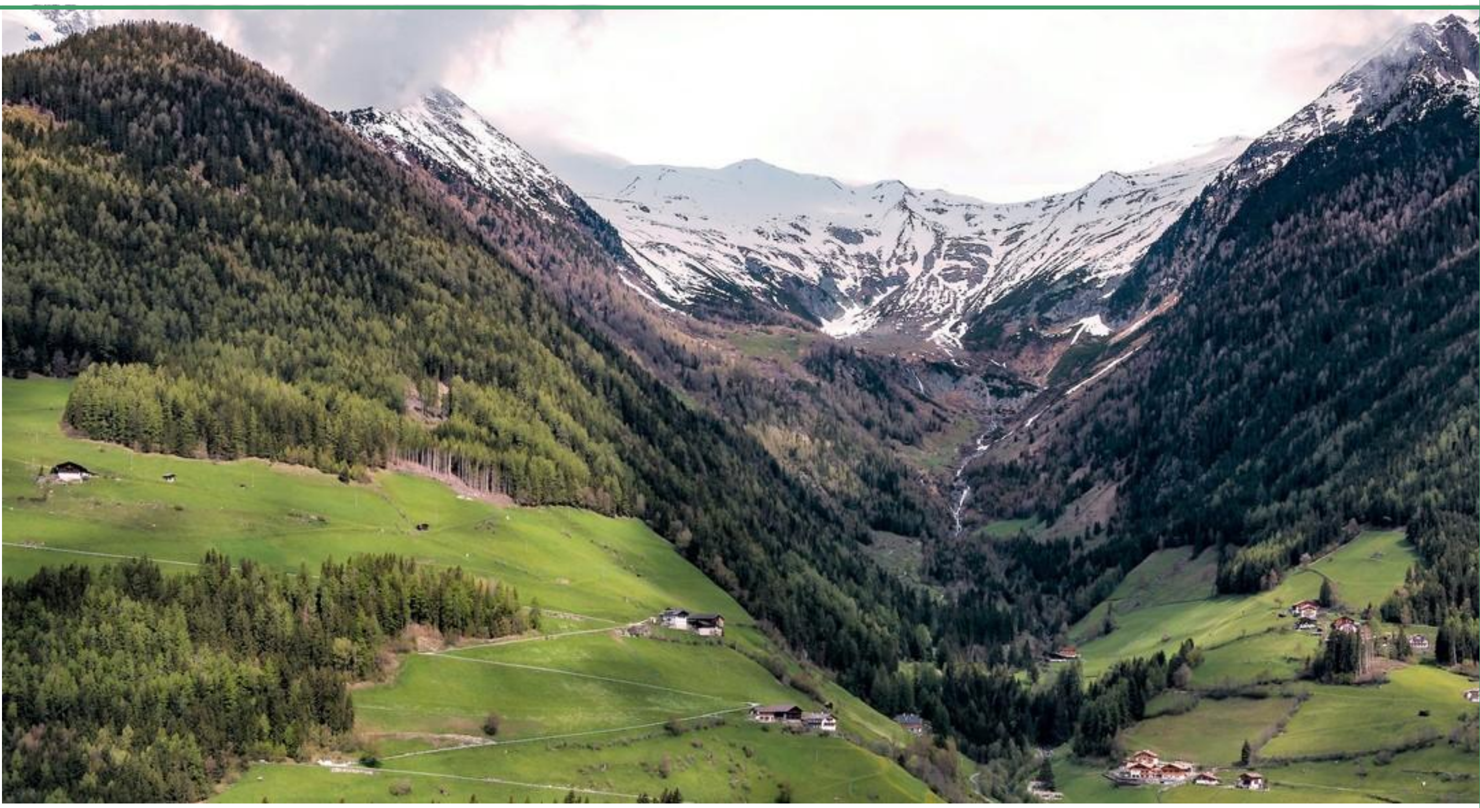
JANUARY 2025

Deliverable 2.2.1

REPORT ON PAST AND FUTURE RISK PATHWAYS

X-RISK-CC

How to adapt to changing weather eXtremes and associated compound and cascading RISKs in the context of Climate Change



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ABOUT X-RISK-CC

X-RISK-CC supports risk managers and policymakers across the Alpine Space (AS) in addressing the compound and cascading risks of Climate Change (CC)-related extreme weather events. The project develops local actions and transnational guidelines based on newly generated, harmonised data and knowledge about past and future weather extremes across the alpine region and the project areas.

Risk management instruments are enhanced through collaborative work with risk managers in the five project pilot areas in the AS, including cross-border regions. The project's outputs are co-developed and disseminated through EUSALP AG8 and PLANALP of the Alpine Convention (AlpConv).

The X-RISK-CC partnership comprises regional risk managers, national authorities, members of EUSALP, PLANALP/ACB of AlpConv and scientists. The project addresses the need for shared knowledge, actions and solutions for managing extreme events under CC, as outlined in the EUSALP AG8 2023-24 work programme.

IMPRESSUM

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Glossary

Capacity	The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience. Capacity may include infrastructure, institutions, human knowledge and skills, and collective attributes such as social relationships, leadership and management (UNDRR, 2020).
Cascading impact	Cascading impacts from extreme weather/climate events occur when an extreme hazard generates a sequence of secondary events in natural and human systems that result in physical, natural, social or economic disruption, whereby the resulting impact is significantly larger than the initial impact. Cascading impacts are complex and multi-dimensional, and are associated more with the magnitude of vulnerability than with that of the hazard (IPCC, 2022).
(Disaster) damage	Occurs during and immediately after a hazardous event or disaster. This is usually measured in physical units (e.g., square meters of housing, kilometres of roads, etc.), and describes the total or partial destruction of physical assets, the disruption of basic services and damages to sources of livelihood in the affected area (UNDRR, 2020).
(Disaster) impact	The total effect, including negative effects (e.g., economic losses) and positive effects (e.g., economic gains), of a hazardous event or a disaster. The term includes economic, human and environmental impacts, and may include death, injuries, disease and other negative effects on human physical, mental and social well-being (United Nations, 2016).
(Disaster) risk	The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. (Disaster) risk is determined probabilistically as a function of hazard, exposure, vulnerability, and capacity. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species (IPCC, 2021).
Economic loss	Total economic impact that consists of direct economic loss and indirect economic loss. Direct economic loss: the monetary value of total or partial destruction of physical assets existing in the affected area. Direct economic loss is nearly equivalent to physical damage.

	Indirect economic loss: a decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts (United Nations, 2016).
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Measures of exposure can include the number of people or types of assets in an area. These can be combined with the specific *vulnerability* and *capacity* of the exposed elements to any particular hazard to estimate the quantitative risks associated with a hazard in the area of interest (UNDRR, 2020).
(Natural) Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation (UNDRR, 2020) Natural hazards are predominantly associated with natural processes and phenomena (United Nations, 2016)
Hazardous event	The manifestation of a hazard in a particular place during a particular period of time. Severe hazardous events can lead to a disaster as a result of the combination of hazard occurrence and other risk factors (United Nations, 2016).
Cascading hazards	Any natural hazard might trigger zero, one or more secondary natural hazards. The secondary natural hazard might be identical or different from the primary hazard. As an example, an earthquake might trigger landslides, which can trigger a flood, resulting in a hazard cascade (Tilloy et al., 2019).
Compound hazards	Different hazards resulting of the same triggering event. In this case there is not a primary and a secondary hazard as the different hazards occur simultaneously or within a reasonably short timeframe. As an example, the co-occurrence of river flooding and sea surge could be the result of the same large-scale process, e.g., tropical cyclone. (Tilloy et al., 2019).
Mitigation	The lessening or minimizing of the adverse impacts of a hazardous event. The adverse impacts of hazards, in particular natural hazards, often cannot be prevented fully, but their scale or severity can be substantially lessened by various strategies and actions. Mitigation measures include engineering techniques and hazard-resistant construction as well as improved environmental and social policies and public awareness.
Multi-hazard	Multi-hazard means (1) the selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous

	events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects (UNDRR, 2020).
Multi-risk	It is related to multiple risks such as economic, ecological, social, etc. It determines the whole risk from several hazards, taking into account possible hazards and vulnerability interactions entailing both a multi-hazard and multi-vulnerability perspective (Carpignano et al., 2009).
Pathway	The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic and/or socio-behavioural trajectories and involve various dynamics, goals and actors across different scales (IPCC, 2022)
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions (IPCC, 2021).
Storyline	A way of making sense of a situation or a series of events through the construction of a set of explanatory elements. Usually, it is built on logical or causal reasoning. In climate research, the term storyline is used both in connection to scenarios as related to a future trajectory of the climate and human systems or to a weather or climate event. In this context, storylines can be used to describe plural, conditional possible futures or explanations of a current situation, in contrast to single, definitive futures or explanations (IPCC, 2021).
(Disaster) risk drivers	Processes or conditions, often development-related, that influence the level of disaster risk by increasing levels of exposure and vulnerability or reducing capacity. Underlying disaster risk drivers — also referred to as underlying disaster risk factors — include poverty and inequality, climate change and variability, unplanned and rapid urbanization and the lack of disaster risk considerations in land management and environmental and natural resource management, as well as compounding factors such as demographic change, non-disaster risk-informed policies, the lack of regulations and incentives for private disaster risk reduction investment, complex supply chains, the limited availability of technology, unsustainable uses of natural resources, declining ecosystems, pandemics and epidemics (United Nations, 2016).

Vulnerability	The propensity or predisposition to be adversely affected. The conditions are determined by physical, social, economic or environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2021; UNDRR, 2020).
Vulnerability social	Characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (Blaikie et al., 2014).
Vulnerability physical	Physical vulnerability refers to the susceptibility of physical assets, infrastructure, or systems to damage or loss caused by exposure to hazards, determined by factors such as design, construction quality, location, and maintenance (IPCC, 2012; UNISDR, 2009).

1. Introduction

This report, Deliverable 2.2.1 (D 2.2.1), documents the methods applied and the results obtained regarding past and future risk pathways in the pilot areas of X-RISK-CC. The activities conducted in this context build upon the work outlined in Deliverable 2.1.1 (D 2.1.1), which described past and future (compound) hazards. The work was carried out within Work Package 2, which aimed to: 1) understand the past and future impacts and risks in pilot areas due to weather extremes under climate change (CC), and 2) establish a practice-oriented concept to generalize and translate the new knowledge into risk management and adaptation options across the Alpine Space (AS).

The methods presented in Chapter 2 were proposed by the scientific partners and applied to the pilot areas. A summary of the outcomes of the pilot analyses is given in Chapter 3. The complete documents developed by the pilot responsible partners as part of work package 2 are included in the annex to D 2.1.1 and 2.2.1. Chapter 4 takes a cross-national perspective by synthesising insights gained by comparing the pilot analyses and presenting the results of the alpine-wide modelling of mass movement impacts. In the conclusion in Chapter 5, we discuss challenges and limitations of the developed approaches and results. Furthermore, we outline how the results of Work Package 2 will be applied over the course of X-RISK-CC inform activities in other work packages.

2. Methodology for risk pathway analysis

Disaster risk management and climate change are complex systems. Risk pathways involve various interconnected factors that contribute to and drive the risk. These factors encompass a broad range of both climatic and non-climatic variables. In X-RISK-CC, we developed tools to investigate the drivers of risk leading to compound and/or cascading events caused by climate extremes in five pilot areas located in the Alps. Our approach combined qualitative and quantitative assessments, bringing together expertise from multiple disciplines, such as climate science, natural hazard modelling, and regional civil protection, forestry, and planning departments.

The concept of 'risk pathways' in the context of climate change is explored in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6), particularly in understanding how climate hazards, vulnerability, and exposure interact to produce risks. Risk pathways represent the chains of events or processes linking climate impacts to adverse outcomes, helping to identify key drivers and vulnerabilities (Intergovernmental Panel on Climate Change, 2023). The IPCC defines risk as the potential for negative consequences arising from the interaction of climate, hazard, exposure, and vulnerability. It underscores the dynamic nature of risks, where each of these elements can change over time due to factors like climate change, socio-economic developments, and adaptive responses. This concept aligns with earlier definitions, such as those in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters, and is integral to understanding both the immediate and cascading impacts of climate events, as well as the strategies needed to manage these risks effectively (IPCC, 2012).

