions. In this context, the CLIMAAX – CMV4CLIMA project served as a key example of how a small mountain institution can act as a practical "testing ground" for context-specific climate risk assessment and local resilience measures.

Participants showed strong interest in understanding how CMV translates adaptation strategies into operational activities and how these efforts are embedded in everyday territorial governance. Many questions focused on existing measures already adopted in Valchiavenna to respond to climate impacts, and on how the CLIMAAX methodology supports decision-making at the local scale.

The discussion generated significant interest in potential future collaboration, particularly regarding knowledge exchange, mutual learning and the transferability of adaptation practices across European regions.

2.1.5.4.3 Interreg ALCOTRA - Thematic workshop – September 2025

The Mountain Community of Valchiavenna took part in the thematic Workshop 1, "Climate change effects and impacts in the ALCOTRA territory", organised by the Interreg ALCOTRA Programme. The session brought together project partners and managers from various ALCOTRA initiatives.

CMV was invited to present its efforts on climate adaptation and shared an overview of its ongoing climate-related activities, with a particular focus on the CLIMAAX – CMV4CLIMA project. The presentation outlined the project's objectives, its approach to context-specific climate risk assessment, and the initial findings emerging for the Valchiavenna area.

Participants showed strong interest, especially in understanding how CLIMAAX structures local risk analysis, the tools employed, and how the methodology could be transferred to other territories. Several attendees requested additional information to compare approaches or explore possible synergies.

No major difficulties emerged, aside from the need to adjust the level of technical detail to match the varied backgrounds of participants. Overall, the workshop offered a valuable opportunity to disseminate the CLIMAAX experience and strengthen exchanges with other Alpine stakeholders.

2.1.5.5 Dissemination through complementary communication channels

In addition to the events described above, CMV ensured continuous dissemination of the CLIMAAX – CMV4Clima project through complementary communication channels. These included articles in regional and national media, regular social media updates on Instagram, LinkedIn, and Facebook, and dedicated content on the institutional website

2.2 Risk Exploration

2.2.2 Screen risks (selection of main hazards)

The characterization of hazards in the Valchiavenna area was completed during the first phase of the project and is detailed in the first deliverable. This work continues to focus on the two main hazards identified (River flooding, Heavy rainfall), integrating local data and information into the workflow.

New developments only concern the further investigation of hazard and risk maps available at the local level, as well as exposure and vulnerability elements, as presented in paragraphs 2.3.2.2 and 2.3.3.2.

2.2.3 Choose Scenario

Available scenarios (RCPs options, combination of GCM and RCM, etc.) utilized in the workflows are going to be discussed in the following sections.

With regard to the Heavy Rainfall workflow, in phase 2 the first part of the analysis considered the same GCM/RCM combinations as in phase 1. Eventually, due to time and resources constraints, focused on:

- scenario RCP8.5 (CORDEX)
- 2041-2070 time period
- the combination GCM/RCM: MPI-M-MPI-ESM-LR/SMHI-RCA4

2.3 Regionalized Risk Analysis

2.3.1 Heavy Rainfall risk - fine-tuning to local context

In phase 1, the Heavy Rainfall workflow was applied in an exploratory mode, with the main objective of testing the usability of selected datasets and methodologies, rather than producing conclusive results. The application of the workflow considered the existing weather forecast and early-warning system, main component of the overall civil protection scheme at the national and regional levels.

The **general objective** of CMV4Clima **to be investigated in Phase 2** is whether it is possible to implement the method currently utilized by the regional Civil Protection system (possibly, with all appropriate modifications) and based on **rainfall critical thresholds** triggering the Early Warning System for hydrological risk, to **verify a trend in the annual number of threshold exceeding** and consequent activations of the Civil Protection; or, at least, the frequency of the conditions (precipitation, equivalent precipitation) that predispose to system activation.

2.3.1.1 The Regional Alert System for Natural Risks

According to the "*Regional Directive for the Organizational and Functional Management of the Alert System for Natural Risks for Civil Protection Purposes*" (d.g.r. 4114, December 21st, 2020), valid in the Lombardy Region, where Valchiavenna is located, the regional territory is divided into homogeneous alert zones, territorial areas that exhibit uniform ground effects in response to meteorological forcing.

Errore. L'origine riferimento non è stata trovata. represents the boundaries of the two zones IM-01 and IM-02. **IM-01** includes the municipalities of *Madesimo, Campodolcino, Piuro, San Giacomo Filippo, Chiavenna, Villa di Chiavenna, Mese, Gordona* and *Samolaco*. **IM-02** includes the municipalities of *Novate Mezzola* and *Verceia*.

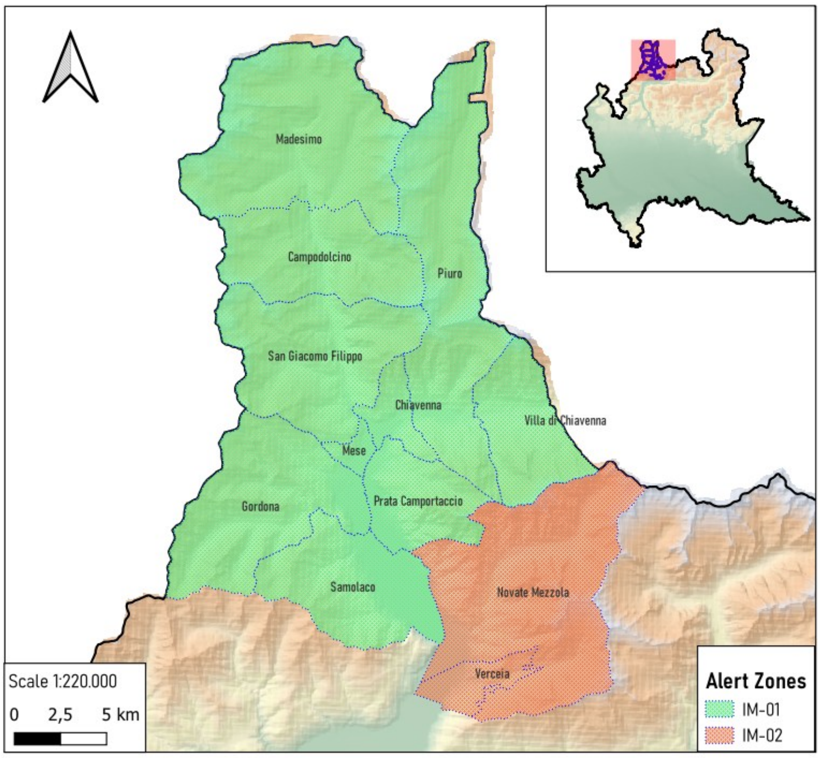

Figure 2. Homogenous alert zones of Valchiavenna from the regional Civil Protection system of Lombardy Region

Present study will only focus on IM-01 because of the higher representativeness for the area of Valchiavenna in surface terms and because IM-01 constitute its own river basin.

The zones have been developed by the regional Civil Protection system for various types of hazards (hydraulic, hydro-geological, strong winds, etc.). More specifically, for the purpose of the present investigation, the study will refer to the *homogeneous zones for hydro-meteorological risk: hydrogeological, hydraulic, thunderstorms, and strong winds*.

The regional directive identifying the homogeneous zones and the procedure to determine the alert thresholds has been issued originally in 2004 and later reviewed and updated in 2020 and again in 2025. Concerning hydrogeological hazards, the directive defines a "equivalent rainfall method" to evaluate predictable rainfall thresholds triggering impacts on the ground, hence the response of the civil protection system in the area.

2.3.1.2 The "equivalent rainfall method"

The latest study describing the development and the specifics of the "equivalent rainfall method", "An empirical rainfall threshold approach for the civil protection flood warning system on the Milan urban area", was published in 2024 in the Journal of Hydrology (Gambini E. et al, 2024). In the study, the authors illustrate a Flood Warning System (FWS) based on the development of catchment-specific empirical Rainfall Thresholds (RTs). *An empirical methodology, based only on historical rainfall-runoff data and applicable to any river catchment, is proposed with the aim to validate and* *improve the existing Rainfall Threshold (RT) defined on the same area by the Lombardy Region civil protection.*

The RTs obtained using the proposed method showed improvements with respect to the existing civil protection RTs, because it allows to derive time-continuous and catchment-specific RTs. Additionally, accounting for the Antecedent Moisture Conditions (AMC) with the proposed "equivalent rainfall" approach results in more accurate RTs, suggesting its consideration for issuing civil protection alerts.

As suggested before, the methodology thereby developed has been institutionalized in the regional directive by Lombardy Region "*Regional Directive for the organizational and functional management of the alerting system for natural hazards for civil protection purposes*" (d.g.r. 4114, December 21st, 2020) and more specifically in the latest update of the annexes to the same (November 2025).

In Annex 1, the Civil Protection authority presents a "*Method for the assessment of rainfall threshold exceedances for hydrogeological and hydraulic risk, taking into account soil moisture conditions*", also referred to as "equivalent rainfall method".

Quoting the same Annex:

"Forecast precipitation represents a precursor of potential hydrogeological and hydraulic criticalities across the territory, such as river flooding, slope instability, debris flows, and similar phenomena. Forecasting the expected precipitation with a certain lead time, and the consequent exceedance of predefined values (rainfall thresholds) indicative of the potential severity of the event, allows the civil protection system to organize itself in advance and to adopt the necessary preventive mitigation actions."

Also:

"Within the framework of the regional alerting system, the adoption of criteria that take into account the actual soil moisture conditions is essential for a realistic and reliable assessment of the hydrogeological and hydraulic risk associated with precipitation events. For the same forecast rainfall, the impacts on the territory may in fact differ significantly depending on the soil's capacity to absorb meteoric water, which is strongly influenced by antecedent rainfall. To account for this variability, the concept of "equivalent rainfall," or more simply "P_{eq}," is introduced, defined as a transformation of the forecast rainfall that incorporates the effect of rainfall occurring in the preceding days. By comparing P_{eq} with the alerting rainfall thresholds, which are defined for dry soil conditions, it is therefore possible to improve the accuracy and consistency of risk assessments."

The method is based on a reformulation of the SCS-CN (Soil Conservation Service – Curve Number) model that introduces a *continuous antecedent moisture parameter*, "M", instead of discreet classes of soil moisture, calculated on the basis of the rainfall over the previous five days (P_5).

In synthesis, the method considers the potential effects of a forecast rainfall over a soil with antecedent moisture conditions, evaluated through combining soil characteristics and the rain fallen in the 5 previous days.

Assuming that the level of hazard is proportional to the degree of saturation (S_r), the **equivalent rainfall (P_{eq})** is defined as **the amount of rainfall on dry soil that produces the same S_r generated by the forecast rainfall (P) preceded by the antecedent rainfall P_5**.

The **operative equations** of the methodology are the following:

$$\begin{cases} M = \sqrt{S[P_5 + \left(\frac{1-\lambda}{2}\right) - \left(\frac{1+\lambda}{2}\right)S} \;\; with\; P_5 \geq \lambda S \; (otherwise\; M = 0) \\ P_{eq} = P + M\left(1 + \frac{\lambda S}{S+M}\right) = P + P_{eq0} \end{cases}$$

where:

- where λ is the initial abstraction (retention) coefficient, typically ranging between 0.05 and 0.20
- *S* depends on the Curve Number (*CN*) characteristic to the soil
- P_{eq0} is the baseline equivalent rainfall, a function of the Curve Number (*CN*) and of the rainfall over the previous five days P_5, which "recharges" the forecast event (*P*) by the hazard increment due to soil moisture. In practical terms, P_{eq0} represents the amount of rainfall that would produce the same degree of soil saturation if the rainfall event were to occur on perfectly dry ground.

2.3.1.3 Hazard assessment

2.3.1.3.1 Rainfall threshold and ground impacts

It should be reminded that the rainfall threshold hereby investigated and defined within the early warning system of the Civil Protection of Lombardy Region are meant to be used in particular as precursors potentially triggering hydrogeological hazards in the area, **including different types of instabilities and phenomena**, such as **landslides**, **mud** and **debris flow**.

In this respect, the study also collected and built the data and information overview about the hydrogeological hazard category for the area of Valchiavenna. The map of Figure 4 (page 23) 23shows the representation of the hydrogeological hazard levels on the territory according to the Hydrogeological Risk Management Plan – PAI. PAI hazard classes are describes as P1 (low hazard), P2 (medium), P3 (high) and P4 (very high hazard). More detailed maps are provided as additional material to the present study.

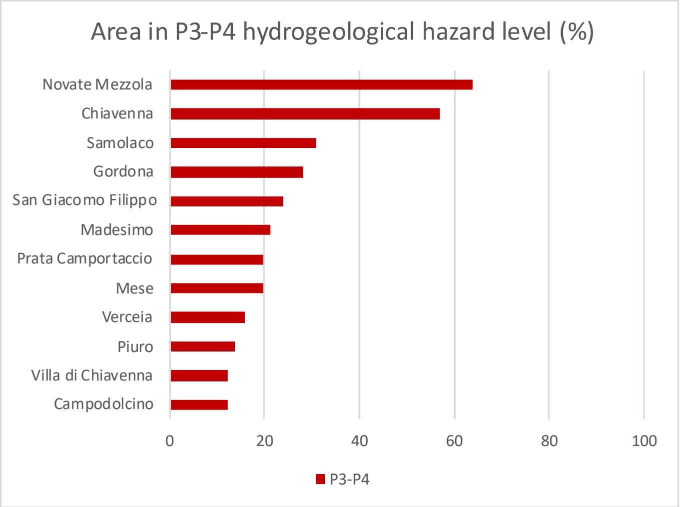

Figure 3. Percentage of municipal area in high and very high PAI hazard classes (P3–P4)

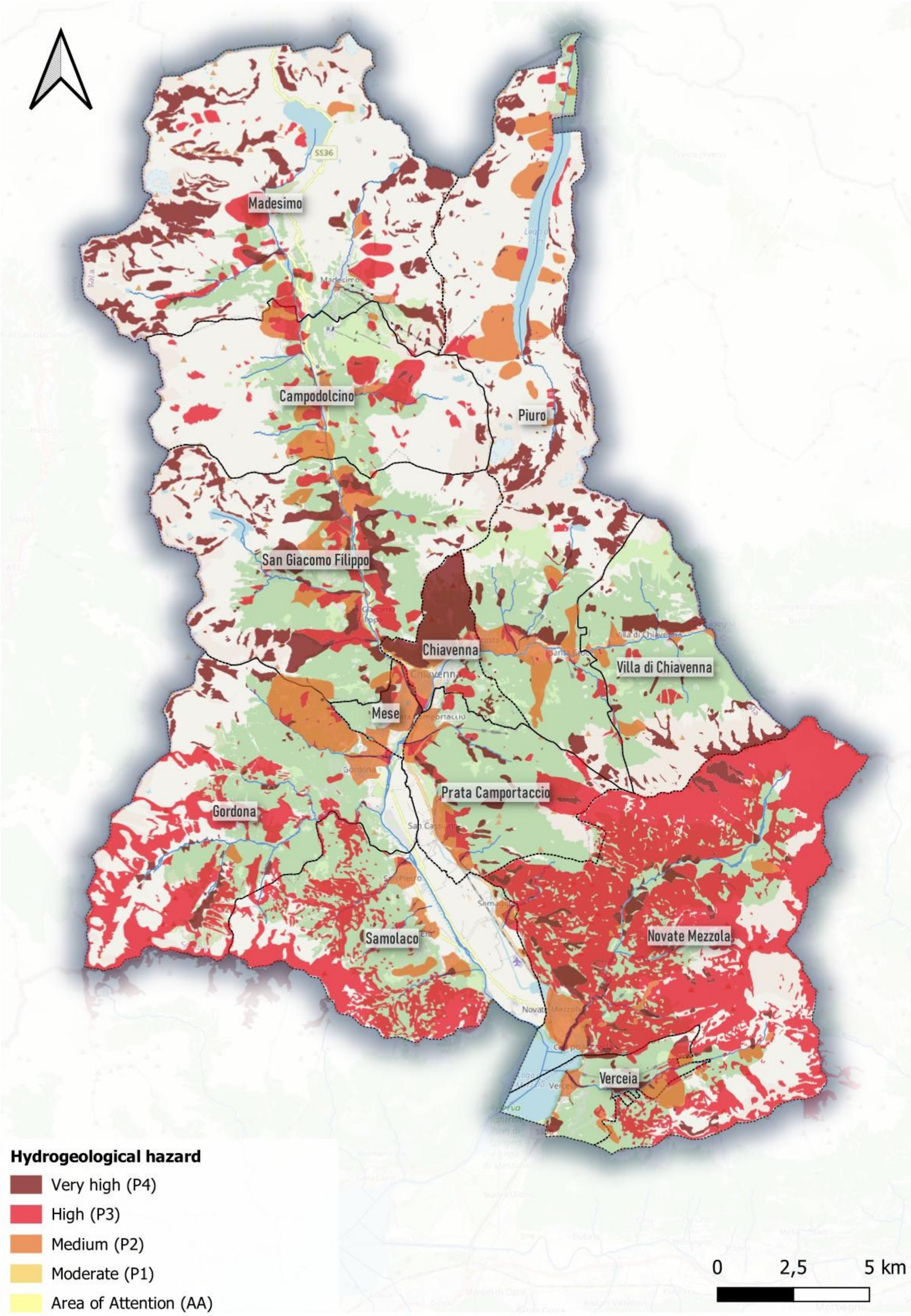

Figure 4. Map of the hydrogeological hazard levels (PAI) on the territory of Valchiavenna