In X-RISK-CC, we analysed climate extremes, hazards, exposure, vulnerability, and risk management for both past and future scenarios in pilot areas in the Alps. As a first step, we created impact chains for each pilot area to understand and visualise the causal relationships between climate changes and their resulting impacts (see D 2.1.1 for a description of the method and results for each pilot area). We then used a set of tools to compile a structured risk questionnaire for analysing the risk components.

Subsequently, we created climate risk storylines as a useful communication tool. These storylines, along with a rapid risk management assessment, were used to create a basis for developing action plans that address the risks caused by climate extremes, involving local experts in the process (see WP3). In the next section, we describe the concept and framework of the risk questionnaire, the methods used to develop the climate risk storylines that were applied in the project (Chapter 2.2), as well as the Alpine-wide impact models developed for mass movement processes (Chapter 2.3). To begin with, the following sections describe the structure of the risk questionnaire and the individual tools.

2.1. A holistic investigation of risk drivers

2.1.1. Risk questionnaire

In X-RISK-CC, risk managers were encouraged to take a holistic view of the hazard and risk landscape in their study area. The methods promoted in this project are purposefully applicable to a large variety of different (compound and cascading) hazards and can be adapted to different depths of analysis, depending on the aim of the local investigation. We are mainly interested in understanding the processes and factors contributing to current risk due to extreme weather events in the pilot regions and how these are likely to change in the future.

For that purpose, a set of guiding questions were provided in the form of a questionnaire that informs on possible contributing factors. The aim of the risk questionnaire is to improve understanding of risks and their drivers. Risk managers and decision makers are asked to provide answers to these questions based on the collective expertise available in their organisations and other important stakeholders in their region of interest. Where possible, the responses should include reference to prior studies and analyses that were performed in the pilot areas, e.g. for the pilot events. The analysis can be supported by referring to a set of concepts, tools and methods suggested within the context of X-RISK-CC to the risk managers in the pilot areas.

Table 1: Structure of the risk questionnaire in X-RISK-CC

Part 1: General climate and (multi-) hazard situation				
I.	Which are relevant **weather extremes** and how do you expect them to change in the future?	see D 2.1.1.	- pilot reports (WP1) - event tables, - impact chain, - hazard-interaction-matrix - frequency-magnitude relation, - predisposing factors checklist	inputs, tools, methods
II.	Which **hazard processes** can be triggered by current and future weather extremes?			
III.	Which processes occur with high/low **frequency** and with high/low **magnitude** and how do you expect this to change in the future?			
Part 2: Key risk pathways				
IV.	What are the most important **exposed elements** at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?	see D 2.2.1.	- event table, - impact chain, - exposure checklist, - system impacts table - vulnerability models - quantitative risk analysis - Rapid Risk Management Appraisal (WP3)	inputs, tools, methods
V.	Which of the exposed elements display high or low **physical or social vulnerability** to the hazard, and how do you expect this to change in the future?			
VI.	Which **risk management measures** (mitigation, preparedness, response, and recovery) are currently in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?			
VII.	How does the **simultaneous** (or within a short time) **occurrence and/or overlapping of hazard areas** influence exposure and vulnerability?			

The questionnaire follows the structure presented in Table 1 covering the perspective of current risk and risk in the near to mid future (up to 2040). The structure of the analysis moves from the general to the specific. This ensures that risk managers can use the general methodology to identify relevant processes for their area and can choose to investigate individual processes in more detail. *Part 1: General climate and (multi-) hazard situation* concerns the general climate and hazard situation in present and future considering the complex interaction between hazardous processes.

A variety of tools, methods and concepts are suggested that can be applied by risk managers to help answer the questions of the risk questionnaire. The tools to support answering questions I-III are discussed in D 2.1.1.

Part 2: Key risk pathways allows an in-depth investigation of the impacts of hazard processes on the socio-economic systems and their capacity to cope with these events. For this reason, the processes identified in *Part 1: General climate and (multi-) hazard situation* are ranked according to importance to identify hazard processes that pose a relevant risk. The following criteria are adapted from the key risk criteria from the IPCC's Sixth Assessment Report:

1. Likelihood of the hazard process
2. Severity of the potential adverse consequences
3. Irreversibility of severe consequences
4. Potential for cascading consequences

The combination of likelihood (1.) and severity of consequences (2.) gives an indication of the risk. Low likelihood-low consequence events are commonly considered low risk, high likelihood-high consequence are commonly considered high risk events. The exact division of the risk score can be adjusted to account for the coping capacity of local risk management. Depending on the aims and scope of the investigation, the number of relevant processes to be analysed in *Part 2: Key risk pathways* of the risk questionnaire can range from individually selected processes to a systematic analysis of all identified hazard processes.

The answers provided to the risk questionnaire in the pilot analysis form the basis for the development of the climate risk storylines.

In the following subchapters, the individual tools and methods proposed to support answering *Part 2: Key risk pathways* (questions IV-VII) of the risk questionnaires are introduced.

2.1.2. Exposure checklist

The exposure checklist provides an overview of different categories of exposure and the types of assets within each category. It serves as a basis for cataloguing the types of assets located in hazard-prone areas. The exact consequences in terms of direct damages or indirect damages of an asset being exposed depend on the vulnerability to each respective hazard magnitude as well as on any mitigation measures and response capacity.

The exposure checklist separately points out mobile assets such as people, livestock and vehicles. In many cases, the evaluation of affected population, livestock or vehicles will be linked to the analysis of immovable assets, such as private properties (for population), road infrastructure (for vehicles) and agricultural lands (for livestock). Some asset types include structures as well as contents, equipment, and other mobile components that could be affected and damaged in a hazardous event. The damages observed for a specific asset type in a hazard event also depend on the possibility to move or evacuate mobile assets. This is linked to the process speed and the warning time and response capacity.

Different metrics can be used for assessing exposure depending on the size of the study area and the available data. For small area hazard events, e.g., landslides, exposure may be assessed on the level of individual buildings and recent registry information/tourist numbers. For large area processes, e.g., drought, or where data and resources for the assessment are limited, it can be performed for a larger area. Suitable metrics are for example affected area [m²], number of affected assets, regional population data.

The data sources on, e.g., land use, spatial planning, and population density, sometimes contain information in aggregated form and it might not be possible to extract all the individual asset types from the data. If there is evidence of individual assets that have a decisive influence on the overall damages (e.g. critical point for cascading damages), information on these assets should be collected separately to make subsequent risk assessment more reliable.

Asset values are needed if a quantitative risk assessment is the aim. Asset values can be based on net-value estimates, reconstruction costs, or similar approaches. Sometimes this information is available based on local inquiry; other times larger scale data is used to assess asset values. Ideally one consistent approach is selected for the analysis.

2.1.3. System impact table

The system impact table relates all hazard types considered in X-RISK-CC (see D 2.1.1) to different exposure categories and lists possible impacts in the form of damages and/or changes in predisposition that can occur as a result.

We differentiate between direct and indirect damages (Meyer et al., 2013). Direct damages occur due to direct physical contact with a hazard. Their impacts include, e.g., the destruction of and damage to buildings and infrastructure, but also intangible effects such as loss of life, health impacts, or the loss of environmental diversity or cultural heritage. Indirect damages refer to any effects that occur outside the hazard extent (e.g., induced economic losses of suppliers/customers of businesses affected by the hazard or business interruption due to interrupted essential services or mobility infrastructure) or inside the hazard extent with a time lag (e.g., business interruption because of destroyed facilities or because or workplaces being cut off). They are often the result of cascading impacts.

Risk managers or practitioners who aim to consider all relevant hazards in the investigation of key risk pathways might have to consider hazards or exposure that are not their main expertise. The system impacts table indicates which damages can be expected and which changes in environmental predisposition or vulnerability can emerge. This is especially relevant when considering the impacts of compound or cascading events where assets might be exposed to multiple hazards within a reasonably short timeframe. The system impact table can provide a starting point; however, it does not replace an in-depth analysis based on the knowledge of experts of the different hazard processes and local conditions.

2.1.4. Vulnerability concepts

Vulnerability depends on physical and social factors. Physical vulnerability includes territory features (e.g., morphology, forest cover, sediment availability, glacier melt) and asset characteristics (e.g., building construction, age, and maintenance). In a narrower definition, it describes the potential for damage from hazards, which vary in type, intensity, and duration. Social vulnerability relates to people's risk perception, age, education, preparedness, and communication with risk managers during emergencies.

Vulnerability models are applied for each type of asset to determine the mean damage for a specific hazard scenario. Vulnerability models are discrete or continuous descriptions of the expected damage or monetary loss of an asset that is exposed to a certain level of hazard intensity.

Vulnerability is sometimes characterised in the form of fragility functions. A fragility function describes the degree of damages that will occur in a specific asset type at variable hazard intensities. In contrast, a vulnerability function includes additional information about the value of the asset to determine the mean damages. Vulnerability functions are the most commonly used model of physical vulnerability in the context of multi-risk studies (Gallina et al., 2016). Alternative forms of vulnerability information include vulnerability indicators (in the context of physical vulnerability) and vulnerability indices (in the context of social vulnerability).

The vulnerability models chosen for individual assets should be selected considering the local asset characteristics and asset values. Comprehensive examples of vulnerability models for various alpine hazard processes can be found for example in the methodology of the Swiss risk-based natural hazard management concept (PLANAT: https://www.planat.ch/en/). In other projects, national approaches for assessing vulnerabilities of various asset types to single hazard types were developed and continue to be applied on the national level. For more localised hazard types such as landslides, rockfalls, avalanches etc. extensive literature is available on empirical and experimental vulnerability studies for different combinations of hazards and asset types.

Most risk frameworks treat vulnerability as static (Gallina et al., 2016). This common simplification is significant when it comes to investigating the impacts of multi-hazard processes, as we can expect vulnerabilities of assets to change as a result of prior exposure to the same hazard or other hazard types. X-RISK-CC deals specifically with the cascading and compound impacts of future weather extremes. Within this context, vulnerabilities and exposure are expected to evolve as a result of climate change and socio-economic trends.

2.1.5. Quantitative risk analysis

Risk arises whenever there are uncertain and potentially adverse consequences to ecological or social systems. In the context of X-RISK-CC, risk stems from the coinciding or cascading impacts of increasingly frequent weather extremes in the alpine space.

Risk is often determined as

$$\boldsymbol{R} = \sum_{\boldsymbol{i},\boldsymbol{j}} \boldsymbol{H_i} * \boldsymbol{E_j} * \boldsymbol{V_{j,i}},$$

where H_i is the probabilistic hazard i, E_j the value of the exposed element j, and $V_{j,i}$ the vulnerability of element j under hazard i. The combination of exposed elements and vulnerability can alternatively be expressed as the expected damage D_{ij}.

Alternatively, in many engineering applications the risk (i.e., the Expected Annual Damages EAD) in a year t can be expressed as

$$\boldsymbol{R} = \int_{\boldsymbol{0}}^{\infty} \boldsymbol{D_t}(\boldsymbol{m}) * \boldsymbol{f_{M,t}}(\boldsymbol{m})\, \boldsymbol{dm}$$

where M describes the magnitude of a hazard and $f_{M,t}(m)$ is the Probability Density Function (PDF) of the annual maximum magnitude of said hazard. Typical parameters used to describe the magnitude of hazards are, e.g., peak discharge or runoff volume for floods, and area or volume for landslides. The damage curve $D_t(m)$ describes the expected damage caused by an event of magnitude m.

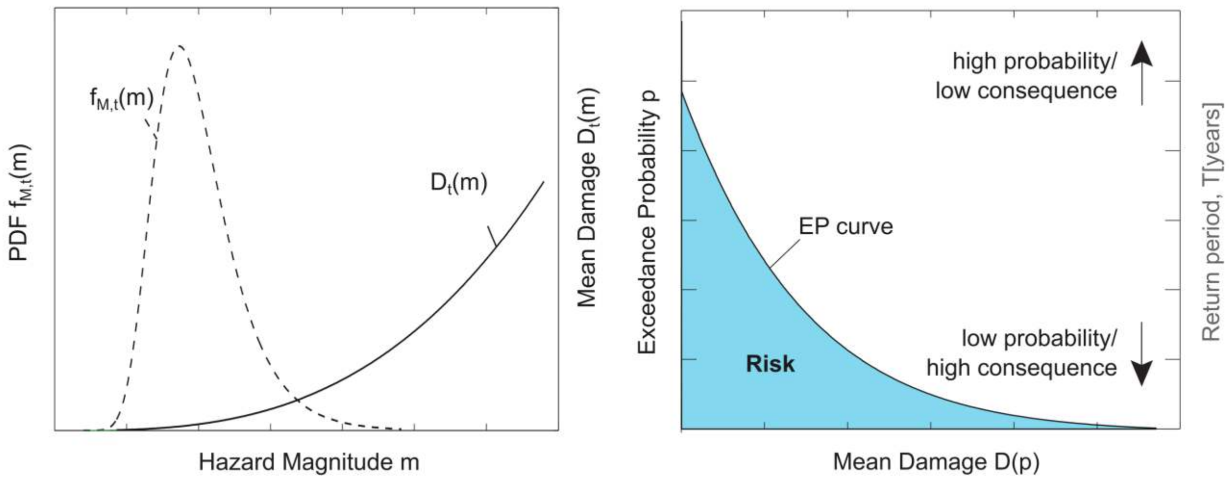

Figure 1: Probability density function of various hazard magnitudes and the damage function expressing the mean damage for an event of given magnitude (left). The exceedance probability curve for a hazard in a specified area of interest (right).

We mostly presume expected damage to increase with increasing hazard magnitude. Because the probability of severe events is relatively low, their contribution to the annual risk is limited (Merz and Thieken, 2009; Ward et al., 2011). This is also reflected in applications of the so-called risk matrices, where high-impact-low-probability events are often classified in the same risk category as low-impact-high-probability events. It must be noted that rare, severe events always constitute the risk of exceeding existing risk management capacity, thereby potentially resulting in disastrous consequences.

The product of damage curve $D_t(m)$ and PDF $f_{M,t}(m)$ is sometimes referred to as a risk curve, damage-probability curve, or loss-exceedance curve. In Figure 1 we call it the Exceedance Probability (EP) curve. It describes the probability that the damages equal or exceed a specific threshold in any given year. The exceedance probability is linked to the concept of the return period. A 100-year hazard event has a probability of being matched or exceeded of $p = 1/T = 1/100 = 0{,}01$, where T is the return period of the hazard event. The exceedance probability of the hazard event equals the exceedance probability of the expected damages, whenever the damage assessment is performed deterministically, i.e., all uncertainty in the damage assessment is neglected.

Approximation of risk

The risk posed by a hazard can be calculated by integrating over the Exceedance Probability (EP) curve. However, the true shape of the full EP curve is rarely known. The damage assessment is generally demanding and can often, for practical reasons, only be performed for a handful of scenarios. With the use of scenarios, we can approximate the shape of the curve and, therefore, the total risk.

It is common practice that the hazard is described in the form of scenarios of different magnitudes (Bründl et al., 2009). A scenario is one realisation of how a hazard can occur in a specific location. It can be derived from past events or generated as a potential hazard event of a certain magnitude and corresponding occurrence probability. Each scenario corresponds with a hazard extent that has been observed or can be investigated by means of hazard simulation. The severity of a scenario within the hazard extent is usually described in the form of one or several intensity measures, which are indicative of its damage capability (examples for landslide risk in Corominas et al., 2023).

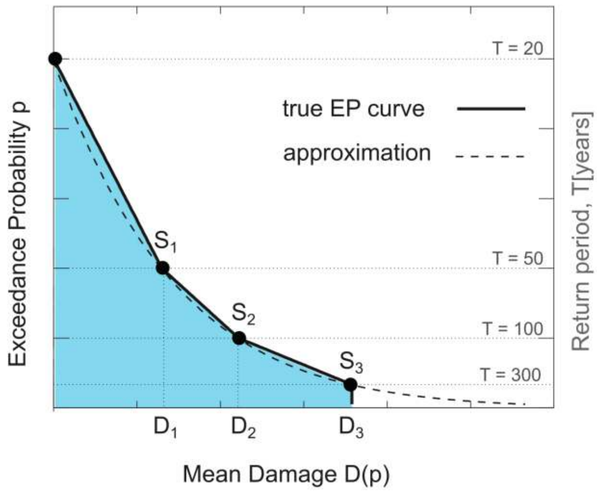

Figure 2: Approximation of the expected annual risk using three hazard scenarios and the estimated expected damages associated with each scenario.

Figure 2 shows how scenarios are used to approximate the area underneath the true EP curve. It is noted that a scenario is not limited to the representation of single hazards but could include a compound or cascading hazard event. For estimating the risk, however, the combined exceedance probability of the compound or cascading hazards must be known.

The quality of our estimation depends on the scenarios we choose as the basis for the approximation. The scenarios should ideally cover the entire span of plausible scenarios. Furthermore, it is important to reflect any significant jumps in the expected damages that could occur, e.g., when the existing protection level is exceeded. It is common to use a minimum of three scenarios corresponding to a frequent, 100-year, and infrequent occurrence interval (Merz et al. 2009). For each of the scenarios, we must know the associated return period.

Over time, developments in hazard, exposure, or vulnerability result in changes in risk. Changes in risk can be reflected in the risk assessment either through changes in the frequency of specific scenarios (and therefore in the return period and exceedance probability) or in the damages that are associated with the respective scenarios. Here, we use the example of climate change as a future development that will impact the total risk. We expect hazard scenarios of a fixed magnitude to occur with increasing frequency because of climate change. For the scenarios used to approximate risk in Figure 2 this means that they will, in the future, be associated with a higher probability, resulting in a change in total risk. In X-RISK-CC, the information on how future climate will influence the exceedance probability of individual hazard scenarios will be derived from WP 1 and WP 2 A2.1 results described in D 2.1.1.

To investigate future development that might impact the area affected by a hazard or its intensity, e.g., new structural mitigation measures, it can be necessary to reassess the hazard extent of the scenario by applying a hazard model.

Quantitatively estimating the expected damage of an individual scenario

The exact process and models used in assessing the expected damages for individual scenarios depend on the type of hazard being assessed. In principle this involves, first, determining the extent of the hazard scenario, second, identifying the assets exposed to the hazard, and thirdly, determining the impact of the event on the exposed assets in terms of monetary losses or other suitable risk metrics.

The hazard extent and intensity are usually investigated by means of hazard modelling. In the case of hydrological hazards, a hydrodynamic model is applied to estimate relevant intensity parameters in association with a scenario e.g., flow depth or flow velocities. If official hazard maps are available or a hazard assessment has been performed in the context of previous studies, these maps can often be used as the basis for a scenario-based risk assessment. For this purpose, it must be possible to assign an exceedance probability to the hazard map.

Information on assets is intersected with hazard maps to determine the type and number of directly exposed assets. In the quantitative study of risk, we generally focus on direct, tangible impacts and costs associated therewith. Indirect effects of hazard events must be evaluated individually and included in the damage assessment, if they are expected to significantly increase the damage costs. For small study areas with only few assets that determine the damages, local knowledge is essential for evaluating the exposure and, in the next step, the vulnerability.

2.2. Deriving future risk scenarios

In X-RISK-CC, we used climate risk storylines to illustrate potential future extreme events and their compound and cascading impacts in pilot areas.

Climate risk storylines represent a narrative-based approach to understanding and communicating potential future climate risks. Rather than focusing on statistical probabilities or averages, these storylines explore specific, plausible sequences of events that could result in severe climate-related impacts. The approach helps stakeholders, policymakers, and communities visualise how a combination of factors — such as extreme weather events, societal vulnerabilities, and response failures — can interact to create significant risks.

Climate risk storylines incorporate the following features:

1. **Focus on Impactful Events**: They emphasize high-impact, low-probability events or cascading phenomena, such as severe floods, heatwaves, or droughts resulting from shifting climate patterns. This highlights the severity of potential consequences rather than just their likelihood.
2. **Narrative-Driven**: Storylines qualitatively describe how various drivers (e.g., weather extremes, hazards, vulnerabilities, or risk management failures) might interact within a complex system. This makes them accessible to non-experts, bridging the gap between scientific models and real-world decision-making.
3. **Plausibility Over Probability**: Rather than relying solely on statistical probabilities or model-based projections, storylines focus on plausible futures derived from current knowledge (e.g., observations, model data, and local insights). This approach helps decision makers prepare for extreme events under high uncertainty.

4. **Context-Specific**: Climate risk storylines are tailored to specific geographical, social, or economic contexts. For example, they may explore the cascading impacts of climate change on mountain valleys, coastal cities, or agricultural regions, considering local vulnerabilities.
5. **Decision Support**: By vividly depicting potential climate risks, storylines guide policy and risk management strategies. They encourage preparedness for worst-case scenarios and foster consideration of long-term resilience measures.

In X-RISK-CC, climate risk storylines were developed for each pilot area to stimulate discussions and assessments with local risk managers about their capacity to prevent, prepare for, respond to, and recover from extreme events under climate change conditions.

The climate risk storylines focus on one type of (compound) event, such as:

- A heavy rain event combined with strong wind gusts, leading to flooding and damage to critical infrastructure and human safety.
- A prolonged period of heat and drought, resulting in forest fires, water scarcity, and heat-related health issues.

The timeframe and design of X-RISK-CC storylines

In X-RISK-CC the climate risk storylines were designed to depict a plausible yet challenging scenario set in the year 2040, functioning as a "stress test," as outlined in the introductory section. The year 2040 represents a near- to mid-term future sufficiently distant to illustrate the potential impacts of climate change, yet close enough to necessitate immediate action. This timeline is particularly important given the extended periods often required to implement risk mitigation measures, such as constructing protective infrastructure or enacting new policies.

We considered a scenario based on a fictional event with a 100-year return period, projected to occur in the year 2040. Events with a 100-year return period are commonly used in current risk management practices as standard design events. However, to ensure preparedness for even rarer occurrences, such as 300-year events, these standard scenarios should be complemented by a "worst-case" scenario involving a 300-year event in 2040.

For pilot areas addressing independent event types, such as flooding and droughts, multiple, independent storylines were developed.

Using storylines in X-RISK-CC

The climate risk storyline for a specific area was introduced as a brief narrative report during an initial internal meeting with local risk managers involved in the project. These managers adapted the storyline to their specific context by incorporating their knowledge and expertise on past extreme and compound events in the area.

The finalised storyline (or multiple storylines) was later presented at a workshop involving all risk managers and other local to regional stakeholders as input for a "Rapid Risk Management Appraisal" (RRMA). The narrative was accompanied by maps and relevant figures to help visualise the situation described in the storyline.

The climate risk storylines served as a "stress test" to systematically assess strengths, weaknesses, and gaps in current risk management practices related to the described event.

Structure of the climate risk storylines in X-RISK-CC

The outline of potential future scenarios was based on the logical structure presented in Table 2.

Table 2: Structure of climate risk storylines in X-RISK-CC

Scope	The spatial scope identifies the area of focus, such as the upper Isarco Valley in South Tyrol, and specifies the timeframe, the year 2040. Scenarios may expand beyond the scale of past events to include more complex situations with cascading impacts.
General Climate Situation	The storyline describes the climate conditions projected for 2040, including changes in temperature, precipitation, seasonality, and the distribution of rain and snow compared to the past. It also highlights changes in the frequency and intensity of extreme events, with plausible examples based on projections for the period from today to 2040
General Effects of Climate Change	Outline long-term effects of climate change, as well as short-term consequences of extreme events, focusing on those that might increase the risk of hazardous events by fostering critical preconditions (e.g., glacier retreat increasing sediment mobilization; heat, drought, and bark-beetle outbreaks damaging protective forests).
Non-Climatic Risk Drivers	○ Buildings: The expansion of built-up areas into hazard zones increases exposure. ○ People: Vulnerabilities may arise from an aging population, linguistic barriers, communication gaps, or limited access to resources, while exposure increases with more tourists and inhabitants. ○ Critical Infrastructure: Vulnerabilities include insufficient maintenance and damage from past events, while exposure may increase with new developments, such as roads. ○ Ecosystems: Vulnerabilities include pre-event damage from storms, erosion, overuse, pests, or tourism impacts. ○ Health Systems: Vulnerabilities include reduced access to healthcare in rural areas and understaffing, while exposure may result from increased demand during crises. ○ Mobility and Transport: High traffic volumes due to tourism and freight increase exposure. ○ Tourism: Vulnerabilities may include communication challenges, such as linguistic barriers and poor coordination, while exposure is driven by significant tourist presence throughout the year. ○ Water Provision: Vulnerabilities may include increased demand from tourism and industry. ○ Social and Economic Factors: Issues such as poverty, inequality, and political instability. ○ Governance and Policy: Gaps in governance and policy measures to reduce risks.
Meteorological conditions	The storyline includes a description of meteorological preconditions, such as the climatic conditions leading up to the event and the general circulation patterns. The event itself is characterised by its intensity, duration, spatial extent, and associated co-factors, such as precipitation and wind gusts.