2.3.1.3.2 Data availability and general approach

Some of the initial hypotheses for the activity have been formulated as follows:

- Rainfall data can be derived in the form of precipitation aggregated on different temporal steps from local sources (observed data from the Regional Environmental Agency ARPA and other sources) and in the form of mean precipitation flux from CORDEX scenario datasets
- mean precipitation flux data can be produced from different combinations of Global Climate Models (GCMs) and Regional Climate Models (RCMs), producing (as seen from the results obtained in phase 1) rather different outcomes
- where appropriate, modelled data can be evaluated against the measured ARPA data (several meteorological stations being available in Valchiavenna)
- data about soil characteristics (i.e. CN) are made available again by ARPA as a gridded dataset over the area
- for the available precipitation data series, it is possible on a daily basis:
    - calculate the cumulative rainfall over the previous 5 days and then the equivalent precipitation, following the method proposed by Lombardy Region civil protection
- according to the method, determining the exceedance of a critical threshold would require a "forecast precipitation" value for the following day

After several rounds of discussion with the Regional Agency for the Environment (ARPA) and the technical centre of the Lombardy Region civil protection and the supervision of the ECMWF as well, some key decisions have been made about the application of the methodology in the scope of CMV4Clima:

- ARPA observed data can and should be used only in terms of characterization of the local climatology and initial reference
- Reanalysis precipitation data will be used as the ultimate reference for the climatology of the area and for the bias-correction of the CORDEX datasets, and the reanalysis data of choice are the CERRA data, with a horizontal resolution of 5.5 square kilometers
- the proposal envisages **calculating, on a daily basis, the Peq0** (or "baseline equivalent rainfall"), which depends on P_5 and ultimately CN (through S), and then **identifying the days on which this P_{eq0} value is greater than or equal to the threshold**. Consequently, the computation would no longer highlight the days on which the forecast rainfall could lead to a threshold exceedance (P_{eq0} + forecast rainfall P ≥ threshold); instead, it would **highlight the days preceded by sufficient antecedent rainfall P_5 to generate a level of soil saturation (expressed as an average over the sub-basin) such that, even in the absence of forecast rainfall, a "hydrogeological/hydraulic risk" is, in general terms, possible**.

Additional considerations that prepared for the application of the methodology are:

- in the equations of the Equivalent Rainfall model (in its current formulation), there are no variables that explicitly account for whether precipitation is liquid or solid. The threshold temperature used to discriminate between **liquid and solid precipitation** typically ranges between 0 °C and 1 °C. Generally, a threshold of 0 °C is adopted, which is conservative in terms of safety, as it tends to overestimate the liquid fraction

- regarding the issue of spatialization, this application of the methodology will run on the area of the alert zone IM-01 and treat the whole zone as **homogeneous in terms of soil characteristics** (by spatially averaging the CN gridded data of the area) and rainfall map data (that is, a single rainfall spatially averaged value is going to be fed to the equations)

Rationale for the methodological sequence

Finally, the workflow has adopted this non-interchangeable sequence:

1. evaluation of datasets over overlapping periods,
2. bias correction applied exclusively to daily precipitation,
3. computation of cumulative precipitation indices,
4. application of the Equivalent Rainfall Method.

Bias correction is intentionally performed **before** the calculation of cumulative indicators. Applying bias correction directly to cumulative quantities or to derived indices would obscure the physical meaning of the correction and potentially introduce artefacts.

Overall, this approach should ensure methodological consistency, transparency, and robustness, and allow the Equivalent Rainfall Method to be applied to future climate scenarios in a way that is fully coherent with both observed and reanalysis-based reference conditions.

2.3.1.3.3 Climate Data Processing Workflow and Application of the Equivalent Rainfall Method

Data sources and hierarchy

The analysis is based on three main categories of climate data, characterized by different levels of realism, spatial representativeness, and intended use:

1. **Observed precipitation data** from the regional environmental agency (ARPA), representing point-scale measurements and used as the primary reference for local-scale climatological validation.
2. **CERRA reanalysis data**, providing spatially continuous, physically consistent gridded precipitation fields, adopted as the reference dataset for bias correction and spatial analyses.
3. **CORDEX regional climate model (RCM) simulations**, including historical and scenario runs

This hierarchy reflects a common and well-established approach in climate impact studies, where in situ observations are used to evaluate reanalyses, and reanalyses in turn are used as a reference for the correction of climate model outputs.

Overall, the analysis was structured over three periods of time, according to the availability of the data:

- **"historical" period**: ARPA observed data, CERRA Reanalysis and CORDEX "historical" (which end with 2005) available and tested
- **"pseudo-historical"** period: ARPA observed data have not been considered, CERRA data available, CORDEX already selected by scenario (RCP8.5)

- **“future” scenario**: only CORDEX modelled data from RCP8.5

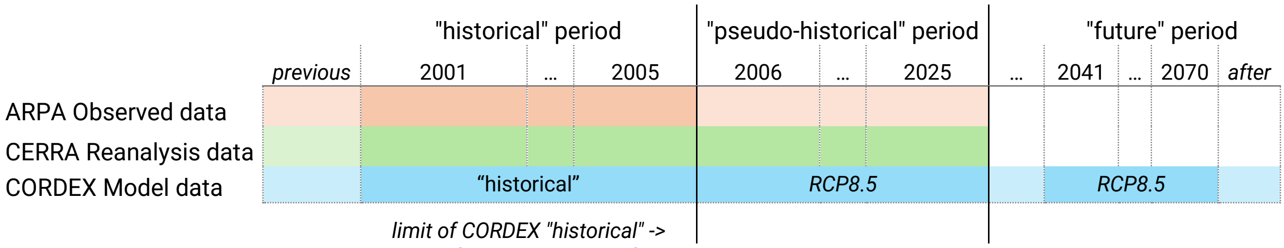

Figure 5. Graph of the time period for the datasets used in the analysis

Before applying any bias correction or impact-oriented indicator, a systematic evaluation of the datasets is performed over their overlapping periods.

2.3.1.3.4 ARPA – CERRA comparison

2.3.1.3.5 Data sources and spatial matching

The comparison between ARPA observations and the CERRA reanalysis was conducted using daily precipitation data from selected ARPA rain gauge stations located within or in close proximity to the area of interest. Station data were quality-controlled and aggregated to daily totals to ensure consistency with the temporal resolution of CERRA. This step allows quantifying the degree to which CERRA reproduces the observed precipitation regime and provides a transparent justification for its use as reference data in subsequent steps.

Two temporally aligned series of 5 years were extrapolated, for *Chiavenna Cerletti* and *Samolaco Vignola*. Then, the following basic descriptive statistics were computed:

- mean monthly accumulated total precipitation
- mean and median daily maximum for the month (that is, mean and median over 5 years of $Rx1day_{month,year} = \max(P_{daily})$), representing the typical upper-end daily precipitation intensity for that month

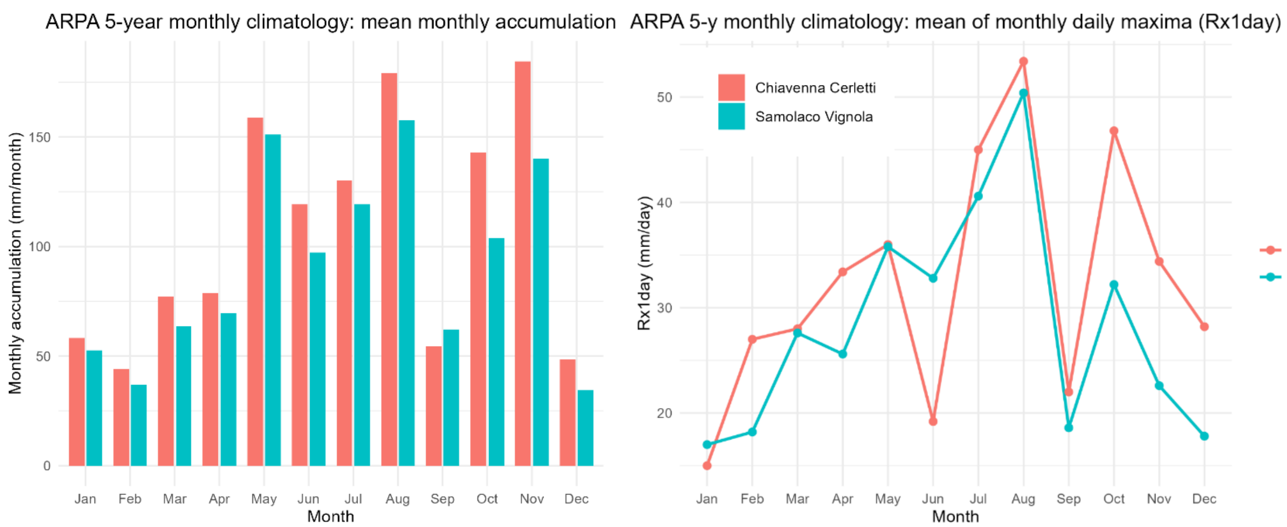

Figure 6. Mean monthly accumulated total precipitation and •mean daily maximum for the month in the ARPA observed data

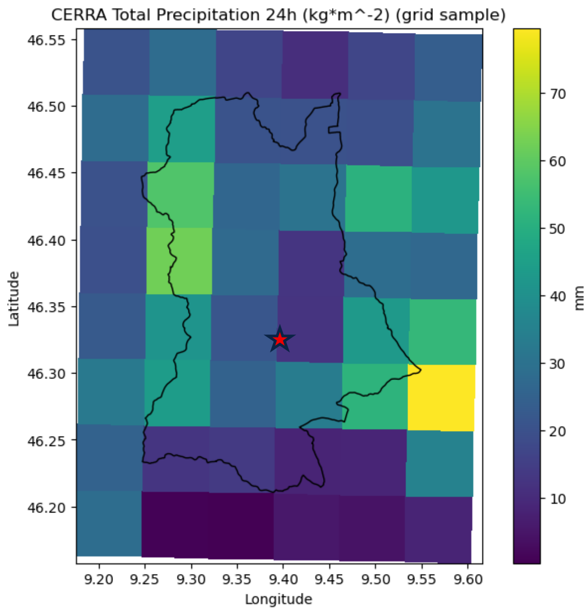

Figure 7. Sample of CERRA gridded data over the AOI of Valchiavenna IM-01 (red star represents the position of Chiavenna Cerletti ARPA weather station)

Figure 6 represent the statistics for the observed data, which appear to be consistent with the climatology proposed by the consulted literature (Aldighieri B. et al., 2011).

A **direct comparison** between point-based ARPA observations and area-averaged CERRA precipitation appear to be **not meaningful** due to scale mismatch differences. The comparison was therefore performed between point-based ARPA observations and CERRA grid-point precipitation extracted at the station locations, in order to **assess the ability of CERRA to reproduce local precipitation climatology and intensity before using area-averaged CERRA data as a reference for CORDEX model evaluation**.

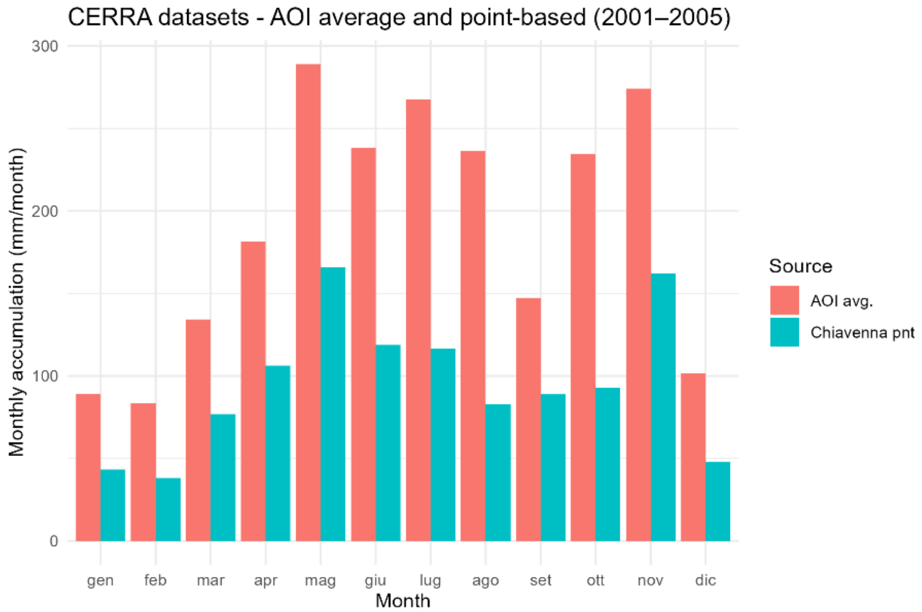

Figure 8. Comparison between AOI averages and point-based monthly climatologies (monthly accumulation)

2.3.1.3.6 Temporal aggregation and indicators

The analysis then proceeded to a comparison of statistical indicators between the ARPA observed data and the CERRA Reanalysis dataset.