Hazards	The hazards associated with the event may involve processes or cascading effects, such as flooding, sediment transport, river clogging, or collapsing trees.
Impacts	○ Immediate Impacts: Damage to buildings, infrastructure, people, and ecosystems. ○ Second-Order Impacts: These might include inaccessibility of areas, power outages, evacuations, healthcare system overloads, water supply interruptions, reduced water quality, and communication disruptions. Necessary response measures, such as evacuations, may also be described.
Post-Event	Potential long-term consequences are described, including prolonged damage to forests, buildings, and economies. Challenges for recovery are also highlighted, such as unfulfilled promises, insufficient insurance schemes, or the absence of "build-back-better" plans to improve resilience

Sources of knowledge for storyline development

Developing climate risk storylines follows the approach of constructing impact chains (Figure 3). This approach aligns with the IPCC and Disaster Risk Reduction (DRR) risk framework, which defines risk as a function of hazard, exposure, and vulnerability.

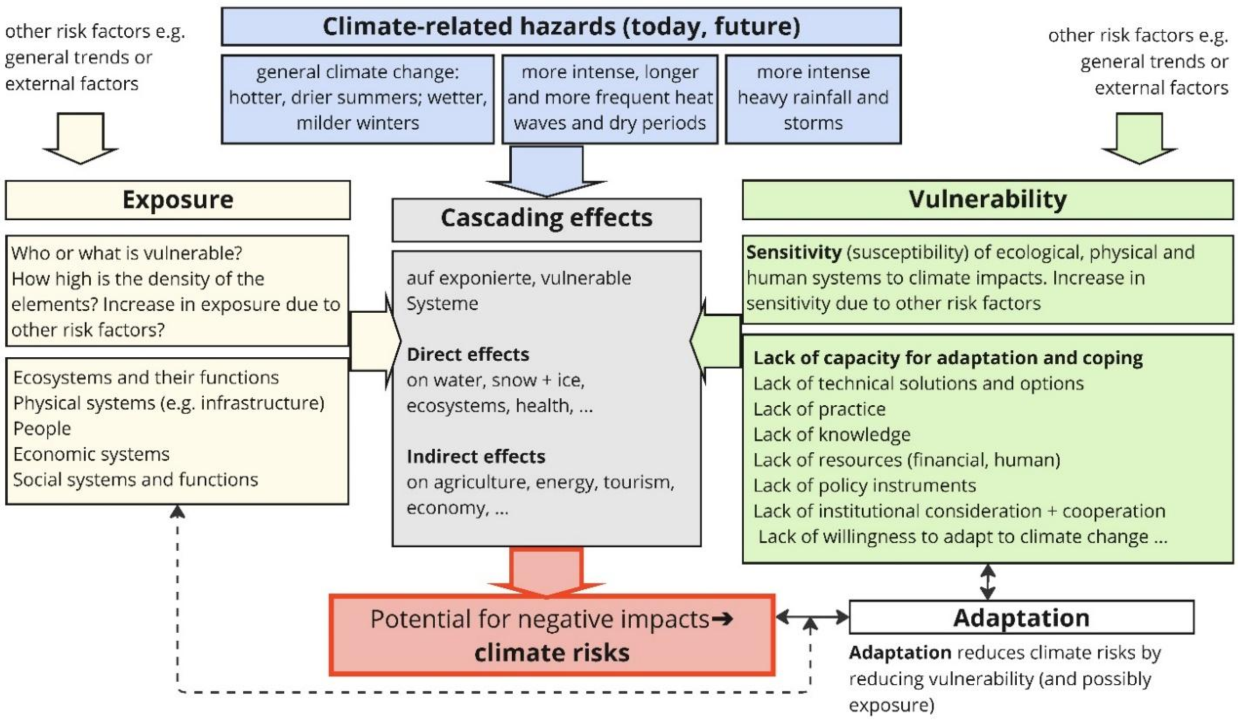

Figure 3: Visualisation of the concept of a climate risk impact chain

Climate risk storylines: Concept and knowledge sources

A climate risk storyline describes a hypothetical situation that, while never having occurred, could plausibly happen as a combination of climatic events and their cascading impacts. While the storyline should primarily be based on evidence or well-founded indications, it may inevitably include some "invented" elements to construct a complex, challenging, yet plausible scenario. The involvement of local experts is therefore essential in designing the storyline.

The storyline should depict an extreme, rather than a standard, scenario. For this purpose, a 100-year return period event is proposed for the year 2040, accompanied by cascading impacts and consequences that incorporate an element of "plausible bad luck." Additionally, a 300-year return period event may serve as a complementary "worst-case" scenario.

Scenarios concerning risk management responses (e.g., "How did we react?") do not need to be included within the storylines, as these are the focus of the discussions and assessments prompted by the storylines.

2.3. From local understanding to data driven models: development of an Alpine-wide mass movement impact model

The methodology used to develop the three mass movement impact models that form the basis of the Alpine wide mass movement impact sections of this report has been documented in detail in the companion D 2.1.1. Therefore, the methods are only briefly summarised here. For further details, including the use of process path areas and the methods used to evaluate model performance and variable importance, please refer to the above-mentioned report.

Using a dataset of landslides, debris flows and rockfalls from Austria and South Tyrol (2005-2021), three machine learning models have been developed within a risk framework to predict the societal impacts of extreme weather events. The models integrate meteorological, geological, hydrological and land-use data with asset exposure to train hierarchical generalised additive mixed models (GAMMs) at the sub-catchment scale. The models are used in this report to identify societal and environmental drivers alongside triggering conditions for mass movements and provide transferable insights applicable across the Alpine region to improve risk reduction measures. The models were developed at a half-basin scale (17,872 spatial units), focusing on process-relevant areas that represent the potential release areas and runout paths (Wichmann, 2017).

While the focus of D 2.1.1 was on understanding the environmental drivers of mass movement processes, the focus here is on understanding and modelling geomorphic impact events. This distinction reflects the "hazard" and "risk" focus of the two reports. Therefore, two additional variables for potentially exposed infrastructure are included in this report. The first is the number of buildings within the process path areas (PPA) per half-basin. The second exposure variable is the proportion of area occupied by roads within the PPA of each unit. Both variables are based on Open Street Map data.

3. Risk pathways: Results from the pilot analysis

Past and future risk factors were investigated for five pilot areas, and their sub-regions, in the Alps (Figure 4). The following subchapters provide an overview of the results of the pilot analyses with a focus on questions IV-VII of the risk questionnaire.

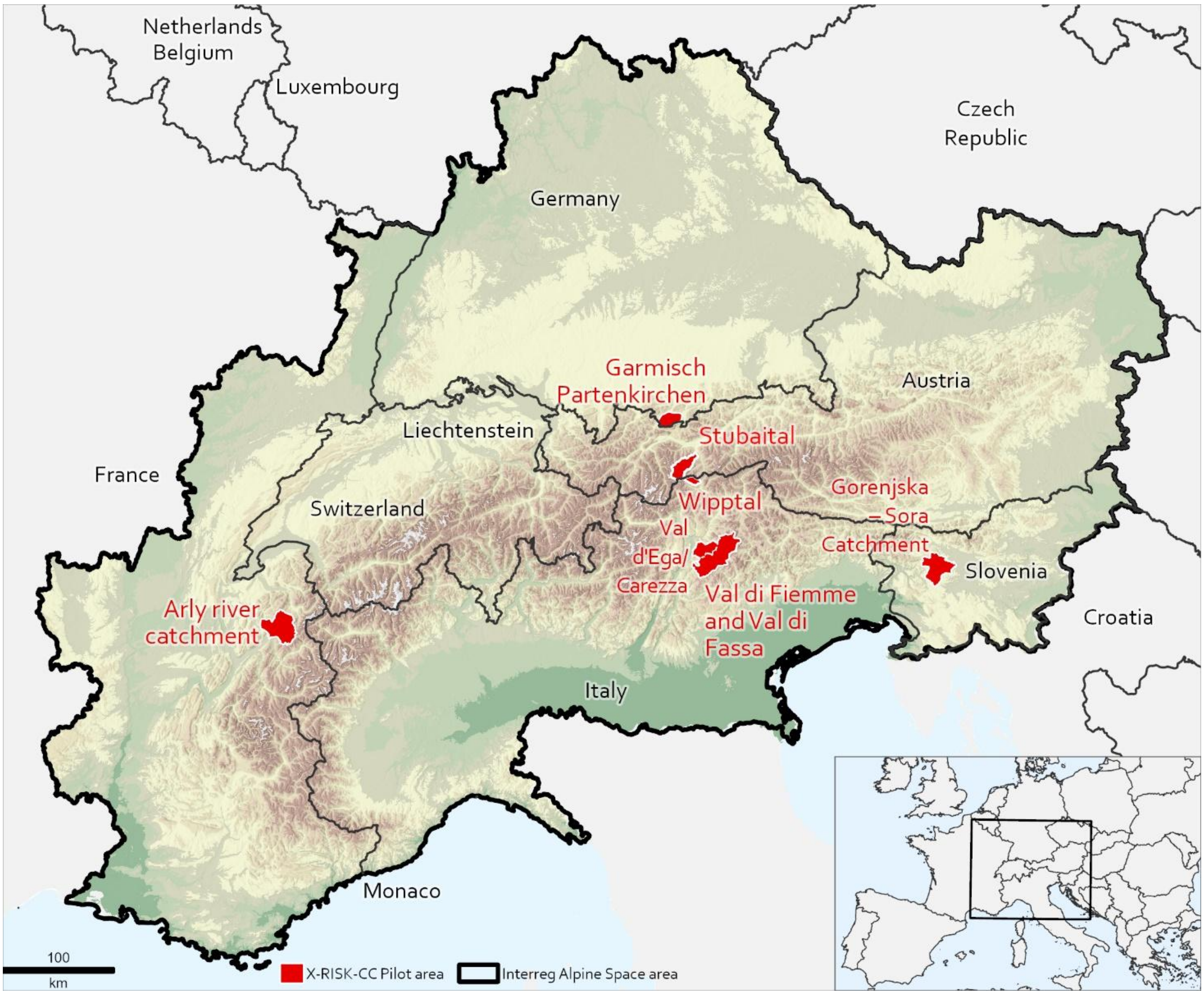

Figure 4: Map showing the location of the X-RISK-CC pilot areas

3.1. Gorenjska, Slovenia

In the Gorenjska pilot area, located in northwestern Slovenia in the eastern Alps, the risk assessment focused on two hazards: drought and flash floods. The impact chains and hazard analyses are presented in D 2.1.1. The following chapters describe the analyses conducted and results achieved regarding the risk components exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.1.1. Exposure and impacts

Past/present

Drought

The 512.5 km² pilot area, with a population of 43,276 (in 2024), is fully exposed to drought. Land use has a significant influence on impacts, particularly on agriculture, forestry, and public water supply.

Regarding agriculture, drought affects crops, increases irrigation costs (only one larger irrigation system – hilly terrain), and impacts livestock care. Agricultural land covers 25 % (125.3 km²), with grasslands and pastures dominating. In 2020, the area had 1,491 agricultural holdings, down from 1,627 in 2010. Damage data is collected only when drought is declared a national disaster, requiring losses exceeding 0.3 ‰ of GDP. Since 2005, data has been recorded in the national system for drought damage assessment in agriculture. Major droughts occurred in 2001, 2003, 2013, and 2022. In 2022, 55 km² (44 % of agricultural land) were affected, with damages totalling €2 million.

Concerning forestry, forests cover 71 % of the area, predominantly composed of conifers (60 % of the wood stock). While generally resilient, severe droughts can reduce fibre production and increase vulnerability to pests such as bark beetles.

With respect to public water supply, drought reduces water availability while increasing demand. The pilot area includes two large water supply systems and several smaller ones, with the latter being more vulnerable to drought. Larger systems benefit from multiple dispersed backup sources whereas some of smaller systems often rely on water deliveries during droughts.

Additional indirect impacts of extreme droughts, for which no data is available, likely include effects on ecosystems, such as lowland forests, wetlands, watercourses, and reducing available habitat for fish and invertebrates. Indirect effects may also occur in sectors like agriculture, forestry, public health, ecosystems, land use, and tourism. Minor impacts on infrastructure and buildings are expected due to more frequent, longer heatwaves and higher temperatures.

In the Sora catchment, past droughts likely affected forestry and agriculture, increasing plant and animal diseases and straining farmers' finances, necessitating state subsidies. Tourism in the area generates lower revenue compared to some other regions in Gorenjska (e.g., Bled), but is more boutique, sustainable and focuses on small businesses in mountain valleys (promotion of local characteristics and specialties, outdoor activities) and the town Škofja Loka. Although drought impacts on tourism are unreported, water shortages may pose challenges, and heatwaves likely reduced outdoor tourist activities. Skiing relies on snowmaking, using 8.5 % of water resources, which could be threatened by winter droughts or high temperatures.

At higher altitudes, drought and heatwaves have limited health impacts, but lower areas may experience effects similar to state-level trends. However, reliable data on this is lacking.

Flooding

For the flood risk assessment in the Sora catchment, we followed the method Flood Damage Reduction Analysis (FDA) (European Commission. Joint Research Centre., 2016), focusing on key elements: population, public activities, industry, agriculture, and infrastructure. Damage was assessed using spatial data (Real Estate Register, Building Cadastre) and flood extent models (Qn10, Qn100, Qn500) for current and future scenarios (RCP4.5 for 2100). The Joint Research Centre (JRC) method estimates direct damages based on building area and flood depth, using standardised damage curves and GDP-based adjustments for maximum damage.

Uncertainties include flood intrusion mechanisms, basement data, and indirect effects such as landslides or sewage impacts. Direct damages cover buildings, crops, livestock, and immediate health effects, while indirect damages, like production losses or intervention costs, are excluded from JRC's model. The method estimates 80 % of total damages by evaluating residential, commercial, and industrial buildings, roads, and agriculture. Parameters account for depreciation rates, material costs, and water height. Although standardised European damage curves are applied, Slovenia-specific curves remain limited due to inconsistent historical data.

Key sectors that are directly affected include:

- **Damaged or destroyed infrastructure and property:** The area is vital for the national road corridor, which is currently under review for road infrastructure upgrades. There is no railway infrastructure in the Sora catchment. The area is also home to many isolated villages and remote communities (accessibility, ensuring reliable connections).
- **Damaged agricultural land:** Flood events have resulted in significant challenges for agriculture, including the destruction and contamination of crops, as well as impaired cultivation due to debris deposition on arable land.
- **Damaged forest and ecosystems:** This issue is most prevalent along riparian zones, where extreme flooding leaves bare areas that are quickly overrun by invasive plant species. These invasive species outcompete and displace native vegetation, causing significant ecological imbalances.
- **Tourism:** Although not a primary focus in the Sora catchment, floods can disrupt tourism by restricting access to sites due to damaged transport routes. These disruptions result in economic losses for local businesses and communities dependent on tourism activities.
- **Interruption in power supply:** Main power lines were disrupted, requiring assistance from utility services and other support providers to restore electricity.
- **Fatalities:** During the 2007 event in Železniki, there were 3 fatalities, while a total of 6 lives were lost across Slovenia.

Potential future developments

<u>Drought</u>

Directly exposed elements:

- **Population:** The area's population is stable, with a slight increase expected to continue (Slovenia Statistical Office, 2024).
- **Agriculture and Forestry:** While agricultural land and holdings are expected to remain stable, the frequency and severity of extreme events are likely to increase the affected areas and economic damage. Current data does not allow for detailed future impact estimates.
- **Water Supply:** Increasing droughts and heatwaves are expected to cause more frequent and prolonged water supply interruptions, leading to a greater reliance on emergency water deliveries by fire brigade's trucks. Demand may rise fourfold during high-magnitude droughts. Water shortages could also hinder firefighting efforts.

Indirectly exposed elements:

Future exposure will depend on socio-economic resilience and adaptation measures. Without targeted programs outside agriculture, estimating indirect impacts is challenging.

- **Public Health:** Increased stress due to heatwaves and droughts.
- **Agriculture and Forestry:** Higher incidence of plant and animal diseases, invasive species, and ecosystem impacts.
- **Tourism:** Lower-altitude areas may suffer, while high-altitude enterprises could benefit from cooler conditions.
- **Infrastructure:** Compound drought-heatwave events may damage roads, railways, bridges, and energy networks.

Flooding

The population in the area is relatively stable, with a slight increase. The increase is most noticeable in the largest municipality, which is also the most urbanised and serves as the sub-regional centre of the area, with several educational facilities and services. It is expected that the population increase will not significantly affect the area's long-term vulnerability.

Directly exposed elements:

- **Population:** The area's population is stable, with a slight increase expected to continue (Slovenia Statistical Office, 2024).
- **Agriculture and Forestry:** Higher incidence of invasive species.
- **Tourism:** We do not anticipate a significant impact on tourism as a result of the floods.

Future exposure will depend on flood protection measures and adaptation measures.

3.1.2. Vulnerability

Past/present

Drought

Physical Vulnerability Factors

- **Public Water Supply:** Higher vulnerability of the local population and agriculture (water for irrigation) in areas reliant on shallow, small aquifers for drinking water and irrigation.
- **Agriculture:** Increased vulnerability in regions with gravelly soils, sunny slopes, and high-altitude farmlands. Water shortages for irrigation and in livestock farming are more likely in areas dependent on small aquifers.
- **Forestry:** Forests damaged by snowfall, windthrow, or fires are more susceptible to droughts, heatwaves, and bark beetle infestations.

Social Vulnerability Factors

- Lack of coordinated drought management protocols at local and national levels.
- Only 1.6 % of registered water usage is allocated for irrigation, despite the availability of renewable water.

- Agriculture is disadvantaged during water scarcity, as drinking water is prioritised, with no systemic regulation for other uses.
- Lack of adaptation measures, including vulnerability mapping, drought-resistant crops, water retention systems, and exploration of new water resources.
- Absence of impact-based forecasting.

Potential future developments

Drought

Social vulnerability to drought is most pronounced in the public health system, where the current impact of drought and heatwaves on mortality and chronic diseases remains unclear. There is no state-level data to downscale for the Sora catchment, and future impacts depend on the health system's adaptation to climate change. Given current trends and an aging population, the outlook is concerning.

Vulnerability also affects water supply and demand in the Sora catchment. Most water usage permits are for drinking water, with many small settlements dependent on water sources vulnerable to temperature increases due to their low yield and shallow recharge areas. In severe droughts, these sources may dry up.

The region's drinking water infrastructure, built when temperatures were lower and snow persisted longer, is also sensitive to heatwaves. Rising temperatures can affect pipes and reservoirs, potentially causing water contamination if system damage occurs. This could have significant socio-economic impacts, especially if it affects large populations.

Flooding

- Snow Precipitation and Coverage: Snow is a crucial retention mechanism, especially in high mountains as well as in ski resorts. A lack of snow will increase runoff in the catchment.
- Technical Floods: These floods result from the maintenance of flood control structures built between 1950 and 1970, which are nearing the end of their design lifespan. These structures were based on past return periods and event intensities, which may no longer be accurate.
- Urban Drainage and Flooding: Only one settlement has a large enough urban centre to develop specific urban runoff control measures. Urban drainage and flooding should be addressed in adaptation plans, especially considering climate change.

3.1.3. Risk Management

Drought

a) Current risk management measures

Preparedness for droughts depends on available data and forecasts, which help stakeholders respond effectively. The Slovenian Environment Agency (ARSO) developed the Sušomer (*Drought meter*) web application, which provides information on state of drought and forecast for topsoil, rivers, and groundwater. This tool is valuable, it could be enhanced with impact-based forecasts that involve all affected sectors.

In the event of water shortages, drinking water is delivered to residents, and reserve sources or usage restrictions are activated. Local water supply operators monitor both quality and quantity, while civil protection and firefighters are on standby for emergencies. The government assesses drought damage and provides reimbursement through civil protection and disaster relief agencies. Current protocols work for severe single events but are inadequate for extreme situations like earthquakes or compound events as extreme floods and landslides.

b) Potential future risk management measures

ARSO plans to expand Sušomer with additional data and stations. The potential for irrigation is high, it remains underutilised. The future development of irrigation systems, particularly in areas with large groundwater aquifers, could enhance agricultural resilience to droughts.

In dispersed settlements, water supply systems will be integrated into interconnected networks, although some areas may remain separate due to economic reasons. In such cases, resilience will be strengthened through the addition of reservoirs and improved intervention measures. Wastewater reuse also presents a valuable strategy for drought prevention.

Flooding

Risk management measures under the EU Floods Directive (2007/60) are in place, with the Ministry of Natural Resources and Spatial Planning and the water agency developing the National Flood Risk Reduction Plan (2023-2027). Several priority flood impact areas have been identified in the Sora catchment, including Železniki, which was heavily affected by the 2007 floods. Flood risk reduction measures have already been implemented, based on national spatial planning documents.

In 2013, the government issued a decree for the relocation of a road and flood protection in Železniki, aimed at protecting the settlement from 100-year floodwaters. The Ministry of Environment and Spatial Planning (MOP) initiated water arrangements, with the Water Directorate of Slovenia (DRSV) taking over in 2016. The Ministry of Infrastructure (DRSI) is responsible for the bypass road.

The water arrangements are divided into two phases: the first phase includes measures to increase flow rate and regulate the riverbed alongside the construction of the bypass road. The second phase involves measures at the reservoir. DRSV has been handling the permitting process, and after both phases are completed, Železniki will be protected from century floods. In April 2017, all three investors signed an agreement to jointly manage the permitting and construction process.

After the 2023 flood, a series of flood protection intervention are carried out on the Sora river and its tributary Poljanska Sora, mainly on the riverbed and the riparian zone, to reduce the risk to the population living along the river. They are led by Slovenian Water Agency (DRSV).

There is also a protection and rescue plan for the immediate response phase in the event of natural disasters, which is currently being updated and improved based on the experience of recent years.

3.2. Garmisch-Partenkirchen, Germany

The Garmisch-Partenkirchen pilot area is located in southern Germany within the central Alps. The main river in the pilot area is the Partnach. The risk assessment focused on compound cascading gravitational mass movements and floods. The impact chain and hazard analysis are presented in

D 2.1.1. The following chapters describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.2.1. Exposure and impacts

Past/present

Extreme precipitation events have caused hazards such as flooding and rockfalls in the Partnach Gorge and Garmisch-Partenkirchen. The Partnach Gorge has experienced flash floods in 1999, 2005, 2010, 2013, 2015, 2017, 2018, 2020, and 2021, along with rockfalls in 1991, 2003, 2017, and 2023.

In 2022, approximately 430,000 people visited the Gorge, primarily during summer. Access is regulated via a turnstile system, with approximately 1,850 daily visitors. The path spans 699 meters in length and rises 80 meters in altitude. Some sections of the path are at risk of flooding, particularly where the path is within 2 meters of the water level. Floods caused by heavy rainfall or blockages could expose an average of 7 visitors per hour to risk. However, the gorge management can evacuate visitors quickly if flooding occurs gradually. Sudden floods, such as in 2018, pose greater risk, with evacuation sometimes difficult.

The Gorge infrastructure includes the entrance, turnstile system, hiking path, and emergency call system. Repair costs vary, with major events resulting in significant expenses for debris removal and slope repairs. Closures of the Gorge for safety or repair work lead to revenue losses from ticket sales.

Direct impacts:

The Gorge's role as a tourist destination affects nearby infrastructure, including hiking paths and inns. Closures can reduce tourism revenue, although visitor numbers have steadily increased, even after a 6-week closure in 2018 due to flood damage.

Garmisch-Partenkirchen faces flooding risks from multiple streams. After the 1999 floods, measures were implemented to protect the city from a 100-year flood event involving two rivers. The current exposure assessment is based on the 2018 update of the Basic European Assets Map (BEAM) dataset (https://emergency.copernicus.eu/mapping/ems/basic-european-assets-map-germany) and official flood hazard maps for frequent and extreme events at these streams. Additionally, we assessed the effects of a compound flood event, where discharge diversion from both rivers might become infeasible.