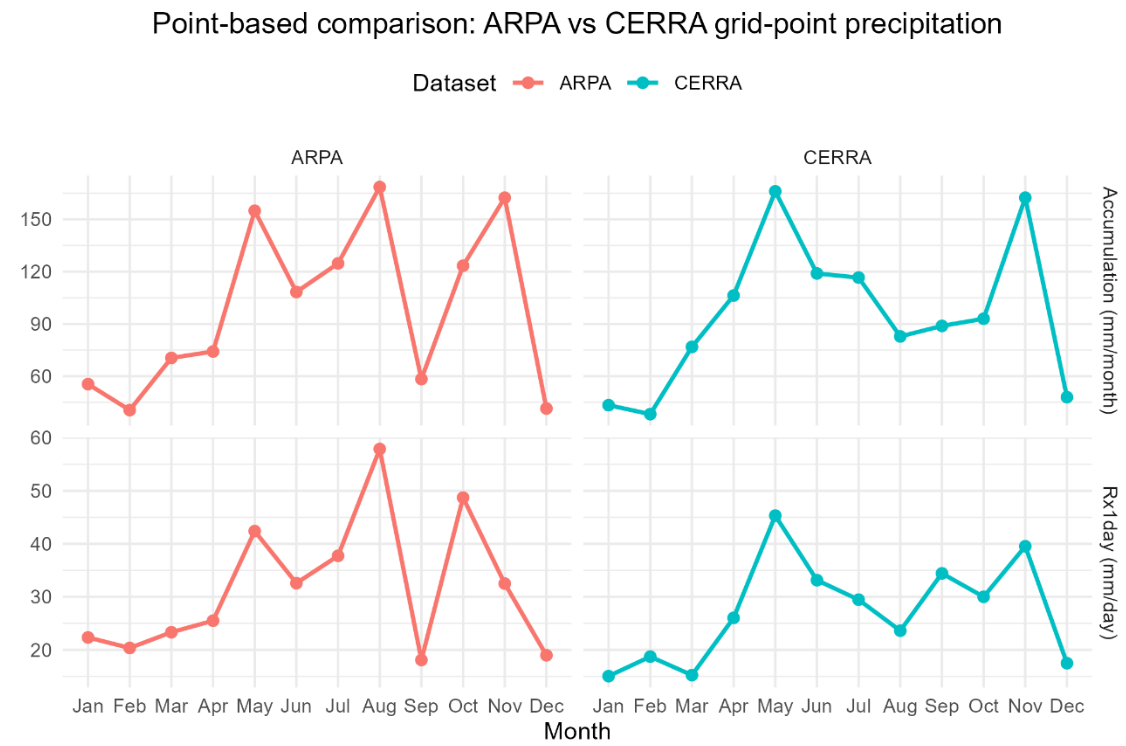

Figure 9. Comparison of Mean monthly accumulated total precipitation and mean daily maximum (R1day) between the ARPA and CERRA dataset

The comparison focused on daily precipitation characteristics and derived indicators, including: **daily precipitation totals** at station locations and corresponding CERRA grid cells, **areal mean precipitation**, **wet-day frequency**, **extreme precipitation indices**, such as annual or seasonal maximum daily precipitation (Rx1day).

Daily data were further aggregated into monthly and seasonal statistics to facilitate the comparison of climatological patterns and to reduce the influence of day-to-day variability.

2.3.1.3.7 Statistical evaluation

The agreement between ARPA observations and CERRA was quantified using standard statistical metrics, as shown in Table 2-2.

These metrics were computed for both accumulated precipitation and extreme precipitation indices, allowing the identification of systematic biases and scale-dependent discrepancies.

Table 2.2 presents the synthesis of the results of the evaluation, providing a brief interpretation of the outputs.

Table 2-2. Metrics for the evaluation of the CERRA reanalysis data with respect to the ARPA observations

Parameter	Value	Interpretation
Bias on monthly accumulation	−3.5 %	*CERRA shows an almost unbiased representation of monthly prec. totals*
Bias on Rx1day	−13.8 %	*CERRA moderately underestimates daily precipitation extremes, while preserving their seasonal occurrence*
RMSE on monthly accumulation	ca. 30 mm/month	*CERRA moderately underestimates*
RMSE on Rx1day	ca. 13 mm/day	*Same magnitude intensity*

2.3.1.3.8 Interpretation framework

The ARPA–CERRA comparison provides an assessment of how well the reanalysis reproduces observed precipitation characteristics at local and areal scales. Particular attention was given to differences in extreme precipitation behaviour, which is critical for hazard and impact assessments. The results of this comparison serve as a benchmark for subsequent analyses involving climate model simulations.

CERRA appears to provide a reliable representation of both monthly precipitation totals and daily precipitation intensity at the local scale, despite a moderate underestimation of daily extremes. This level of agreement is considered, at the moment, sufficient to justify the use of area-averaged CERRA precipitation as a reference dataset for the evaluation and bias correction of CORDEX simulations.

2.3.1.3.9 CERRA – CORDEX evaluation

The subsequent analysis is based on daily precipitation data from the **CERRA reanalysis** and multiple **CORDEX regional climate model simulations** obtained from different combinations of global and regional climate models (GCM/RCM).
All datasets were processed over a common **area of interest (AOI)**, defined by a vector polygon and applied consistently to both reanalysis and model data.

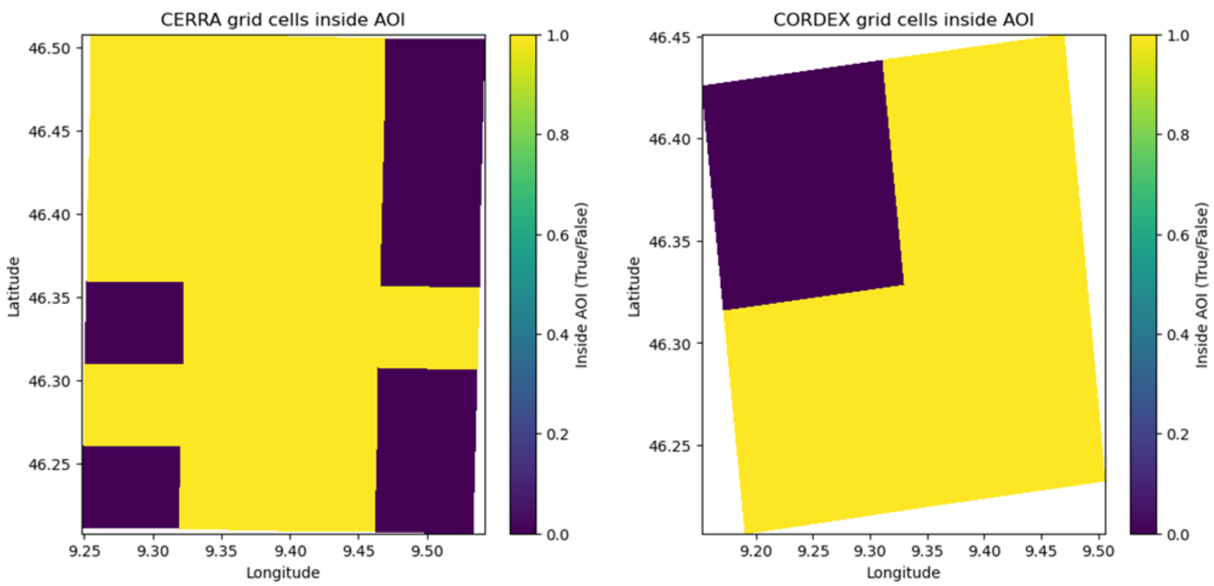

Figure 10. Representation of the CERRA and CORDEX respective grids and cells included in the AOI

Daily precipitation fields were spatially aggregated over the AOI and analysed over the common reference period 2001–2005 to ensure temporal consistency across datasets.

2.3.1.3.10 Aggregation and statistics

For each day, precipitation values were extracted for all grid cells falling within the AOI. Then, **daily areal statistics** were computed to provide complementary information on both the overall intensity of precipitation affecting the area and its spatial heterogeneity: **areal mean precipitation, spatial maximum precipitation.** To characterize the seasonal cycle of precipitation, daily statistics were aggregated into **monthly climatologies**, using variable-specific aggregation rules (for mean and max).

Spatial variability metrics have been computed as well: **interquartile range (**defined as the difference between the 90th and 10th spatial percentiles of daily precipitation) and **spatial standard deviation.**

A **wet day** was defined as a day with areal mean precipitation exceeding a fixed threshold (1 mm/day). Based on this definition, the following indicators were derived: **wet-day frequency** over the analysis period, **wet-day intensity (**mean areal precipitation conditional on wet days) and **relative spatial variability** (ratio between the spatial interquartile range and the areal mean precipitation, computed only for wet days)

Finally, **spatial variability metrics (iqr_mm, stdev_mm)**:

- iqr_mm was aggregated as the **median** of daily values within each month, to reduce sensitivity to extreme outliers.
- stdev_mm was aggregated as the **mean** of daily values within each month

Monthly climatologies were then obtained by averaging these monthly aggregates across years.

These metrics were analysed using seasonal distributions and monthly climatologies to assess differences in the spatial structure of precipitation between reanalysis and climate model simulations.

2.3.1.3.11 Comparative evaluation and ranking of CORDEX simulations

CORDEX simulations were evaluated relative to CERRA using a **multi-criteria comparison framework**, based on the following metrics:

- Root Mean Square Error (RMSE) of the **monthly climatology of areal precipitation totals**, to assess the representation of the seasonal cycle.
- Absolute differences in **wet-day frequency** and **wet-day intensity**.
- Differences in high-end precipitation extremes, quantified using the 95th percentile of daily spatial maxima.
- Differences in spatial structure, quantified using the median relative interquartile range on wet days.

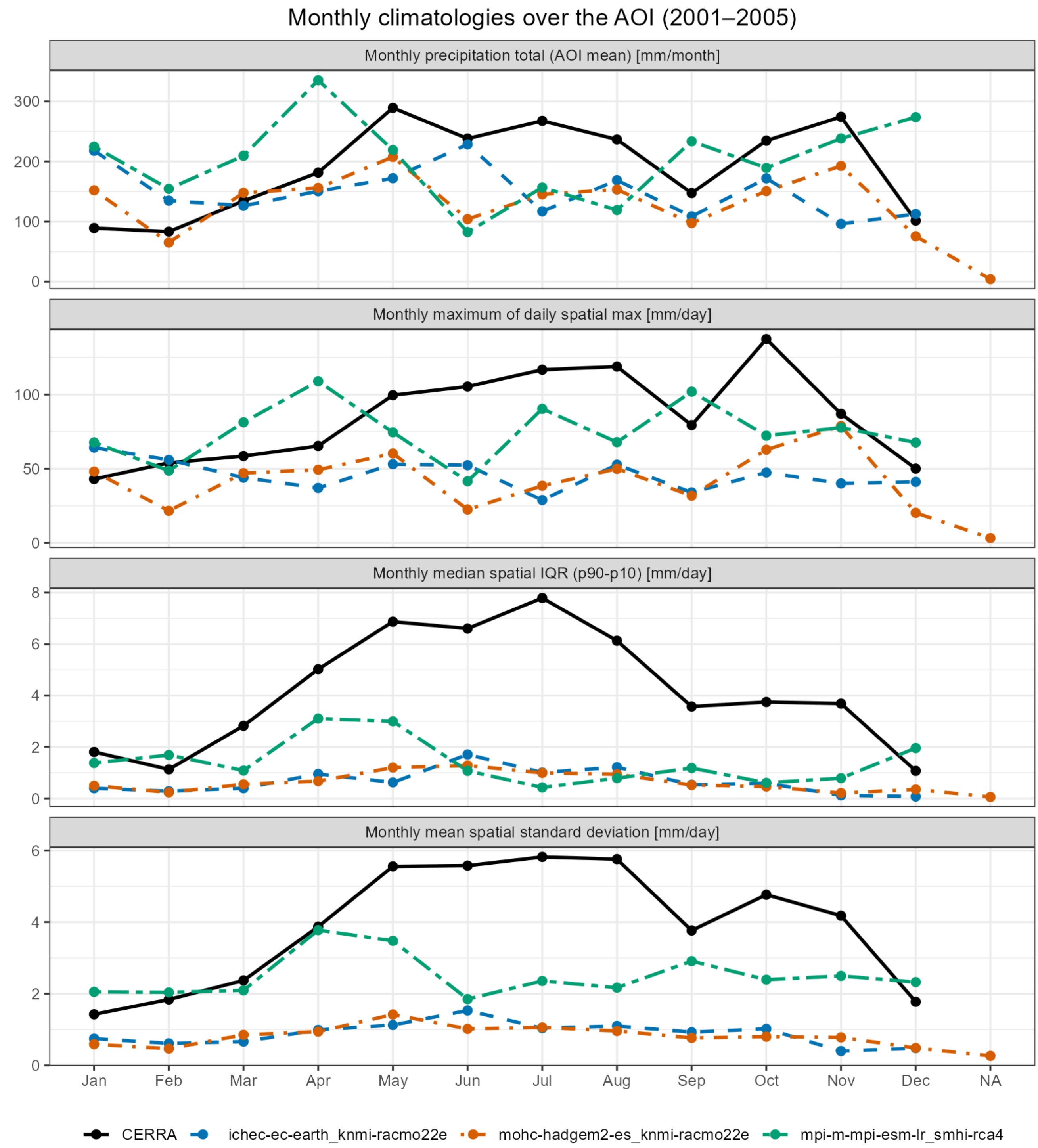

Figure 11. Representation of the metrics utilized in the comparative evaluation of CERRA and different CORDEX datasets

All metrics were normalized and combined into a **weighted composite score**, where lower values indicate closer agreement with the CERRA reanalysis. The resulting ranking is intended as a **relative comparison among the considered CORDEX simulations**, rather than as an absolute measure of model skill.

Table 2-3. Relative ranking for the analysed CORDEX datasets (lower values indicate closer agreement with CERRA)

dataset	*rmse_clim_total*	*wet_frac_err*	*wet_int_err*	*p95_max_err*	*iqr_rel_err*	*rmse_wet_frac*	*rmse_stdev*	*total_score*	*rank*
mpi-m-mpi-esm-lr/ smhi-rca4	1,00	0,00	1,00	0,00	0,00	1,00	0,00	0,50	**1**
mohc-hadgem2-es/ knmi-racmo22e	0,00	1,00	0,29	1,00	1,00	0,00	0,94	0,54	**2**
ichec-ec-earth/ knmi-racmo22e	0,41	0,92	0,00	0,85	1,00	0,09	1,00	0,60	**3**

2.3.1.3.12 Interpretation framework

By jointly analysing areal precipitation climatologies and spatial variability metrics, the methodology allows the assessment of precipitation amount and seasonal timing, event frequency and intensity, representation of extremes, spatial structure and localization of precipitation events.

As a result of this analytical step, and in consideration of constraints in time and resources, the following analysis has been performed only on:

- the CORDEX dataset originated by the **MPI-M-MPI-ESM-LR/SMHI-RCA4** model combination
  - **historical** for the years **2001-2005**
  - **RCP8.5** scenario for the years **2006-2025** and **2041-2070**

2.3.1.3.13 Bias correction of CORDEX simulations

Following the evaluation phase, **bias correction is applied to CORDEX precipitation data**, using CERRA as the reference dataset.

The chosen method is **Quantile Delta Mapping (QDM)**, which is intended to correct systematic biases in the simulated precipitation while preserving the climate change signal projected by the model across the distribution.

Bias correction is applied to **daily precipitation values** and **separately for each calendar month**, in order to account for the strong seasonal dependence of precipitation distributions.

For each grid cell (or spatial unit of analysis), the procedure uses:

- **CERRA** precipitation during the **historical period** as **reference**,
- **CORDEX historical simulations** for **model calibration**,
- **CORDEX scenario** simulations as the target **dataset to be corrected**.

The output of this step is a **bias-corrected daily precipitation time series**, which retains the original temporal resolution and sequencing of events, ensuring consistency with subsequent analyses based on cumulative precipitation.