The BEAM dataset includes information on the following asset distributed over various land-use classes: Buildings, agriculture, industry, services, vehicles and population.

Additionally, the dataset provides asset values in €/m² (2018 prices) for various land-use classes. These values are updated using a mixed index of construction prices and consumer prices. The asset values are thus adjusted upward by 39 % to 2023 prices. The mixed index reflects that most flood damage (about 80 %) affects building structures rather than contents.

In the damage calculation, the highest asset values are assigned to services, followed by buildings and industry. Building assets are concentrated in urban areas, while industrial and service assets are primarily in industrial zones, with some overlap in urban areas. Vehicle assets are distributed across urban, industrial, and infrastructure areas. Vulnerability varies across exposure classes, such as between private buildings and household contents.

Indirect impacts of hazard events can exacerbate response and recovery efforts, increasing overall monetary losses. Key sectors potentially affected include:

- Mobility: Garmisch-Partenkirchen is vital for transalpine traffic. Past events, like the 2019 floods, have disrupted road access and caused train service interruptions.
- Tourism: Localised events, such as those affecting the Partnach Gorge, can reduce tourism and spending. Larger events may also impact hotel availability, restaurants, and overall accessibility.

Potential future developments

Future exposure in Garmisch-Partenkirchen is shaped by various developments that may increase or decrease risk:

- Population: Between 2014 to 2023, the population grew from 28,200 to 29,700. By 2050, projections estimate a population of 33,100. The elderly population, more vulnerable to flooding, is expected to rise significantly.
- Settlement Development: Future exposure depends on settlement growth in hazard-prone areas. An increase in population or assets within these zones would elevate the risk.
- Tourism: While overall tourism may rise, visits to the Partnach Gorge are unlikely to increase significantly due to capacity limits and ongoing discussions about managing visitor numbers.
- Traffic: Traffic volumes along two main roads may decline due to two new bypass tunnels under construction and planning.

3.2.2. Vulnerability

Past/present

The Partnach Gorge is accessible to visitors without experience in mountain hazards, making them unaware of the risks associated with extreme precipitation.

- Vulnerability of People: The gorge manager closely monitors risks and restricts access if extreme weather threatens visitor safety. There have been no flood-related casualties in the gorge, though scenarios involving rapid water level rises (e.g., logjams or damming) pose significant danger. Past events, such as in 2018, demonstrate that visitors can evacuate; however, the high velocity of the Partnach River means that even shallow floods could be fatal for those caught in them.
- Vulnerability of Infrastructure:
  - Damage to the gorge can include erosion and debris accumulation.
  - In the city, flood damage to buildings, agriculture, and industry depends on the inundation depth and other hazard factors such as flow velocity and sediment transport.
- Vulnerability by Exposure Category:
  - Buildings: Vulnerability is based on factors such as construction materials, age, and presence of basements.

  - Contents: Household items are more vulnerable than buildings and can be destroyed by even minor flooding.
  - Industry: Industrial buildings and equipment are highly vulnerable, especially at ground level.
  - Services: Similar to industrial assets, but with greater vulnerability for retail stock.
  - Agriculture: Vulnerable, especially for items stored at ground level.
  - Vehicles: Vulnerable to flooding, with an estimated 30% vehicles damaged due to evacuation possibilities.
- Vulnerability Factors: Flow velocity, sediment, and water rise rates are critical, with prior flood experience and timely warnings helping to mitigate vulnerability. Social factors like wealth, health, and social capital also influence vulnerability.

The impact on people is assessed using population data from the BEAM dataset. A 2.2 % population increase between 2018 and 2023 is applied to affected populations based on density.

- Physical Vulnerability: People are most vulnerable to high water depths and flow velocities. Even at depths of less than 1m, speeds exceeding 1 m/s can be critical, while mountain floods can surpass 3 m/s. Vulnerability increases if people do not evacuate to higher floors.
- Social Vulnerability Factors: Key factors include demographics, wealth, occupation, knowledge, health, housing, social capital, and access to infrastructure, such as transportation and services

Potential future developments

Overall, the Partnach gorge will become safer due to improved management. Vulnerabilities in Garmisch are unlikely to change significantly. Developments in exposure and hazard factors are expected to be more dominant. The impact of improved preparedness and response is difficult to assess.

3.2.3. Risk Management

The Partnach Gorge and its surroundings are managed by the Gorge Management team and are closely monitored.

- **Hydrological Hazards:** Water levels are monitored at the gauging station and via cameras at the Gorge exits. Exceeding threshold levels and precipitation forecasts trigger alerts. After the 1991 rockfall, flow patterns changed, leading to flood protections such as concrete railing.
- **Gravitational Hazards:** Slope protections are in place both upstream and downstream. After the 2018 flood, repairs included embankments and new path construction. Avalanche and debris barriers protect paths upstream.
- **Forest Management:** Deadwood removal prevents driftwood accumulation and potential logjams.
- **Access Control:** The turnstile entry system can close access during threats, and emergency call points were added after the 2021 flood.

Following the 1999 floods, Garmisch-Partenkirchen implemented comprehensive flood protection measures, including:

- A retention basin, raised embankments, and widened channels manage floodwaters, with a diversion structure directing excess water to the Partnach.
- Raised embankments and adapted channels to safely discharge floodwaters.

3.2.4. Potential future impacts of compound/cascading hazard events

Regarding sediment-laden flow risks, the following future impacts are possible.

- Increased probability, e.g., due to the following scenarios:
    - Sediment-laden flows damming from landslide
    - Post-wildfire debris flows
- Different impacts compared to (flash) floods. More erosion damage (channel widening) is expected downstream of the gorge.
- Greater damage is expected in the gorge, with higher efforts required for post-event recovery. How will the debris inside the gorge be removed?
- Buildings and infrastructure that are located in the hazard area are likely to experience larger damages.
- Possibly destruction of flood mitigation measures along the Partnach. How should the increased risk be managed after the destruction?
- To maintain the current level of debris flow risk in the gorge, extensive investments in managing debris upstream of the gorge are expected.

3.3. Stubaital, Austria

Stubaital is the Austrian part of the Wipptal/Stubaital pilot area. It is located in western Austria, in the central Alps. The main river is called Ruetz. The risk assessment focused on gravitational mass movements. The impact chain and hazard analysis are presented in D 2.1.1. The following sections describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.3.1. Exposure and impacts

Past/present

Exposed elements at risk were identified through the intersection of hazard zones with land use data, using the Basic European Assets Map (BEAM). BEAM provides regional data on population density, building values, and land use, but lacks local vulnerability details. Direct costs were calculated using GIS, assuming destruction levels of 0.8 (red hazard zones) and 0.3 (yellow hazard zones). Mobile elements' variable exposure is not considered, as BEAM provides only average values. Hazard zone maps exclude non-settled areas, such as roads and trails.

Indirect costs, including business interruptions and intangible impacts (e.g., on health or the environment), require socio-economic data that is unavailable. Mitigation measures have reduced affected areas and stabilised costs in some catchments but rising event frequencies are increasing casualty risks. Inaccuracies in BEAM, such as undervaluing retention basins, may lead to underestimated costs. Event costs recalculated from BEAM align with reported figures, confirming the method's reliability.

The results determined by the introduced method include:

- Affected areas for the red and yellow hazard zones (Table 3),
- Affected values in the red and yellow hazard zones (Table 4) and
- Development of likelihood of casualties (Table 5).

Since the current likelihood of casualties is unknown or not quantifiable with currently available data, only the projected development of people at risk can be determined.

The analysis showed varying impacts across catchments:

- Grawanockbach: Mitigation measures reduced affected areas; hence annual costs did not change (Table 4). However, more frequent events could increase casualty risks (Table 5) without additional measures like road closures controlled by an early warning system.
- Margaretenbach: Rezoning significantly increased areas at risk and annual costs (Table 3 and Table 4), with rising risks in the enlarged yellow zones.
- Mühltalbach, Mutterbergbach, Oberbergbach: Moderate cost increases due to low value affected areas, but event frequency increases risks (Table 3 and Table 4). In Oberbergbach, retention basins are undervalued in the BEAM dataset, potentially underestimating costs.

Table 3: Affected area (m²) of events in the five catchments, hazard zones (red/yellow) and the current frequency/magnitude (GZP), the frequency/magnitude estimated 2050 (xrisk) and the calculated difference (Diff).

[m^2]	GZP red	GZP yel	**sum**	*xrisk red*	*xrisk yel*	***sum***	***Diff***
Grawanockbach	51355	16847	**68202**	30629	16716	**47345**	**-20857**
Margaretenbach	11120	2352	**13472**	27535	43638	**71173**	**57702**
Mühltalbach	11904	40162	**52066**	15649	38003	**53652**	**1586**
Mutterbergbach	34565	20499	**55064**	38184	16953	**55136**	**72**
Oberbergbach	305192	227297	**532489**	320264	227297	**547561**	**15072**

Table 4: Annual direct average costs of events in the five catchments for the hazard zones (red/yellow) and the current frequency/magnitude (GZP), the frequency/magnitude estimated 2050 (xrisk) and the calculated difference (Diff).

[€/year]	GZP red	GZP yel	**sum**	*xrisk red*	*xrisk yel*	***sum***	***Diff***
Grawanockbach	1916	310	**2226**	1935	129	**2063**	**-162**
Margaretenbach	35553	2915	**38468**	68462	53900	**122362**	**83894**
Mühltalbach	7365	5252	**12617**	11092	4575	**15666**	**3049**
Mutterbergbach	66483	15155	**81638**	68635	14348	**82983**	**1345**
Oberbergbach	55976	24407	**80383**	58808	24407	**83214**	**2832**

Table 5: Semiquantitative estimation on the development of people at risk (P) in the red and yellow zones in 2050

	A GZP red	A GZP yel	Δ A red	Δ A yel	rel. red	rel. yel	P red	P yel
Grawanockbach	51355	16847	-20725	-132	-0.40	-0.01	**2.6**	**3.0**
Margaretenbach	11120	2352	16415	41286	1.48	17.55	**4.5**	**20.6**
Mühltalbach	11904	40162	3745	-2159	0.31	-0.05	**3.3**	**2.9**
Mutterbergbach	34565	20499	3618	-3546	0.10	-0.17	**3.1**	**2.8**
Oberbergbach	305192	227297	15072	0	0.05	0.00	**3.0**	**3.0**

Indirect costs (e.g., business interruptions and intangible losses) require detailed socio-economic data, unavailable for this study area.

Likelihood of Casualties: Current values are undeterminable, but development trends indicate increasing risks due to event frequency and expanded hazard zones.

Mitigation Measures: Effective but require adaptation and maintenance to counter rising event frequency.

Recalculated event costs align with observed figures, confirming reliability.

Potential future developments

Projected climate change impacts are expected to triple event frequency in hazard zones, adding new areas at risk. Casualty risks are likely to increase due to higher event frequency and expanded hazard zones unless additional mitigation measures, such as early warning systems or road closures, are implemented.

A semi-quantitative method estimated future casualty risks by combining hazard zones with projected changes, emphasising the need for detailed local data to refine the assessment. The results suggest that areas with current mitigation measures require continued adaptation and maintenance to manage increasing hazard frequencies.

Indirect costs remain unquantified due to a lack of socio-economic data.

Reliable predictions for the future development of infrastructure in the pilot area are not currently available. Instead, population growth forecasts were used due to their significant influence on infrastructure development. Over the past century, the communities experienced notable population growth, resulting in a substantial increase in exposure elements potentially at risk. in the three municipalities of the catchments, growth is evident; in one municipality, the population tripled between 1971 and 2021. This rise is linked to growing population density and the increasing value of buildings, households, industries, vehicles, and other assets (Source: http://www.bevoelkerung.at). Furthermore, summer tourism has expanded significantly in the Stubaital region, increasing from approximately 3 million arrivals and 21 million overnight stays annually to over 6 million arrivals and 23 million overnight stays (Land Tirol, 2024). Leisure activities in Alpine terrain are increasing, especially in areas like the Stubaital, where rising temperatures contribute to higher summer tourism. Between 2005 and 2015, overnight stays in North and South Tyrol's core Alpine regions grew by 10 %. Tourist developments, such as gondola stations and leisure parks, raise infrastructure and visitor exposure.