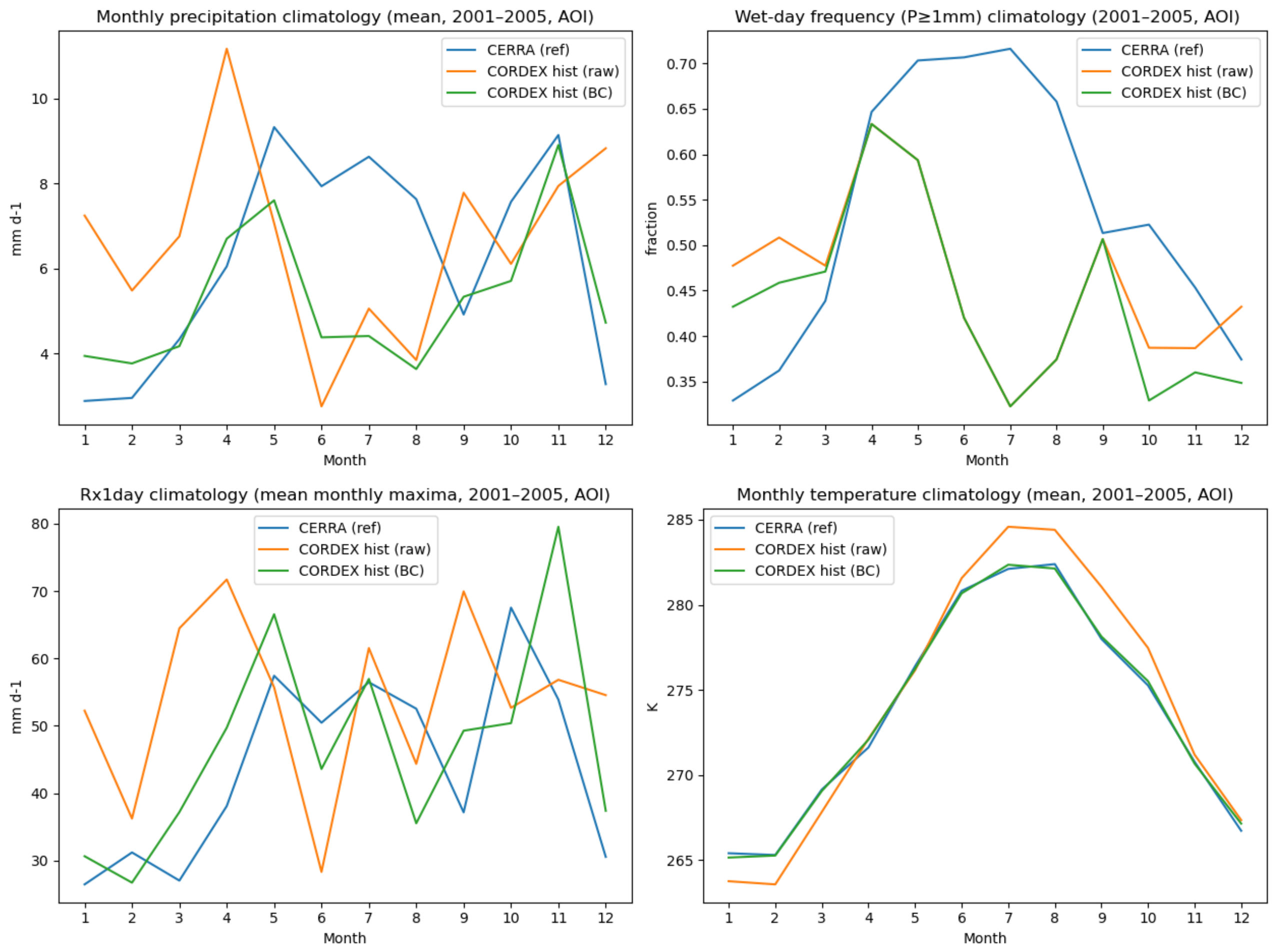

Figure 12. Representation of the test metrics for the bias-correction process of the CORDEX datasets

A key aspect of the adopted bias correction strategy is that it **does not alter the temporal ordering of daily values**. While intensities and distributions are adjusted to match the reference climatology, the day-to-day sequence of wet and dry conditions remains intact.

This property is essential for the application of the **Equivalent Rainfall Method**, which relies on precipitation accumulation over multiple consecutive days.

2.3.1.3.14 Application of the Equivalent Rainfall Method

The Equivalent Rainfall Method is applied consistently across datasets and periods, using daily precipitation as the primary input.

For historical conditions:

- the method is applied to **CERRA data** in order to characterize the reference behaviour of equivalent rainfall indicators under past climate conditions.

For future projections:

- the method is applied to **bias-corrected CORDEX scenario simulations**, ensuring that the input precipitation series is both climatologically consistent with the reference and representative of projected climate change.

The method is based on daily precipitation and antecedent cumulative rainfall (e.g. five-day accumulated precipitation), and therefore directly benefits from the improved realism of the bias-corrected series.

Annual exceedance counts were computed using the Equivalent Rainfall method and analysed as time series.

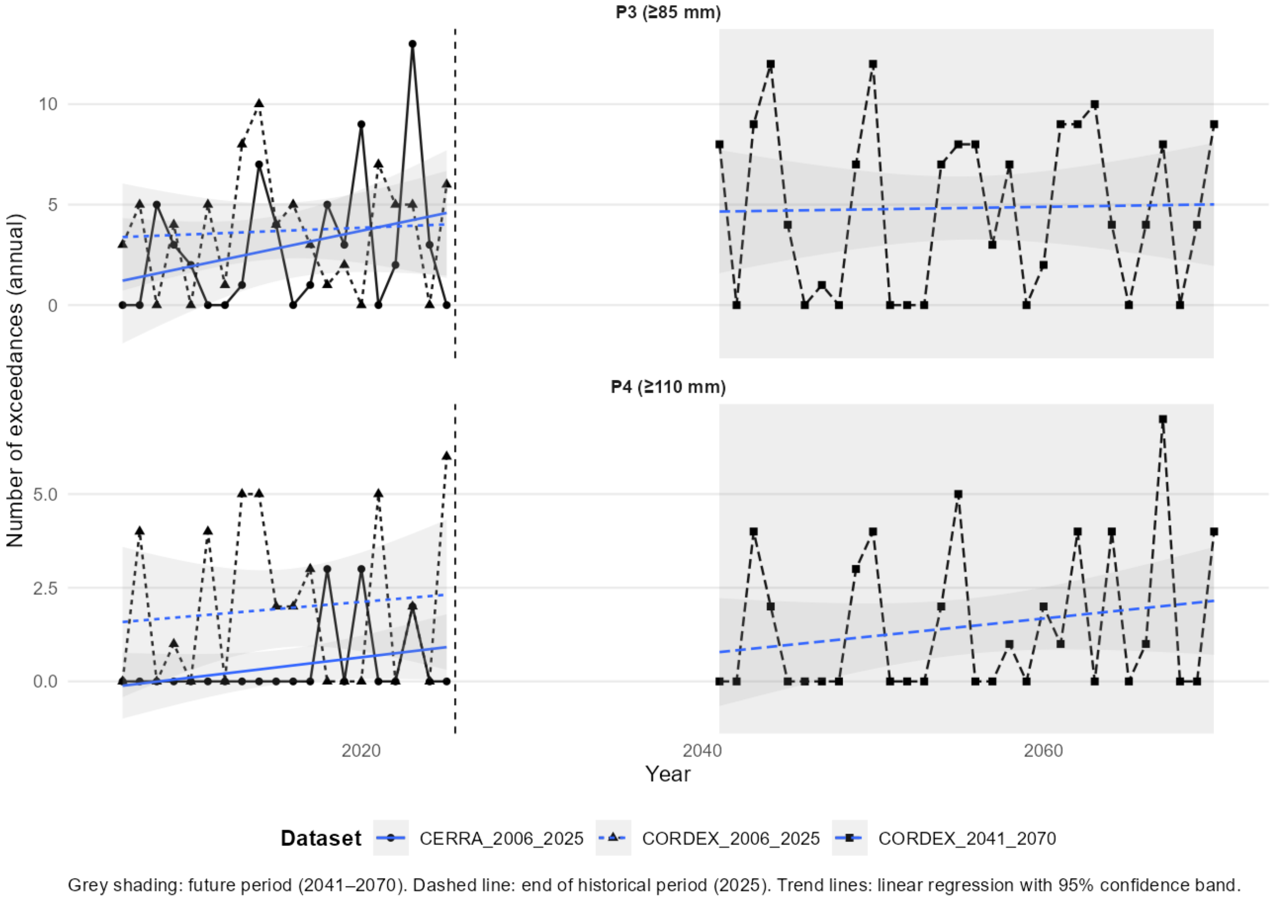

Figure 13. Temporal evolution of threshold exceedances (Equivalent Rainfall method – CERRA and CORDEX annual counts) (the shaded area in the figure highlights the future period (2041–2070), while the dashed line marks the end of the historical period (2025))

Although the current results seems to show a positive trend, particularly for the P4 threshold exceedings, a cautious statistic interpretation of the data is due.

For each dataset and threshold, a linear trend (ordinary least squares) was fitted to annual exceedance counts, and **uncertainty was reported as a 95% confidence interval (CI) on the slope (events per year)**. A trend was considered robust only when the 95% CI of the slope excluded zero; otherwise, the direction of change was treated as not distinguishable from no trend within the analysed period.

For both P3 (≥85 mm) and P4 (≥110 mm), no series show neither a robust positive or negative trend; all series trends are not distinguishable from zero (95% CI includes zero).

Table 2-4. Parameters characterizing the interpretation of the results in the application of the Equivalent Rainfall method

Dataset	Thr	n_years	year_min	year_max	slope	ci_low	ci_hi	R2	trend_direction
CERRA Pseudo-hist	P3	20	2006	2025	0.177	-0.103	0.458	0.09	not distinguishable from zero
CORDEX Pseudo-hist	P3	20	2006	2025	0.033	-0.206	0.273	0.00	not distinguishable from zero
CORDEX Future	P3	30	2041	2070	0.012	-0.169	0.193	0.00	not distinguishable from zero
CERRA Pseudo-hist	P4	20	2006	2025	0.054	-0.025	0.133	0.10	not distinguishable from zero
CORDEX Pseudo-hist	P4	20	2006	2025	0.038	-0.142	0.218	0.01	not distinguishable from zero
CORDEX Future	P4	30	2041	2070	0.047	-0.038	0.132	0.04	not distinguishable from zero

2.3.1.4 Risk assessment

Available sources for the risk assessment on the area are, in particular:

- Lombary Region opendata:
  - slope instability maps (through geological studies as defined by Article 9 of the Hydrogeological Risk Management Plan – PAI)
  - SIRBEC: catalogue of inventoried Cultural Heritage sites of Lombardy
- ISPRA landslide inventory mosaic, which also includes elaborations and statistics based on data from ISTAT, the National Institute for Statistics, and the Italian Ministry of Cultural Heritage

Data collected include, in particular:

- **Population and buildings**
  - *Population in high, medium and low hydraulic hazard areas (no. of inhabitants)*
  - *Population in very high and high landslide hazard areas (P4 + P3) (no. of inhabitants)*
  - *Buildings in high, medium and low hydraulic hazard areas (no.)*
  - *Buildings in very high and high landslide hazard areas (P4 + P3) (no.)*
- **Economic activities**
  - *Local business units in high, medium and low hydraulic hazard areas (no.)*
  - *Local business units in very high and high landslide hazard areas (P4 + P3) (no.)*
- **Cultural heritage**
  - *Cultural heritage assets in high, medium and low hydraulic hazard areas (no.)*
  - *Cultural heritage assets in very high and high landslide hazard areas (P4 + P3) (no.)*

Hereby, we present some synthetic statistics of the above mentioned data.

Table 2-5. Population and buildings exposed to risk (P3 and P4 areas) according to the PAI

Municipality/Area	*Population in P3+P4 (no.)*	*Population in P3+P4 (%)*	*Buildings in P3+P4 (no.)*	*Buildings in P3+P4 (%)*
Madesimo	19	3,59	172	11,51
Novate Mezzola	38	2,02	20	1,49
Campodolcino	74	7,97	104	6,95

Municipality/Area	Population in P3+P4 (no.)	Population in P3+P4 (%)	Buildings in P3+P4 (no.)	Buildings in P3+P4 (%)
Chiavenna	165	2,28	70	3,68
Gordona	9	0,47	12	0,56
Mese	18	0,99	11	1,32
Piuro	89	4,68	129	8,54
Prata Camportaccio	43	1,47	67	4,02
Samolaco	89	3,08	37	1,77
San Giacomo Filippo	23	6,23	44	2,71
Villa di Chiavenna	39	4,03	41	3,01
Verceia	40	3,76	20	2,71
CM Valchiavenna	**646**	**2,62**	**727**	**5,00**

Table 2-6. Cultural heritage sites and local business units in P3 and P4 hydrogeological hazard areas in Valchiavenna

Municipality/Area	Cultural Heritage sites in P3+P4 (no.)	Local business units in P3+P4 (no.)
CM Valchiavenna	9	28

2.3.2 River flooding risk - finetuning to local context

In Phase 2 of the CLIMAAX project, more detailed information about the flood hazard and risk levels over the territory of Valchiavenna were collected and elaborated and the workflow on **flood-related building damage and exposed population** was investigated.

Concerning the application of the specific workflow, similarly to what has been done in phase 1, the elaboration have been performed over the area of the Mera River basin, as show in **Errore. L'origine riferimento non è stata trovata.**.

The risk component of the workflow was run twice:

- using the original datasets provided by the project, and
- using local data sources, to enable a more detailed territorial analysis.

The resulting outputs were then compared and discussed.

The workflow aims at assessing how this hazard affects built-up areas by looking at economic damage represented by building damage, impact on critical infrastructures, as well as the impact on the population by estimating the number of people exposed to the food hazard and the number of people displaced by it.

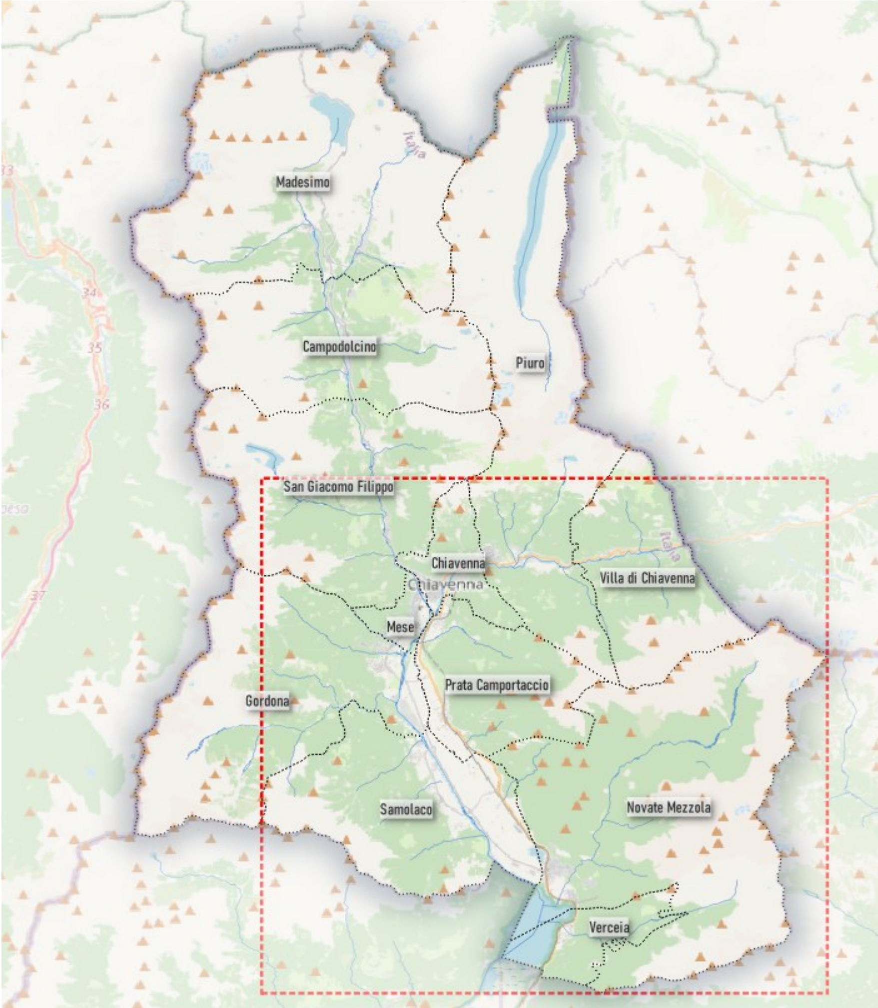

Figure 14. Bounding box of the area of Mera river basin, Valchiavenna

2.3.2.1 Hazard assessment

Hydraulic hazard in the Valchiavenna area has been assessed using the hydraulic hazard maps provided by the Po River Basin District Authority for the Mera River basin. Hazard zones are classified into three categories:

- low hazard (P1), associated with catastrophic events and a return period (RP) of not less than 500 years;
- medium hazard (P2), with an RP of not less than 200 years;
- high hazard (P3), with an RP of not less than 30 years

Within the workflow of River Flood - Phase II, the objective was to integrate information on the expected water depth in flood-prone areas for the three return periods across the Mera River basin. However, the Flood Risk Management Plan (PGRA) does not include water-depth datasets, and it was not possible to obtain such information within the project timeframe.

Yet, local studies are currently under development to elaborate also the information about expected water depth and flow speed, and will be integrated into the ongoing review of the local Civil Protection plans.

More detailed maps are provided as an annex to the present deliverable.

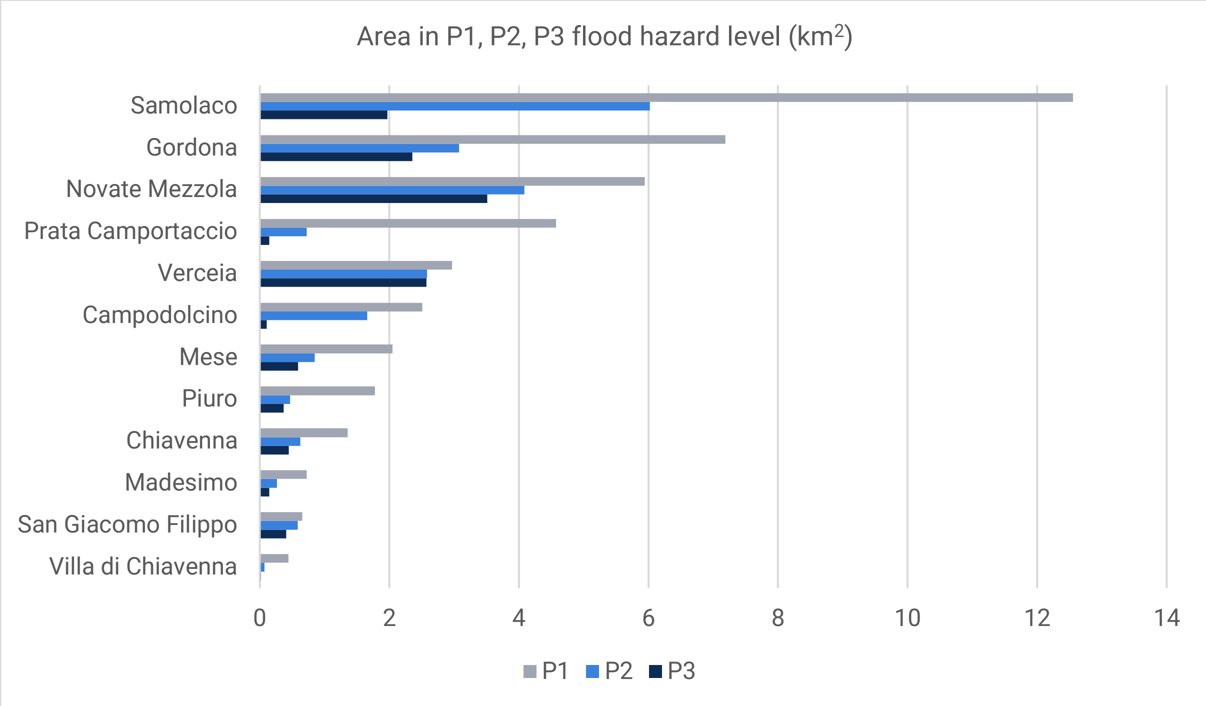

Figure 15. Percentage of municipal area in high, medium and low hydraulic (flood) hazard classes (P1–P3)

Table presents the overall values for the entire territory of Valchiavenna.

Table 2-7. Area of territory prone to flood risk according to the Flood Risk Management Plan classification (P1-P3)

Territory	Area (km^2)				Percentage		
	Tot	P3	P2	P1	P3	P2	P1
CM Valchiavenna	575,33	12,64	21,01	42,75	2,20	3,65	7,43

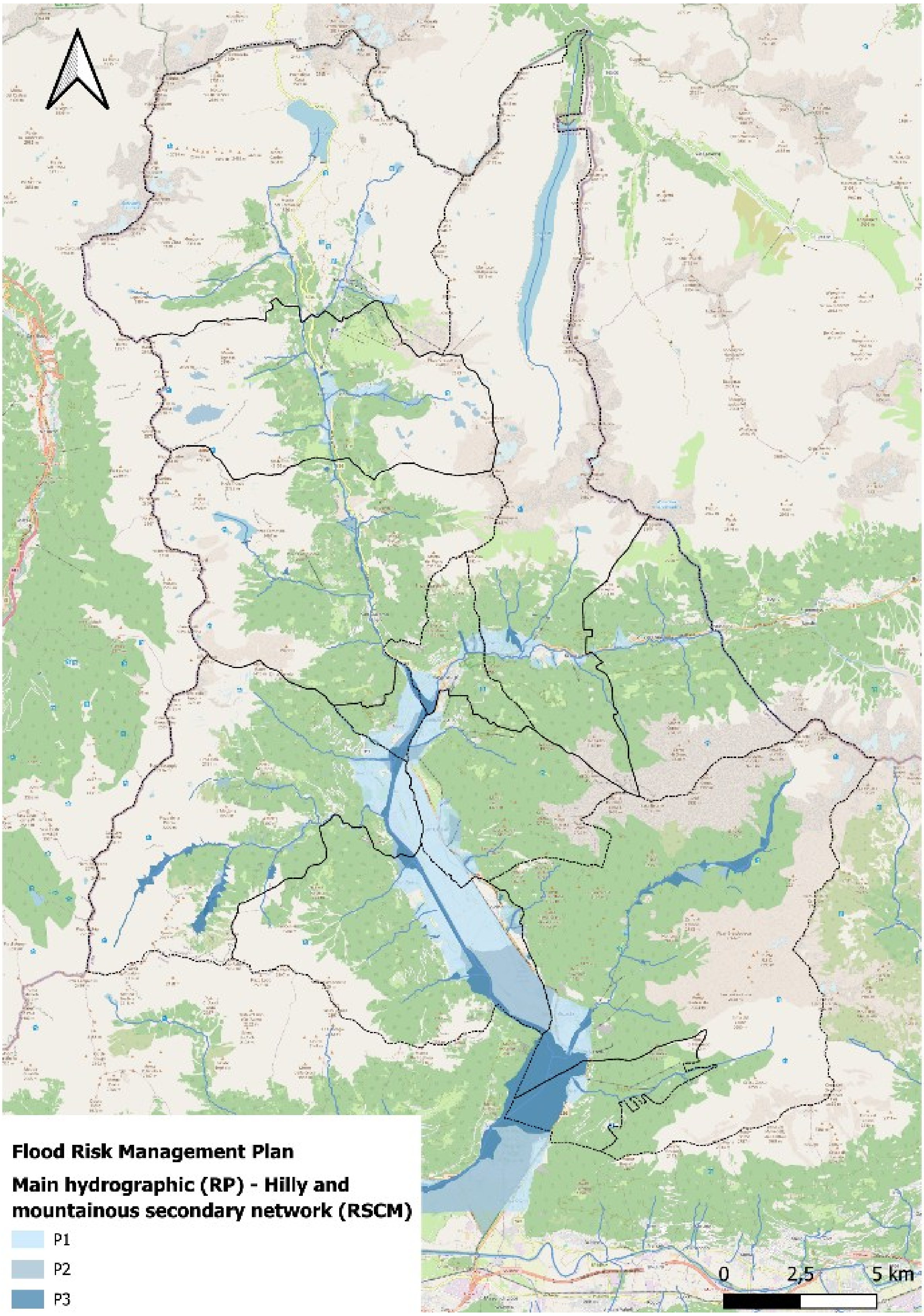

Figure 16. Map of the hydraulic (flood) hazard levels (PGRA) on the territory of Valchiavenna

In the scope of the flood-related building damage and exposed population workflow applied in phase 2, JRC Flood depth maps have been used as a basis of hazard data, being currently the only source providing the information about water depth.
Flood water depth maps for return periods of 50, 200, and 500 years, with a spatial resolution of 3 arc-seconds, covering the entire Mera basin and surrounding areas have been utilized.

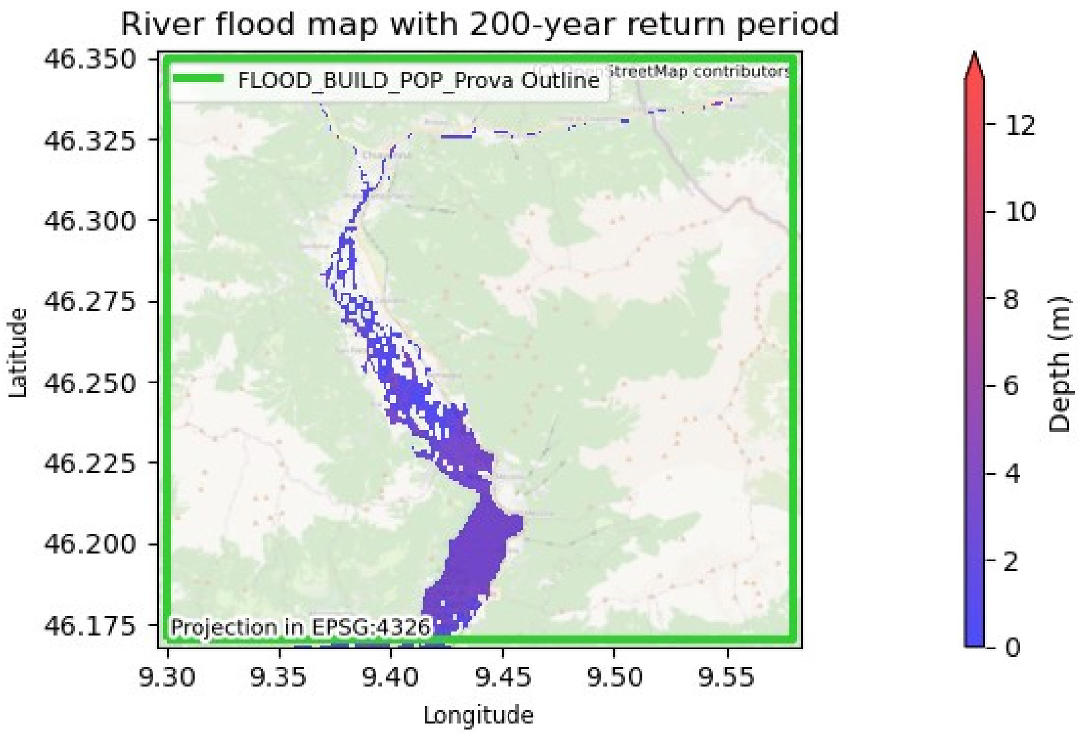

Figure 17. JRC Flood depth map for the Mera river basin with 200-years return period

2.3.2.2 Risk assessment

Regarding flood risk, hydraulic flood-risk maps produced by the Po River Basin District Authority and Lombardy Region are available for the Mera River basin as well.

Risk zones are classified as:

- low risk (R1), referring to areas with minor expected impacts or where risk is considered low or negligible;
- medium risk (R2), corresponding to areas with an intermediate level of risk requiring mitigation measures;
- high risk (R3), identifying areas with significant risk where more structured intervention plans are required;
- very high risk (R4), representing the most critical areas, characterized by a very high damage potential and requiring the most urgent and stringent risk management measures.

A preliminary analysis was carried out to estimate the number of exposed buildings and the potentially affected population within the study area and particularly in urbanized areas. More detailed data and information will be available as an annex to the present deliverable.

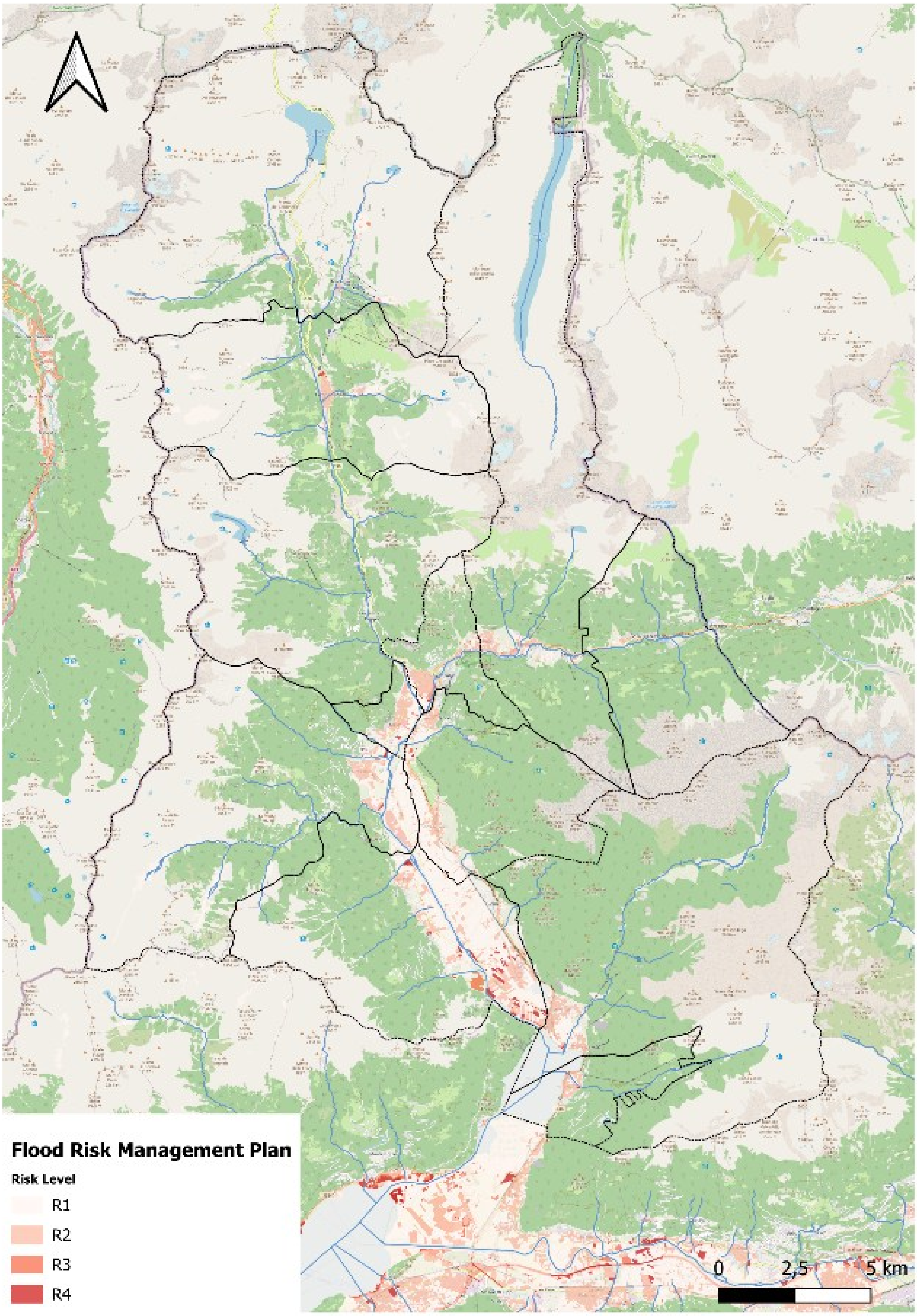

Figure 18. Risk data layer for the territory of Valchiavenna, based on data provided by Lombardy Region

Table 2-8. People exposed to flood risk (municipalities)

Municipality	***No. of people exposed (P1-P3)***
Madesimo	124
Piuro	1452
Campodolcino	637
San Giacomo Filippo	1
Villa di Chiavenna	89
Chiavenna	3580
Mese	3262
Gordona	1609
Prata Camportaccio	2494
Samolaco	1932
Novate Mezzola	1812
Verceia	1088

Table 2-9. Buildings exposed to flood risk

Building Category	***No. of buildings in exposed urban areas (P1-P3) (Valchiavenna)***
Universal	7
Transportation	48
Residential	15228
Industrial	448
Cultural	249
Commercial	200
Agricultural	1256

Table 2-10. People exposed to flood risk (Mountain Community)

Hydraulic Risk level	***No. of people exposed***
R2 – medium	16060
R4 – very high	655

Table 2-11. Cultural Heritage sites and business units exposed to flood risk (Mountain Community)

Type	***P1***	***P2***	***P3***
Cultural Heritage (CM Valchiavenna)	53	22	22
Local business units (CM Valchiavenna)	817	105	74

2.3.2.2.1 Application of the flood-related building damage and exposed population workflow

As mentioned before, the workflow proposed by CLIMAAX was applied in two ways in the scope of the present study.