3.3.2. Vulnerability

Past/present

Debris flow and flooding events predominantly affect summer tourism, particularly hikers and cyclists in unprotected areas. While extreme precipitation likely keeps people indoors, those in accommodations or travelling to tour starting points may still face risks.

In Austria, damages caused by natural hazards such as flooding or debris flows are only partially covered by insurance, and relevant information is usually not available. Event documentation typically does not include spatially allocated costs that could be correlated with the spatial classification of the BEAM dataset.

Potential future developments

The vulnerability in the pilot area is assumed to remain constant.

3.3.3. Risk Management

Past/present

Austrian hazard zone maps are created using event chronicles, field surveys, and increasingly, modelling. The WLV maintains an event register (WLK) for damage documentation, with detailed analyses conducted for major events. Hazard zone maps are expert reports with predictive value, aiding the WLV in planning and prioritising mitigation measures while informing spatial planning at federal and municipal levels. These legally binding maps focus on hazards, partially considering risks based on potential damages.

Since 1970, WLV experts have compiled hazard zone maps, updated continuously, and made freely accessible to municipalities or via federal state GIS. Maps cover relevant areas at a slope scale of at least 1:5,000, identifying red zones (building prohibited) and yellow zones (restricted settlement development) for avalanches, flooding, sediment transport, and debris flows. Other hazards, like landslides and rockfalls, are shown as brown reference areas requiring further investigation.

These maps are a proven, widely accepted planning tool. However, introducing new instruments, such as risk planning, faces resistance due to potential socio-economic impacts and conflicts of interest. Hazard maps also guide emergency services, indicating hazard levels and necessary measures (e.g., evacuation). Balancing safety and development needs is crucial, as communities require opportunities for economic growth alongside risk mitigation.

Municipalities are responsible for local security, rescue, and disaster mitigation during natural hazard events. They manage resources, train staff, and coordinate multiple actors, including torrent and avalanche control, state geology, and local authorities. Fire stations often serve as operation centres, concentrating decades of experience.

Emergency plans link preparedness and response in the risk management cycle. Fire brigades and civil protection organisations play key roles in both event response and awareness-raising. Networking and coordination among stakeholders are essential.

The Regional Centre for Crisis and Disaster Management provides a model disaster prevention plan template, adaptable to local conditions. Hazard surveys and risk analyses are the foundation of these plans. Torrents are inspected annually and after heavy rain by local forest rangers to assess maintenance needs for structures and stream channels.

The disaster prevention plan includes:

- A description of local features (e.g., accessibility, economy, tourism challenges)
- A hazard catalogue with risk assessments of natural and technical hazards
- Legal frameworks for civil protection organization
- Checklists and flowcharts for risks (e.g., floods, blackouts, earthquakes, traffic accidents)
- Emergency contacts and communication protocols for decision-making under pressure, typically led by the mayor
- Public warning systems and press coordination
- Lists of emergency personnel, accommodation resources, and evacuation plans
- Inventories of critical buildings, support operations, and protective structures
- Alarm plans and sample forms

Risk assessments were conducted for all municipalities in the region around 2015. However, the risk matrix does not account for ongoing changes and is recommended for review every 5–6 years. The region provides crisis management seminars, covering emergency team structuring and disaster planning. Joint exercises foster familiarity and preparedness. While Stubaital municipalities have emergency plans, some processes overly depend on individuals, necessitating written, person-independent checklists.

Forest Management

Locally adapted forest stands mitigate torrential damage. Forest rangers work under the District Forest Inspection (BFI) to promote resilient forests, focusing on mixed tree species (e.g., larch, walnut) and shrub vegetation. Reforestation with spruce is no longer subsidised. Landowners must reforest damaged areas, and pasturing in reforested zones is banned to prevent long-term harm. Fragmented forest ownership poses challenges, but BFI provides technical support and funding assistance, ensuring effective cooperation in Stubaital.

Weather Forecasting

Weather forecasts, provided via the Weather Box of the region, inform risk management. Data includes expert analysis and high-resolution (1x1 km²) nowcasting from GeoSphere Austria (GSA). However, forecast accuracy for precipitation in mountainous terrain remains low. Warnings are issued via SMS or direct contact but require tailored responses. Small-area events, such as the 2022 Stubaital thunderstorm, are difficult to predict precisely.

Collaboration and Resources

Competent personnel, including volunteers (e.g., fire brigades, Red Cross), are critical. Austria's volunteer system requires supportive policies (e.g., employee leave for emergencies). The military assists if disasters exceed local resources. Coordination between emergency management and services is vital, ensuring smooth implementation of measures like roadblocks and evacuations. Essential tools and equipment are provided by public and private entities, with necessary contacts established in the test areas.

Potential future developments

Risk Management Analysis and Improvements

Conducting workshops to evaluate risk management during July 2022 events. Participants identified deficits and proposed future improvements, presenting findings in plenary sessions. We also consulted mayors (Summer 2024) to gather their assessments. We reviewed event records from post-2022 damage events and discussed with BFI in order to gain insights into forest conditions. The following actions to improve risk management were gathered:

Scenarios

Hazard maps are static and focus on spatial planning, not accounting for changes like climate or land use. While modules incorporating risk scenarios could aid decision-makers, uncertainty complicates practical use. Enhancing hazard maps with better methods, event documentation, and accurate spatial data can improve utility.

Early Warning Systems

Existing protective measures are often insufficient for future needs. Temporary protective measures require reliable early warnings, which are currently absent in the catchments. The existing warning systems for Debris Flow have high accuracy but short lead times (minutes) for limited actions like traffic control are needed. Also existing are rainfall thresholds that use real-time or forecasted data for longer lead times but lower accuracy. Efforts to refine spatial warnings are ongoing, and these systems could enhance road safety if high positional accuracy is achieved.

Involving the Local Population

Civic participation has grown in importance, enhancing risk awareness, especially concerning climate change. Efforts include raising awareness, involving citizens in disaster exercises, and utilising their event documentation. Young people's education (e.g., school projects) boosts hazard awareness. However, some groups lack experience with local risks. Clear communication of residual risks is crucial, especially for tourist-heavy areas in Stubaital, requiring diverse information channels. Onlookers often hinder emergency services, necessitating clear warnings and personal responsibility.

Strengthening Risk Awareness

Emergency plans must ensure access to equipment and pre-identified debris deposit areas. Sharing resources across regions and planning depositional areas in advance can streamline responses, but legal, environmental, and compensation issues must be addressed.

Reviewing Past Events

Operational and lessons-learned protocols guide future responses. While municipalities with frequent disasters share valuable knowledge, those facing new challenges from climate change could benefit from this experience.

Financial Risk Management

Financial aspects often overwhelm municipal authorities, with fragmented processes for private and public damages. A centralised unit to manage funding and settlements could provide structural support. Uniform natural hazard insurance (as in Switzerland) and short-term liquidity options like

Kontokorrent loans could reduce financial vulnerability. Early investment in risk cycle measures saves recovery costs.

Current impacts of compound/cascading hazard events

Compound events occur due to shared meteorological triggers or the region's susceptibility to multiple hazards. Examples include:

- Debris flow material entering water, potentially blocking rivers and causing dam breakage.
- Rockfalls or landslides blocking channels, triggering debris flows.
- Windthrows causing woody debris blockages.
- Deforested areas from windthrows, forest fires, or bark beetles leading to:
  - Increased erosion and landslide activity, adding sediment to torrent channels.
  - Higher surface runoff, increasing sediment transport capacity.

Difficult reforestation may extend the period of heightened natural hazard risk. The current probability of compound events is assessed in D 2.1.1 as part of hazard zone mapping.

Temperature Rise and Permafrost Degradation: Permafrost's impact on debris supply depends on the type of torrential system:

- Transport capacity-limited torrents: Sediment supply is unlimited, and runoff increase alone triggers debris flow activity.
- Debris-limited torrents: More sediment increases both debris flow frequency and magnitude.

Permafrost degradation influences debris supply via:

- Rock walls and glaciers destabilizing.
- Melting interstitial ice reducing cohesion, making debris more mobile.
- Changes in water supply, either limiting infiltration or providing more water.

Temperature rise and reduced snow cover buffering accelerate runoff during the thunderstorm season, increasing peak discharge. Runoff delay depends on snow depth, with deeper snow delaying runoff. Frozen soil results in lower runoff, influenced by snow water equivalent, liquid content, and snow density.

Runoff Coefficients

The runoff coefficients in the experiments ranged from 0.4 to 0.8. The reduction depends not only on snow parameters but also on the snow-covered area and the difference in runoff coefficients between snow-covered and snow-free areas.

Temperature Rise, Drought, and Forest Destabilisation

Rising temperatures weaken forests, making them less adapted to site conditions and improving reproduction conditions for insects. Windthrows and mass reproduction of destructive insects, like the spruce bark beetle, create significant hazard potential. In the pilot area, where spruce forests dominate, bark beetle infestations are increasing. Longer droughts further weaken trees, and combined with factors like windthrows and forest pests, may reduce root reinforcement, increasing the risk of debris flows due to impacts such as landslides and woody debris. Windthrow, forest fires, and pests, such as bark beetles and fungal infestations, amplify debris flow risk. Since 2017, frequent windthrows in the Stubaital have caused significant forest damage, including 35 ha in July 2023, with wind gusts of up to 240 km/h. These conditions contribute to the mass reproduction of pests like Hylobius abietis, further damaging forests. Snow breakage at higher altitudes due to wet snow also affects trees, like oaks in 2018. The damaged timber causes economic losses, with high harvesting and transport costs that may lead to untreated areas, increasing hazard potential.

Increased Risk of Forest Fires

Forest fires have a minor role in the Stubaital, but droughts are expected to increase fire risk. Reforestation on south-facing slopes is difficult, reducing protective effects. Post-fire root reinforcement initially remains but decreases over time, limiting mitigation options. Wildfires are not expected to significantly impact torrential processes in the future.

3.4. Wipptal, Italy

Wipptal is the Italian part of the Wipptal/Stubaital pilot area. It is located in northern Italy, in central-eastern Alps. It covers the valley of Pflerscherbach/Rio di Fleres. The risk assessment focused on compound debris flows and river flooding. The impact chain and hazard analysis are presented in D 2.1.1. The following chapters describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.4.1. Exposure and impacts

Past/present

Key exposed elements include private properties, agricultural land, infrastructure, and tourism assets, primarily located in areas prone to flooding and debris deposition during extreme events. Roads, bridges, and energy infrastructure are critical, as their damage can cause indirect impacts to other assets. The following checklist outlines the assets damaged during the heavy rainfall event on August 16th, 2021.

Directly exposed elements

The directly exposed elements are those at risk of direct damage from floods, flash floods, or mass movements. We intersected the spatial locations of the different elements with the available hazard maps by the municipality, to assess the presence or absence of the element in a hazard zone (Table 6).

Table 6: Table listing the directly exposed elements in Wipptal and the areas affected during the event

Exposure element	Exposure description and elements affected by the past event
People	The Brenner municipality and Fleres valley are residential and tourist areas. Population data shows an increase in both residents and tourists over the last 20 years, with the population doubling during peak tourist seasons. During the August 16, 2021, event, 30 people were evacuated as a precaution.
Vehicles	Four vehicles were damaged during the August 16, 2021, event
Roads and Bridges	The Fleres valley has 264 km of roads, 45 % of which intersect hazard zones, and 34 bridges. The main road was blocked by debris during the event, isolating upper villages.

Buildings	Of the 630 buildings in the valley, only 32 % are outside hazard zones. Most buildings predate hazard planning. Five were damaged during the August 16, 2021, debris flow.
Infrastructure and Energy Supply	The valley contains 50 km of infrastructure lines, including aqueducts, sewerage, and power lines, with most located in hazard zones. The August 16, 2021, event damaged a power plant, disrupting electricity in some villages.
Tourism and Recreation	About 7 hectares are dedicated to tourism and sports, mostly in low-hazard areas.
Agricultural Land	Agriculture spans the valley bottoms and slopes, with 70 % of livestock farms in hazard zones. The August 16 event affected 5,261 m² of agricultural land and five agricultural buildings.

Overall, most buildings, infrastructure, and farms (70 %) are located in hazard zones (mostly medium and high), primarily at the valley bottom, where risks are highest. Roads and agricultural areas are more dispersed throughout the region.