Given the current unavailability of local data for the characterization of the hazard and the distribution of the population over the territory, the analysis could focus only on **different sources of information with respect to the building and critical infrastructure**.

After a first application at the level of the entire Mera River basin, it was decided to apply the workflow on two limited urban areas, **Piuro** and **Chiavenna**, within the same subcatchment, due to the better capacity of the methodology to represent smaller areas. The two subdomains have been chosen for their built density and presence of flood-prone areas.

Table 2-12 Data overview workflow Flood-related building damage and exposed population

Hazard data	Population data	Building and critical infrastructure data
JRC Flood Depth	*GHS-POP R2023A dataset*	*OSM dataset (as originally proposed in the workflow)*
		Topographic Database (DBT) of the Province of Sondrio

Building and infrastructure data

The Topographic Database is a complex database compiled at local level upon national defined standards. It contains several layers, some of which dedicated to buildings and infrastructure. Items are described by different attributes and categories per typologies of use and destination, plus physical parameters describing volumes, heights and such. The Topographic Database (DBT) of the Province of Sondrio was used to collect building information, both geometric and categorical. DBT building classes were reclassified into the four categories adopted by the workflow: *Residential, Commercial, Industrial, and Universal.*

In comparison to the original OSM data, the classification of the buildings was customized using the types occurring in the DBT. The recoding of the classes according to the DBT is as follows:

- *classResidential = ['residenziale', 'abitativa', 'sede albergo, locanda', 'campeggio']*
- *classCommercial = ['cinema', 'commerciale', 'ricreativo', 'supermercato', 'sede di attività sportive', 'sede di centro commerciale', 'sanità', 'sede di servizio socio assistenziale', 'sede di ospedale', 'sede di poste-telegrafi', 'sede di forze ordine', 'sede di vigili del fuoco', 'caserma', 'militare', 'municipio', 'parcheggio multipiano coperto', 'servizio pubblico', 'sede di banca', 'sede provincia']*
- *classIndustrial = ['industriale', 'centrale elettrica', 'centrale idroelettrica', 'depuratore', 'edificio di area ecologica', 'impianto di produzione energia', 'impianto tecnologico', 'stabilimento industriale', 'stazione di trasformazione', 'stazione di telecomunicazioni']*
- *classCultural = ['luogo di culto', 'convento', 'palaghiaccio', 'museo', 'biblioteca', 'teatro, auditorium', 'sede di scuola']*
- *classAgricultural = ['agricolturale', 'fattoria', 'fienile', 'stalla']*
- *classTransportation = ['casello ferroviario', 'stazione autolinee', 'stazione cabinovia', 'stazione funivia', 'stazione seggiovia', 'ferroviario', 'stazione metropolitana', 'stazione passeggeri ferroviaria', 'fermata ferroviaria']*
- *classUniversal = ['altro', 'militare']*

With these data, it was possible to assess the effects of flood hazard on built-up areas by analysing economic damage in terms of building losses, impacts on critical infrastructures.

Population density

The GHS-POP R2023A dataset (Schiavina et al., 2023), published by the European Commission's Joint Research Centre, was used to map population estimates and projections. It offers global coverage at a 3 arc-second resolution.

The workflow allows the selection of population estimates at 5-year intervals between 1975 and 2020, as well as projections for 2025 and 2030. For this analysis, the **projected 2030 population** was used.

Data from the Italian population census cannot be utilized for the purpose of the workflow, because the quantitative information about resident people are related to census tracts, that is polygons defined through criteria established by the National Institute for Statistics (ISTAT). Therefore, local data are not natively available on a regular grid; gridded data provided by ISTAT are available, but with a coarser resolution compared to the GHS-POP data.

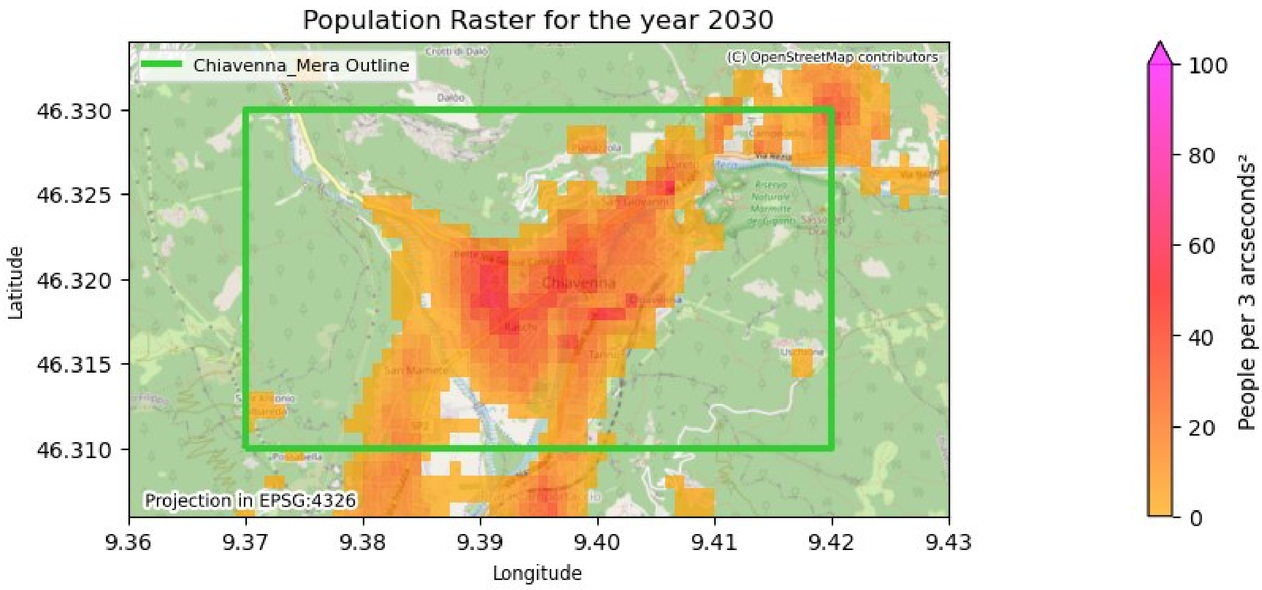

Figure 19. Population density (GHS-POP) for year 2030 – area of Chiavenna

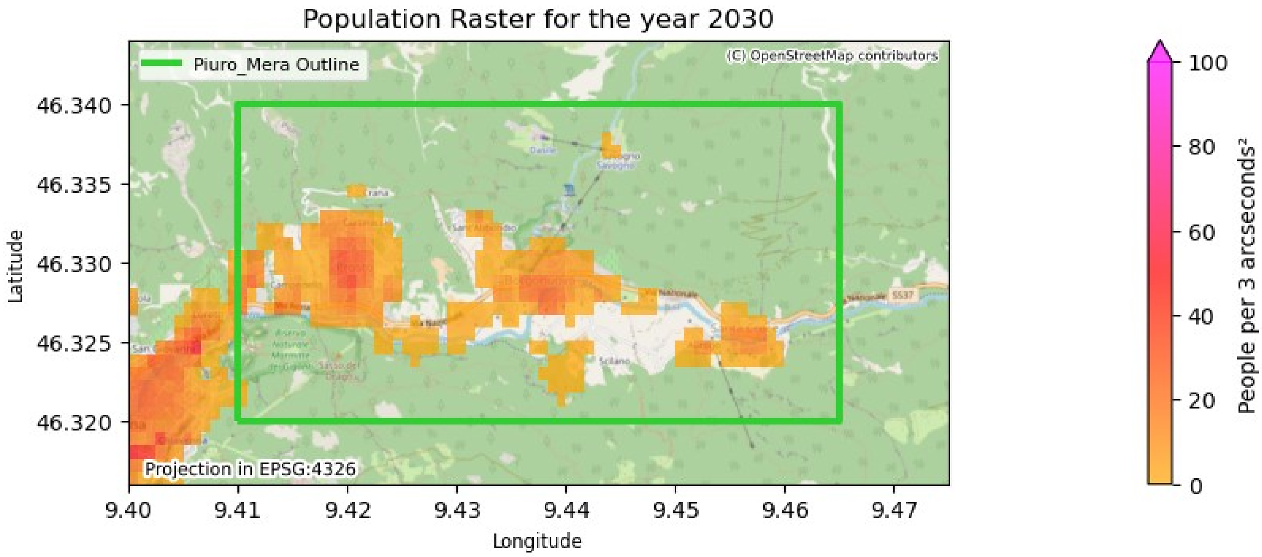

Figure 20. Population density (GHS-POP) for year 2030 – area of Piuro

Outputs

The results obtained by the application of the workflow should be considered preliminary.

The two applications of the workflow can be in fact compared only by the means of the estimation of damages to buildings and mapping of infrastructure, since the only variation in input data between the two is related to the building and infrastructure datasets.

Figure 21 and Table 2-13 show, at this stage, significant differences in the total values estimated by the OSM and DBT applications, with OSM estimated values nearly double the DBT values. These results suggest that the construction of the dataset of basic structures and infrastructure, the classification of building types into classes, and the damage curves associated with those classes must result from a meticulous process in order to provide outputs that are useful for realistic considerations regarding the economic estimation of damages.

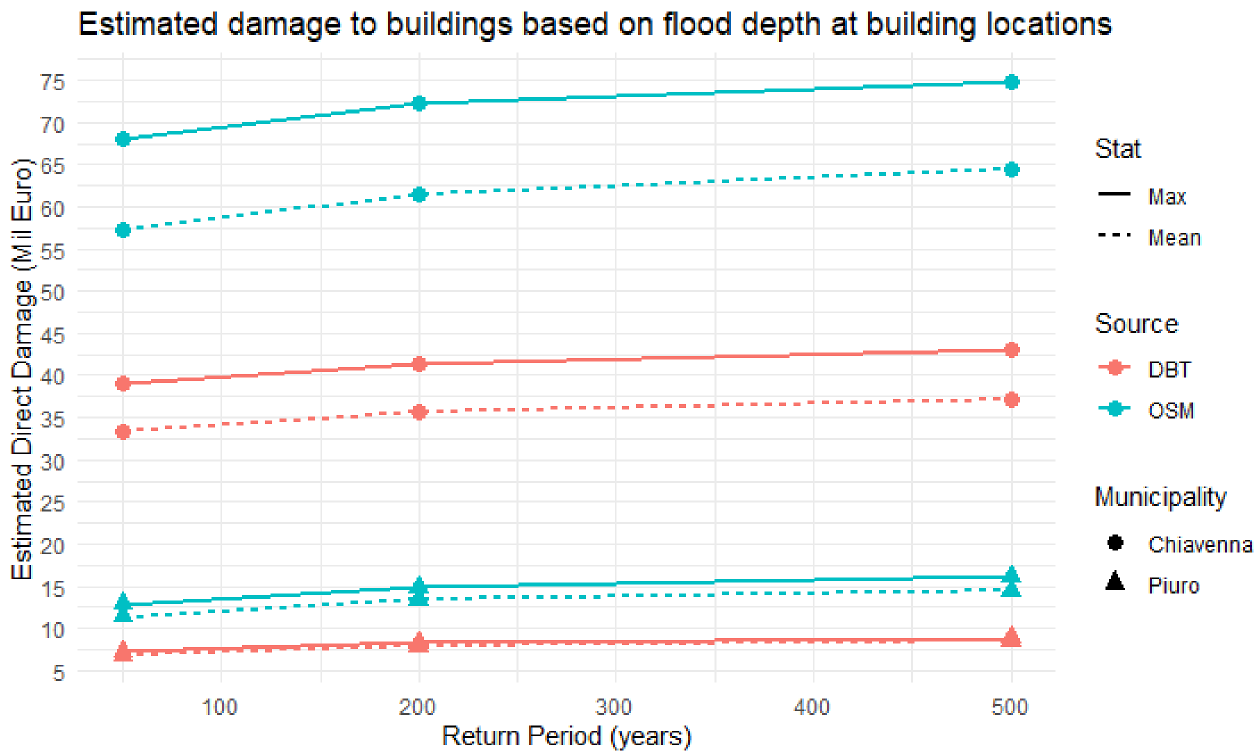

Figure 21. Curves of the Estimated damage to buildings for Chiavenna and Piuro – comparison between OSM and DBT data

Table 2-13. Estimated annual damage to buildings for Chiavenna and Piuro – comparison between OSM and DBT data

Municipality	Source	Stat	EAD (Mil €)
Chiavenna	DBT	Max	0.73
	OSM	Max	**1.27**
	DBT	Mean	0.62
	OSM	Mean	**1.07**
Piuro	DBT	Max	0.14
	OSM	Max	0.25
	DBT	Mean	0.13
	OSM	Mean	0.22

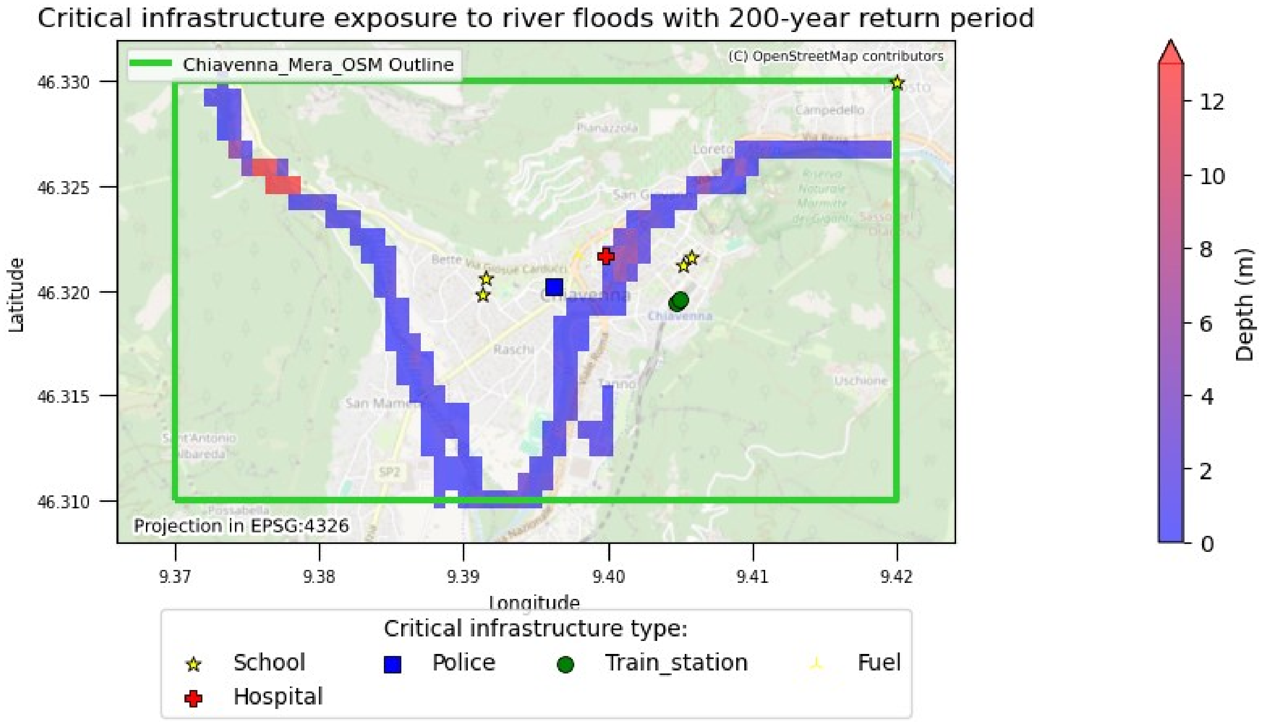

Figure 22. Critical infrastructures mapped over the territory of Chiavenna according to OSM data

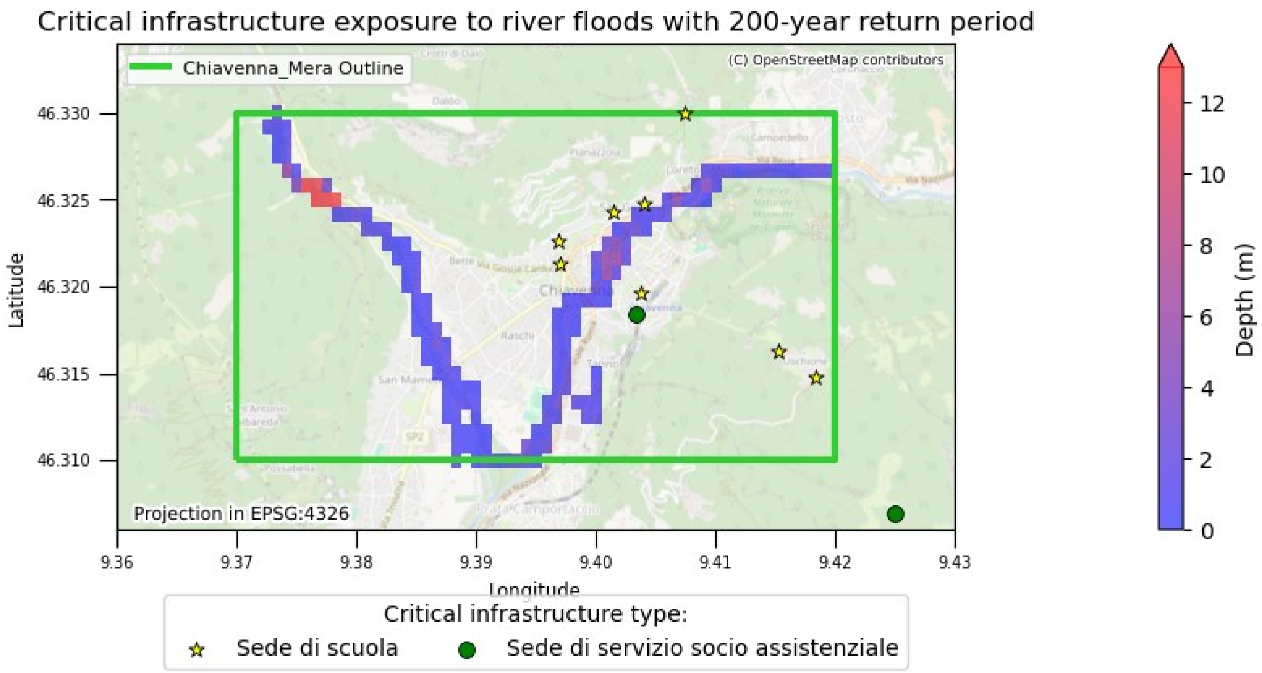

Figure 23. Critical infrastructures mapped over the territory of Chiavenna according to DBT data

2.3.3 Additional assessments based on local models and data

In perspective, it has been investigated the possibility to utilize information related to the height of buildings provided by a specific section of the DBT (namely, **building volumetric units)**, in order to provide a ranking associating a higher risk to lower buildings.

The interest stems from the consideration of the typical civil protection procedures of "vertical evacuation" (that is, moving to upper floors of a building in case of emergency) for flood risk. Nevertheless, also this type of analysis would require a very robust evaluation and validation of the information provided by the DBT, which is at the moment out of the scope of the project and the integration with other parameters related to the actual accessibility of the single buildings.

Three classes have been proposed, for the preliminary analysis:

- 0-3 metres - high risk (no possibility of vertical evacuation)
- 3-6 metres - medium risk (low possibility of vertical evacuation)
- over 6 metres - low risk (possibility of vertical evacuation)

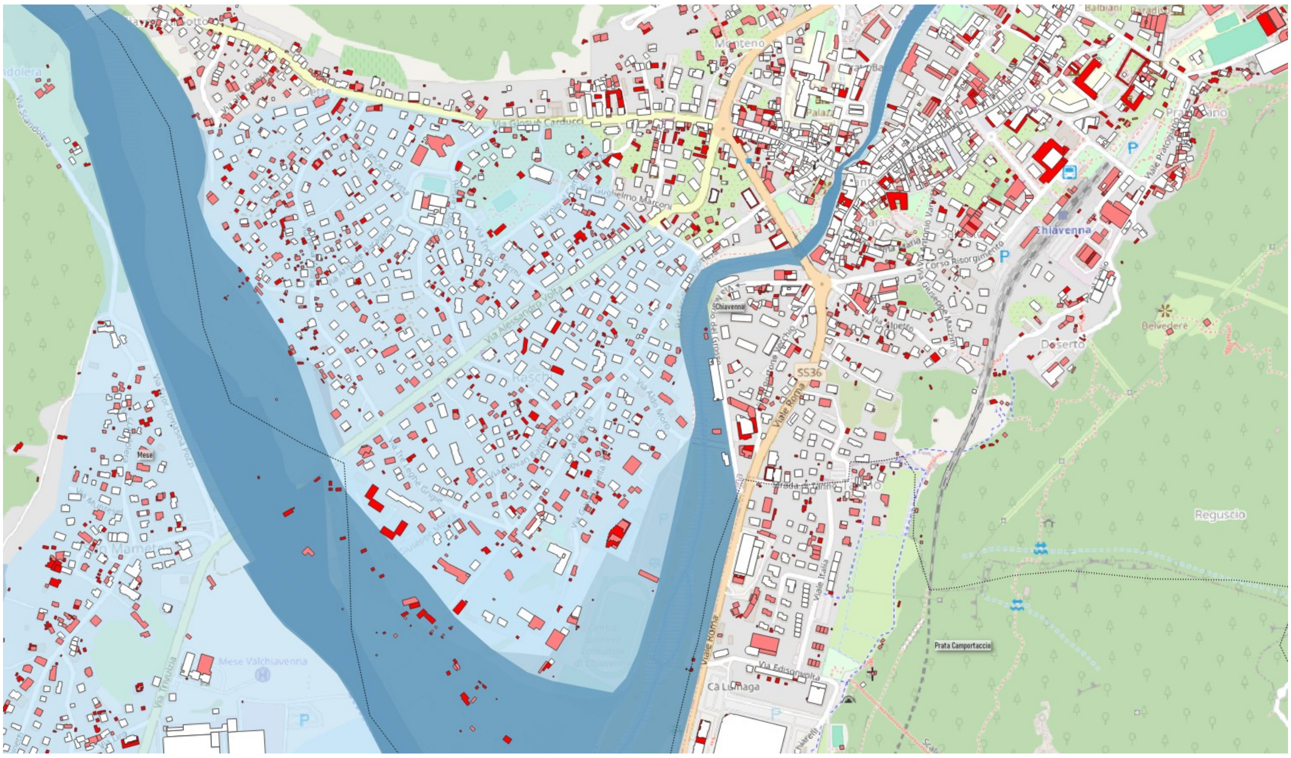

Figure 24. Example of the ranking of buildings according to their heights (red buildings are lower ones) – area of Chiavenna

2.4 Key Risk Assessment Findings

The Key Risk Assessment step aims to synthesize the results of the regionalized risk analysis by translating quantitative and qualitative evidence into an integrated evaluation **of risk severity, urgency and resilience capacity**. This step supports the prioritisation of climate risks and provides a structured basis for decision-making and follow-up actions in Phase 3. The assessment follows the CLIMAAX Key Risk Assessment Protocol and is designed to facilitate engagement with institutional stakeholders and technical experts.

2.4.1 Mode of engagement for participation

The evaluation of key climate risks was conducted through a combination of technical analysis and structured institutional engagement. The process built upon the stakeholder interactions already established during the scoping and risk exploration phases and further involved regional and local actors with direct responsibilities in risk management and civil protection.

Key interlocutors included the Lombardy Regional Civil Protection authorities, the Regional Environmental Agency (ARPA), the Po River Basin District Authority, and technical experts involved in the drafting of Municipal Civil Protection Plans and sectoral risk management instruments. These actors were engaged through targeted meetings and exchanges aimed at validating assumptions, discussing preliminary findings, and interpreting the approach in light of operational experience.

Rather than relying on formal participatory workshops, the engagement approach focused on **expert-driven validation and co-interpretation**, reflecting the technical and regulatory nature of the risks addressed. Feedback collected during these interactions contributed to refining the interpretation of risk severity, urgency and capacity, and to aligning the assessment with real-world decision-making constraints and practices.

It needs to be noted that the **outcomes of phase 2 still need to be more thoroughly discussed** with the stakeholders for interpretation and decision on the next developments.

Main key messages emerging from the exchange with experts and stakeholder are:

- In the context of Lombardy (and Italy, in general), the process of hazard and risk mapping for flood and hydrogeological risks is at the moment mature and well-established: the mosaic is complete over the whole territory, providing information that can be considered robust and operable. The process is yet iterative and constantly improved by incorporating local detailed studies, as they are finalized, under the supervision of a regional authority that guarantees the overall quality and consistency of the data
- The major difficulty comes from events that are extremely localized both in time and space, such as sudden meteorological events and phenomena occurring in smaller valleys. These events, although localized, can produce severe damage and impacts over broader areas. The dynamics underlying these events are yet very hard to model and this is still shown in the outcomes of phase 2:
    - Precipitation data suffer from scale-match limitations and representation capacity of local events. It is common opinion that downscaling approaches can easily produce artifacts in the data
    - Flood hazard maps are useful to create risk scenarios with respect to the primary and main water courses, but on the general level they perform more poorly on lateral minor torrents, which are a main source of hazard especially in the alpine environment
    - It is still extremely difficult to compute robust and effective meteorological thresholds for triggering effects related to hydrogeological hazard (landslides, debris and mud flow, etc.), so that hazard maps are still based more on the representation of historical events and on a general parametric evaluation of the territory proneness to slope instability

2.4.2 Gather output from Risk Analysis step

The Key Risk Assessment draws on multiple outputs produced during the Risk Analysis step in Phase 2, including:

- Results from the **Equivalent Rainfall Method**, applied to observed, reanalysis and bias-corrected climate model data, providing information on the frequency and temporal evolution of threshold exceedances relevant for hydrogeological and flood risk.
- Spatial analyses of **flood and hydrogeological hazard** based on PAI and PGRA classifications, complemented by JRC flood depth datasets.
- Quantitative assessments of **exposure and vulnerability**, including population, buildings, economic activities and cultural heritage assets located in areas subject to high and very high hazard levels.
- Preliminary estimates of **flood-related economic damage** to buildings and impacts on critical infrastructure, derived from the application of the CLIMAAX flood-related building damage and exposed population workflow using both standard and locally refined datasets.

These outputs were considered jointly to inform an integrated understanding of current and future risks, recognising both the strengths and limitations of the available data and methodologies.

2.4.3 Assess Severity

Risk severity was assessed for both current and future conditions using the four categories defined in the CLIMAAX protocol: limited, moderate, substantial and critical.
River flooding was assessed as having **limited severity in the current period**. The analysis highlights limited but still significant exposure of population, residential buildings, economic activities and cultural heritage in flood-prone areas, particularly within the main urban centres along the Mera River. Even medium-probability floods can generate non-negligible damage and disruption, including impacts on critical infrastructure and transport networks. The potential for cascading effects, such as prolonged isolation of parts of the valley and economic losses, further supports this severity classification. The **uncertainty** related to future scenarios, associated with the general impression of a worsening of the phenomena induced to assign a **moderate severity for future conditions**.

Heavy rainfall and associated hydrogeological risk was assessed as **moderate in severity for the current period**. Although the trend analysis of Equivalent Rainfall threshold exceedances does not yet show statistically robust trends, the combination of high-intensity precipitation events, steep terrain, and widespread landslide-prone areas results in potentially severe impacts. These include slope failures, debris flows, infrastructure damage and risks to human safety, often occurring over short timescales and affecting multiple municipalities simultaneously. Stakeholder input confirmed that such events represent one of the most challenging and impactful risk types for civil protection operations in the area, particularly coming from extreme meteorological events that seem to increase in frequency and are especially hard to forecast. Similarly to the river flooding risk, **uncertainty** suggested to assign a **substantial severity for the future**.

For other hazards (e.g. heatwaves, drought, wind, snow), severity was assessed as limited to moderate, reflecting their current impact levels and the relative exposure of the territory.

2.4.4 Assess Urgency

Urgency was evaluated using the four CLIMAAX categories: no action needed, watching brief, more action needed, and immediate action needed.

Heavy rainfall was classified as requiring **more action needed**. The hazard is associated with sudden-onset events, limited predictability at local scale, and potentially severe consequences even in the absence of clear long-term trends. The operational relevance of rainfall thresholds for early warning and civil protection activation further increases urgency, as improvements in monitoring, data integration and interpretation can yield immediate benefits in risk preparedness and response. Moreover, in the face of the manyfold uncertainty related to this phenomena, reason suggest a precautionary approach and the implementation of further risk mitigation measures and a stronger effort in vulnerability assessments over the territory.

River flooding was classified as **watching brief**. While existing mitigation measures and planning instruments contribute to risk reduction, the analysis highlights the need for further refinement of vulnerability assessments and economic damage estimation using local-scale data. Future climate conditions may exacerbate existing risks, and proactive action is required to prevent an increase in residual risk over time. Nevertheless, also the presence of numerous hydraulic works for water retention basins (related to hydro-power production) tend to structurally reduce the urgency.

For the remaining hazards, urgency was generally assessed as watching brief or no immediate action needed, reflecting either slower-onset processes or lower expected impacts in the near future.

2.4.5 Understand Resilience Capacity

Resilience capacity was assessed across financial, human, physical, social and institutional dimensions, using the categories low, medium, substantial and high.
For **river flooding**, resilience capacity was assessed as **substantial**. The territory benefits from established civil protection structures, hazard mapping, planning instruments and experience in emergency response. However, limitations persist in terms of detailed hazard characterisation (e.g. water depth and flow velocity), integration of vulnerability data, and availability of high-resolution exposure datasets. These gaps constrain the effectiveness of both preparedness and long-term risk reduction strategies.

For **heavy rainfall and hydrogeological risk**, resilience capacity was also assessed as **substantial**. While early warning systems and operational procedures are in place, the complexity of the terrain, the spatial dispersion of exposed assets, and the rapid onset of events limit response capacity. Existing measures reduce risk but do not fully offset the potential impacts, particularly under extreme or compound events.

Overall, the assessment highlights a solid institutional basis for risk management, coupled with clear needs for improved data, analytical tools and targeted capacity-building.

2.4.6 Decide on Risk Priority

Based on the combined assessment of severity, urgency and resilience capacity, climate risks were prioritised as shown in the risk matrix.

Heavy rainfall emerges as a **very high priority risk**, due to the possibility of an increasing trend in severity and the rather high level of urgency.

River flooding is identified as a **high priority risk**, reflecting substantial severity and the uncertainty for future scenarios.

Fire risk is generally considered rather high, due to the vast presence of woodland in the area, generally worsening conditions in terms of climatic precursors and a concern about the capacity for a efficient management of forests. Further consideration are yet out of the scope of the present analysis.

Other risks were assigned lower priority levels, consistent with their assessed impact and urgency. This prioritisation provides a clear rationale for focusing Phase 3 activities on heavy rainfall and flood-related risks, particularly through enhanced data integration, refinement of vulnerability assessments and stronger linkage with civil protection planning and adaptation measures.

This prioritisation framework directly informs the monitoring, evaluation and forward-looking planning activities described in Sections 2.5 and 2.6.

Table 2-14. Key Risk Dashboard for Valchiavenna

Risk Workflow	Severity		Urgency	Capacity	Risk Priority
	C	F		Resilience/ CRM	
River flooding	1	2	2	3	high
Coastal flooding	-	-	1	-	none
Heavy rainfall	2	3	3	3	very high
Heatwaves	1	1	1	3	low
Drought	1	1	2	2	limited
Fire	2	2	3	2	medium-high
Snow	1	1	2	3	limited
Wind	1	2	2	2	medium

2.5 Monitoring and Evaluation

The Monitoring and Evaluation step of Phase 2 focuses on assessing the effectiveness, robustness and added value of the climate risk assessment process, with particular attention to learning outcomes, stakeholder involvement, data and methodological challenges, and implications for future phases.

A key lesson from Phase 2 is the importance of **methodological consistency and data hierarchy** in climate risk assessments. The structured comparison between observed data, reanalysis and regional climate model simulations proved essential to ensure the credibility of subsequent impact-oriented analyses. The use of CERRA as a reference dataset, supported by an explicit evaluation against ARPA observations, strengthened confidence in the bias correction of CORDEX simulations and in the application of derived indicators.

The operation of **spatial average of precipitation fields** required by the approach is a conceptual conundrum, as it is a rather simple operation from the computational point of view, but implicates plenty from the conceptual point of view and would require further consideration.

One of the main difficulties encountered concerns **data availability and resolution**, particularly for hazard and vulnerability components. While climate data are relatively abundant, high-resolution and locally validated information on flood water depth, building characteristics and population vulnerability remains limited. This constraint affected the level of detail achievable in economic damage estimation and exposure analysis, highlighting the need for closer integration between climate assessment workflows and local planning datasets.

Stakeholders played a central role in the M&E process, primarily through **expert feedback and institutional validation**. Regional and local authorities involved in civil protection, environmental monitoring and risk planning provided critical insights into the operational relevance of the approach and helped identify priority gaps between analytical outputs and decision-making needs. First preliminary feedback confirmed the interest in investigating the usefulness of the Equivalent Rainfall Method as a conceptual and operational bridge between climate information and early warning procedures, while also stressing the importance of cautious interpretation of trends and uncertainties.

Learning was and will be further ensured through an **iterative process** combining technical analysis, internal review and stakeholder discussion. Intermediate results were shared and discussed at multiple stages, allowing assumptions to be revisited and methods refined. This iterative approach enhanced transparency and fostered a shared understanding of both the potential and the limitations of the assessment.

New data have become available or are expected to become available as a result of parallel planning processes, notably the updating of Municipal Civil Protection Plans and ongoing hydraulic studies for the Mera River basin. However, additional resources are needed to fully exploit these opportunities, including access to harmonised high-resolution hazard datasets, improved socio-demographic information at fine spatial scales, and further technical capacity for data integration and analysis.

Communication of results was carried out through a combination of technical reporting, institutional meetings and public dissemination activities, also thanks to the synergy with other European projects in which the Mountain Community is actively involved. This multi-channel approach proved effective in reaching different audiences, from decision-makers and technical experts to local communities and educational institutions, and will contribute to raising awareness of climate-related risks in the Valchiavenna territory.

Overall, Phase 2 demonstrated a **positive impact on integrating different competences, jurisdictions, and territorial analysis processes into a coherent framework**. At the same time, the evaluation highlights clear areas for improvement, especially regarding data availability, methodological refinement and the integration of assessment results into concrete adaptation and risk reduction measures.

2.6 Work plan Phase 3

Building on the results of Phase 2, Phase 3 will primarily focus on heavy rainfall and river flooding, which were identified as high priority risks. A careful evaluation of the **residual resources** in the project is due in order to assess the possibility to **refine the application** of the Equivalent Rainfall method, broadening the computational database. Also, the risk quantification with respect to flood river hazard (local flood depth data), improve the representation of vulnerability and exposure (real estate values, **detailed population distribution and characterization**, etc) will depend on **parallel processes** which may provided the data and information needed, not controlled by the present project. Finally, the goal is to strengthen the **linkage between climate information and civil protection and adaptation measures**, by continuing and improving the exchange with the regional authorities and by setting up **awareness-raising and risk education** events for the stakeholders and the population.

A first key effort will thus consist in the refinement of flood-related damage and exposure assessments using local-scale datasets. In particular, Phase 3 will seek to integrate information on **expected flood water depth** and, where available, flow velocity, derived from ongoing hydraulic studies for the Mera River basin and from data produced within the updating process of Municipal Civil Protection Plans. The inclusion of these variables is expected to substantially improve the reliability of economic damage estimates and impact assessments.

In parallel, the analysis of **population exposure and vulnerability** should be enhanced through the use of georeferenced demographic information, with particular attention to age structure and potentially vulnerable groups. Where feasible, population datasets will be refined to better reflect local conditions and to support more targeted risk management and emergency planning measures.

For heavy rainfall and hydrogeological risk, Phase 3 will focus on consolidating the application of the Equivalent Rainfall Method as a monitoring and analytical tool. This will include extending the analysis to **additional time periods** and, where resources allow, to a **broader set of climate model simulations**, in order to improve robustness and better characterise uncertainty. Particular attention will be given to the **interpretation** of threshold exceedances in an operational context, in close coordination with regional civil protection stakeholders.

Another important activity will be the integration of climate risk assessment results into existing **planning instruments**, including **Civil Protection Plans** and sectoral risk management strategies. This will support the uptake of project outcomes beyond the analytical phase and contribute to strengthening local adaptation capacity.

Phase 3 will also include targeted stakeholder engagement, capacity-building, risk awareness activities, aimed at supporting the **interpretation and use of climate risk information** by local authorities technical staff, civil protection actors and the general population (with a particular focus on the **correct and effective interpretation of the information and alerts** provided by the Early Warning System). These activities will build on the networks and engagement mechanisms established in previous phases.

Certain aspects will **not** be addressed in Phase 3 due to scope and resource constraints. These include the comprehensive assessment of additional climate hazards not identified as priority risks, and the development of fully quantitative long-term economic cost–benefit analyses of adaptation measures. These elements are acknowledged as important but fall outside the immediate objectives of the project.

At the same time, some of the planned activities may depend on processes of which the project is not in control, in particular those that could provide water depth and detail population data.

Overall, Phase 3 is designed to move from risk understanding to risk-informed action, ensuring continuity with the analytical work conducted in Phase 2 while maximising the practical relevance and long-term value of the CMV4Clima project.

3 Conclusions Phase 2- Climate risk assessment

A key outcome of Phase 2 is the consolidation of a **transparent and defensible climate data framework**, based on the systematic comparison of observed data, reanalysis products and regional climate model simulations. The evaluation of CERRA against ARPA observations confirmed the suitability of reanalysis data as a reference for impact-oriented applications, while the intercomparison and ranking of CORDEX simulations supported an informed and documented model selection. The application of bias correction further improved the consistency of climate inputs used for risk analysis.

The adaptation of the **Equivalent Rainfall Method** to a climate risk assessment context represents an important and promising methodological contribution. This approach may effectively link climate information with operational civil protection procedures. Although no statistically robust trends in threshold exceedances were detected over the analysed periods, the results provide meaningful insights and a solid base for future implementation. The absence of clear trends highlights the need for cautious interpretation, without undermining the practical relevance of the method.

The application of the methodology shows encouraging results, which nevertheless remain too preliminary to support a conclusive judgement regarding the presence of a trend in the number of threshold exceedances.

The results will, in any case, be further discussed with stakeholders, with particular reference to those involved in Regional Civil Protection activities.

For **river flooding**, Phase 2 enhanced the characterisation of hazard, exposure and potential impacts, particularly in densely populated areas along the Mera River. The application of flood-related damage and exposure workflows demonstrated the possibility and opportunity of integrating local datasets into a dynamic risk assessment tool that can easily evolve and improve when fed with better data, while also revealing current limitations related to data resolution and availability.

The **Key Risk Assessment** identified heavy rainfall as a very high priority risk and river flooding as a high priority risk for the Valchiavenna territory. This prioritisation reflects a balanced evaluation of severity, urgency and resilience capacity, informed by both analytical results and stakeholder expertise.

Overall, Phase 2 significantly improved the understanding of climate-related risks and strengthened the connection between climate analysis and local risk management practices. Remaining limitations, particularly regarding data availability and uncertainty, are explicitly acknowledged and directly inform the objectives and activities planned for Phase 3.

4 Progress evaluation

Phase 2 of the CMV4Clima project demonstrates clear progress in both analytical depth and practical relevance compared to Phase 1. While the first phase focused on scoping and exploratory testing, Phase 2 deepened the assessment through refined climate data processing, impact-oriented risk analysis and structured risk prioritisation. The activities carried out in this phase directly support the transition toward Phase 3, as illustrated in paragraph 2.6.

Explicit discussion of methodological and data-related limitations ensures transparency and realism in planning subsequent activities.

The analysis related to heavy rainfall events has been clearly linked to the hydrogeological hazard, therefore a complete hazard mapping has been gathered and elaborated for the territory. Similarly, river flood hazard and risk maps have been provided, prior to the implementation of the flood damage evaluation workflow.

The analysis of climate and meteorological data from different sources allowed to construct a robust climatology for the area, also confirming the information available in literature, and to deepen the understanding of the characteristics and performance of CORDEX climate scenarios data.

Whilst characterization of exposure reached a satisfactory level in phase 2 and was functional to the application of the foresee methodology, the investigation also shed light on the limitations in the available sources. Similarly, the vulnerability analysis that already collected some information in this phase and in the previous one (e.g. demographic pyramid, age structure, etc.), further effort is going to be made in phase 3 to improve quantity and quality in this regard.

Progress against the Key Performance Indicators defined in the Individual Following Plan also confirms effective implementation of communication and stakeholder engagement actions. As summarised in Tables 4-1 and 4-2, Phase 2 contributed to public dissemination, engagement with educational institutions, interaction with public authorities, and participation in European-level events. These actions strengthened stakeholder awareness and ownership of the project outcomes.

From an efficiency perspective, Phase 2 made effective use of available resources by prioritising analyses with high added value and by leveraging existing institutional processes and datasets. Constraints related to time, staffing and data availability limited the scope of some analyses, particularly those requiring high-resolution local information. These constraints were managed transparently and are reflected in the design of Phase 3.

Overall, Phase 2 had a positive impact on the Climate Risk Assessment process. It improved institutional capacity to interpret climate information, reinforced the understanding of the link between climate data and operational risk management, and established a solid foundation for the development of targeted adaptation and risk reduction actions in the final phase of the project.

Table 4-1 Overview key performance indicators

Key performance indicators	***Progress***
[2] number of communication actions taken to share results with your stakeholders	*[1/2]:* *Second deliverable:* *communication actions taken to share results with your stakeholders done: "Biodiversity loss resulting from climate change" – Conference – April 2025*
[2] number of leaflets	*[2/2]* *First deliverable:* *Roll Up and leaflet*
[4] number of dissemination actions focused on educational establishments, environmental territorial associations (WWF, Legambiente), forestry consortiums, cooperatives)	*[3/4]:* *First deliverable:* *1) Kick-off meeting with project presentation; 13/12/2024* *2) environmental territorial associations (WWF, Legambiente, forestry consortiums, cooperatives; 17/02/2025* *Second Deliverable:* *3) High school students, workshop at "Istituto Leonardo da Vinci" - 01/04/2025*
[2] Communications with public authority: Regione Lombardia, Provincia di Sondrio, Bim (mountain catchment basin)	*[1/2]:* *First deliverable:* *Regione Lombardia 12/11/2024*
[4] number of articles in regional media mentioning the project	*[4/4] Article in locale/regional media:* *First deliverable:* *1) Centro Valle; 10/08/2024* *2) Centro Valle – articolo kickoff meeting; 21/12/2024* *3) Valchiavenna mensile; 03/2025* *Second deliverable:* *4) Touring club rivista mensile; 09/2025*

Table 4-2 Overview milestones

Milestones	***Progress***
M4: Climate scenarios for Valchiavenna elaborated	*Initiated in phase 1, completed in phase 2 (may be furtherly improved in phase 3)*
M5: Completed hazard mapping for Valchiavenna	*Hazard mapping for Valchiavenna completed - see CLIMAAX M16_Annex_I_Atlas_Hazard_Risk_Maps (may be furtherly improved in phase 3)*

Milestones	*Progress*
M6: Completed exposure mapping for Valchiavenna	*Exposure mapping for Valchiavenna completed - see CLIMAAX M16_Annex_II_Atlas_Exposure_Maps (may be furtherly improved in phase 3)*
M7: Vulnerability factor evaluated through participatory approach and integrated in risk analysis	*Initiated in phase 2, will be completed in phase 3*
M10	*CLIMAAX workshop in Barcellona (10–11 June 2025) - Attended*

5 Supporting documentation

- CLIMAAX CMV4Clima_Deliverable_2_19012026 (PDF)
- CLIMAAX CMV4Clima_Annex_I_Atlas_Hazard_Exp_Risk_Maps (PDF)
- Deliverable_2_CMV_Commun_Dissem_activities (PDF)
- Documentation on Communication and Dissemination activities (ZIP)
- Flood-Related Building Damage and Exposed Population OUTPUTS (ZIP)
    - Piuro DBT run
    - Piuro OSM rum
    - Chiavenna DBT run
    - Chiavenna OSM run
- Datasets:
    - ARPA observed data
        - Chiavenna Cerletti 2001-2005
            - total precipitation
            - mean daily temperature
        - Samolaco Vignola 2001-2005
            - total precipitation
            - mean daily temperature
    - CERRA Reanalysis daily spatial average over AOI
        - Historical (total precipitation, 2m air temperature)
        - Pseudo-historical (total precipitation, 2m air temperature)
    - CORDEX model daily spatial average over AOI
        - Historical (total precipitation, 2m air temperature)
        - Pseudo-historical (total precipitation, 2m air temperature)
        - Future (total precipitation, 2m air temperature)
    - River Flood Damage total and annual (Chiavenna, Piuro)

6 References

Aldighieri B., Mazzoleni G., La Valchiavenna: un bacino pilota per il controllo dell'ambiente alpino; Quaderni di Geodinamica Alpina e Quaternaria, Volume 10, ISBN 978-88-86596-12-1, Milano 2011

Gambini E., Ceppi A., Ravazzani G., Mancini M., Valsecchi I. Q., Cucchi A., Negretti A., Tolone I., An empirical rainfall threshold approach for the civil protection flood warning system on the Milan urban area, Journal of Hydrology, Volume 628, 130513, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2023.130513, 2024

ISPRA (2024) Pericolosità e indicatori di rischio frane – Piattaforma IdroGEO https://idrogeo.isprambiente.it (licenza CC BY 4.0: https://creativecommons.org/licenses/by/4.0/deed.it)

Lombardy Region, Regional Directive for the organizational and functional management of the alerting system for natural hazards for civil protection purposes, d.g.r. 4114, December 21st, 2020

Morris M., Kushner P.J., Smith K.L, Guidebook for the University of Toronto Climate Downscaling Workflow, Version 1.1.0 – Last updated 19 August 2024, https://utcdw.physics.utoronto.ca/UTCDW_Guidebook/README.html

Taesombat W., Sriwongsitanon N., Areal rainfall estimation using spatial interpolation techniques, ScienceAsia 35 (2009): 268–275