Indirectly exposed elements

Some exposed elements face direct and indirect impacts from hazards (Table 7).

Table 7: Table listing the indirectly exposed elements in Wipptal and the areas affected during the event

Exposure element	Exposure description and elements affected by the past event
People and Villages	Road damage or flooding disrupts movement and isolates villages. During the August 16 event, 30 people were evacuated.
Tourism	Indirect impacts include damage to host facilities (e.g., hotels) or road and trail disruptions. Facility damage can take months to repair, while trail or road issues are usually shorter-term.
Economic Activities	Damaged energy infrastructure affects businesses, especially those relying on cooling systems for livestock and food supply.

Potential future developments

The municipal urban plan designates areas for new construction, referred to as "completion zones" and "expansion zones." In the Fleres Valley, eight such areas, covering a total of 7.5 hectares, are allocated for development. Although these zones are located within hazard zones, they exclude class 4 hazard zones where construction is prohibited. The inclusion of expansion zones within hazard areas reflects the valley's geographic constraints, characterised by steep slopes and limited flat land.

Currently, 95 % of these expansion areas have been developed, leaving only 5 % available for future construction. With a growing population and increasing tourism demand, further development may be necessary. However, the tourism sector is expected to prioritise improving service quality rather than expanding capacity, which could stabilise or slightly reduce visitor numbers.

A significant concern for future development is the potential escalation of hazard risks. If the hazard frequency and intensity of hazards increase, areas currently classified as hazard zone class 3—accounting for 40 % of the expansion zones—could be reclassified as hazard zone class 4, where construction is prohibited.

Data from ASTAT (the regional statistical office) shows a steady increase in both residents and tourists over the past 20 years, indicating that a larger population could be at risk from intensified hazard events.

3.4.2. Vulnerability

Past/present

Quantifying vulnerability is complex, and in South Tyrol, it is typically assigned a value of 1 for simplicity, representing a worst-case scenario. The 16th of August 2021 event revealed both physical vulnerabilities, such as sediment availability and steep slopes, and social vulnerabilities, such as inadequate multi-risk management and insufficient protection plans. Existing hazard maps do not account for compounded risks, such as river blockage leading to flooding.

Potential future developments

Vulnerability is set to the maximum value (1) across the province and is not expected to change unless the calculation method is updated. Changes in predisposing factors depend on land use evolution, such as glacier melt increasing sediment availability or improved forest management reducing deadwood in channels.

Risk management is evolving, with increased focus on compound and cascading events, awareness of rising hazard intensity due to climate change, and greater public awareness of risk, all of which could reduce vulnerability.

3.4.3. Risk Management

Risk management measures are categorised into the four phases: prevention, preparedness, response, and recovery.

Prevention
Prevention measures include both structural and non-structural approaches.

- **Structural Measures**: The Wipptal area has 317 protection structures: 185 for hydraulic hazards, 103 for avalanches, and 29 for rockfall. Hydraulic protection structures are the most numerous, likely due to the significant exposure of agricultural and industrial land to hydraulic hazards. These structures focus on water management and protecting economic activities and infrastructure.
- **Non-Structural Measures**: Non-structural prevention primarily involves planning instruments, such as the Hazard Zone Plan. This plan evaluates hydrogeological hazards (mass movements, hydraulic hazards, and avalanches) at the municipal level, providing hazard maps, reports, and specific planning legislation. For example, new construction is prohibited in hazard zone class 4, red-zone areas, where hazards are most intense.

Preparedness
The Autonomous Province of Bozen – Bolzano has developed a Risk Map to comply with national and provincial legislation. This map prioritises the protection of existing exposed elements and

guides municipalities and risk managers. Since urban development can change the distribution of risks, the map serves as a snapshot and requires regular updates. It functions as an indicator for mitigation measures, including both passive (e.g., urban planning) and active (e.g., structural interventions) strategies.

Response

The Civil Protection Plan, developed during the prevention phase, helps manage emergencies and protect people, property, and services. Most South Tyrolean municipalities already have a customised plan with clear instructions for handling potential critical situations. For some municipalities the Civil Protection Plan is still in development. Volunteer organisations like firefighters, the Red Cross, and mountain rescue teams provide immediate assistance, secure affected areas, and support evacuation and relief efforts.

Recovery

The Province allocates various funds and resources for reconstruction after extreme events. These funds, managed by specific offices (e.g., agricultural funds by the Agricultural Service), target municipalities, public associations, private citizens, and farmers, depending on the intervention needs.

3.5. Val d’Ega/Carezza, Italy

Val d’Ega/Carezza is the portion of the pilot area of Storm Vaia located in the Autonomous Province of Bolzano/Bozen (northern Italy, central-eastern Alps). The risk assessment focused on compound windstorm and heavy rain event. The impact chain and hazard analysis are presented in D 2.1.1. The following chapters describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.5.1. Exposure and impacts

Past/present

The pilot area encompasses three municipalities in a mountainous region, featuring villages, agricultural land, forests, and pastures. It is a popular tourist destination, especially during the winter and summer seasons. Key exposed elements include private properties, agricultural land, infrastructure, and tourist facilities, along with roads, bridges, and energy supply systems.

The Vaia storm (27–30 October 2018) caused in Val d’Ega/Carezza no reported impacts on buildings or people but did damage some roads and infrastructure. Approximately 70-75 % of the area is forested, providing protection against hazards. During the storm, about 25 % of the forest was damaged by wind, with both direct and indirect impacts detailed subsequently. We assessed the exposed elements that could be directly damaged by wind, flooding, or mass movement, superimposing hazard maps for analysis (Table 8).

Table 8: Vaia Storm: Exposure and impacts across sectors in Val d'Ega/Carezza

Exposure element	Exposure description and elements affected by the past event
People	The population has been increasing with tourists significantly raising the population during the peak seasons but also outside winter and summer months (i.e. in autumn).
Vehicles	Vehicles are mobile and difficult to track, but no data on vehicles damage were available from the Vaia storm.
Roads and Bridges	The area has two main roads connecting the municipalities to the valley and other regions. The total road network is about 1,556 km, with 15 % intersecting hazard areas. During the Vaia storm, roads and bridges were damaged, complicating connections between villages.
Buildings	There are 4,198 buildings in the area, with commercial and service buildings being the most common. Approximately 18 % of the buildings are located in hazard zones. No damage to buildings from the storm was reported.
Infrastructure and Energy Supply	The area has 278 km of infrastructure lines, including water, sewage, and high-voltage lines, along with power plants, water supplies, antennas, and intakes. Only 15 infrastructure points were damaged during the Vaia storm.
Tourism and Recreation	The area has 39 hectares dedicated to tourism and leisure activities, mostly located outside hazard zones.
Agricultural Land	Agricultural land, primarily in the valley and on mountains, is largely outside hazard zones, with 90% of agricultural land and livestock farms protected.
Forest	Forests cover 70-75 % of the area, playing a significant role in the economy and protecting against natural hazards. The Vaia storm caused significant wind damage, particularly to protective forests, with 5-18 % of the forested areas affected.

The exposed elements discussed can be impacted directly or indirectly by hazards. Below are the potential indirect consequences:

- <u>People and Villages:</u> Road damage by fallen trees and flooding or debris flows can isolate villages and disrupt mobility, indirectly affecting people during road closures for cleanup.
- <u>Tourism:</u> Indirect impacts include damage to tourist accommodations (e.g., hotels, agritourism) and to roads or hiking trails. While trail damage may be resolved within hours (but it is a low-urgency intervention in such a scenario), rebuilding accommodations can take months, and this could affect negatively the touristic offer in the longer term.
- <u>Economic Activities</u>: Damage to energy infrastructure disrupts businesses, particularly those reliant on cooling systems (e.g., livestock and food supply). Forestry-related activities are also impacted in the long-term by long-lasting consequences of direct damage to forested areas, i.e. the timber market was impacted due to downed trees, and increased avalanche and landslide risks due to the loss of natural barriers.

Potential future developments

The municipal urban plan designates areas for new construction, known as "completion zones" and "expansion zones," covering about 84 hectares in the pilot municipalities. Most of the new expansion areas are located outside hazard zones, with only a small portion in the medium and high hazard zones. However, 93 % of these areas are already built, leaving only 7 % available for future development. The growing population and tourism sector will require additional space for housing and tourist accommodations.

A key concern for future expansion areas is the potential increase in the frequency and intensity of hazard events, particularly for areas in the high hazard class or near hazard zones. Increased intensity could worsen the hazard classification of these areas.

Additionally, assets near windthrown areas are at risk due to the loss of protective forests, and artificial protection structures have been installed until the forest regrows. As noted earlier, indirectly exposed elements include people, villages, and economic activities, all of which depend on infrastructure and forests. With an increasing number of residents and tourists, more people and activities may be affected by intensifying hazard events.

3.5.2. Vulnerability

Vulnerability depends on physical and social factors. Physical vulnerability considers territorial features (e.g., morphology, forest presence, glacier melt) and asset characteristics (e.g., infrastructure, building age, maintenance). It also includes potential damage based on hazard type, intensity, and duration. Social vulnerability focuses on people, including their age, risk perception, preparedness, education, and communication with risk managers during emergencies.

Quantifying vulnerability is complex, and in the Autonomous Province of Bolzano, it has been done only in specific cases. Physical vulnerability changes due to hazard variability and territorial features like forest protection or sediment availability. Building value and changes are difficult to predict. Social vulnerability relies on risk awareness and communication speed during emergencies, so in South Tyrol, vulnerability is always set to 1 to account for the worst-case scenario.

Past/present

The Vaia storm revealed a major vulnerability in the pilot area's forest system, primarily consisting of old, even-aged trees. The storm heavily impacted protection forests, crucial for safeguarding settlements and infrastructures. About 25 % of the damaged forest was protection forest. As a result, the loss of protective forest increased the need for temporary protection structures. This "temporal" vulnerability will persist until the forest regrows.

For the Vaia area, key social vulnerabilities include poor spatial and forest planning, lack of multi-risk management, and gaps in response management and early warning systems, which struggle with unexpected events. Additionally, there are issues with population preparedness and education.

Potential future developments

The vulnerability of the damaged forested areas has increased due to the loss of protection forest, requiring protective structures in high-risk areas. This vulnerability will decrease as the forest regrows. Changes in other predisposing factors depend on land use evolution, such as glacier melt or landslides leading to more sediment availability, and better forest management reducing dead wood in channels.

Risk management is evolving with increased attention to compound and cascading events, awareness of rising hazard intensity due to climate change, and greater public risk awareness. These factors can help reduce vulnerability.

3.5.3. Risk Management

This chapter outlines risk management measures across the four phases: prevention, preparedness, response, and recovery.

- **Prevention Measures**: These include both structural and non-structural actions. Structurally, 3406 protection structures exist in Vaia municipalities in South Tyrol, primarily for hydraulic hazards (3008), rockfall (393), and avalanches (5). Non-structural prevention relies on planning tools such as the Hazard Zone Plan, which maps hydrogeological hazards and establishes planning rules, such as banning construction in high-risk zones.

- **Preparedness Measures**: The Autonomous Province of Bozen – Bolzano has developed a Risk Map to prioritise the protection of exposed elements, focusing on mitigation rather than just planning. The map reflects current risks and requires regular updates to adapt to urban development. It supports both structural and non-structural interventions.
- **Response Phase**: Each South Tyrolean municipality has a Civil Protection Plan for emergencies, detailing resources, procedures, and responsibilities. Volunteer groups, including firefighters and mountain rescue teams, provide immediate response, secure affected areas, and assist with evacuation and basic needs.
- **Recovery Phase**: The province offers funds for post-event reconstruction through specialised offices, targeting municipalities, public associations, private citizens, and farmers based on specific needs (e.g., agricultural recovery).

Future risk management in the Vaia area must address the potential increase in hazard intensity and frequency, new processes caused by territorial changes (e.g., treeless areas prone to avalanches), and the interaction of multiple hazards.

3.6. Val di Fiemme and Val di Fassa, Italy

Val di Fiemme and Val di Fassa is the portion of the pilot area of Storm Vaia located in the Autonomous Province of Trento (northern Italy, central-eastern Alps). The risk assessment focused on compound windstorm and heavy rain event. The impact chain and hazard analysis are presented in D 2.1.1. The following chapters describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.6.1. Exposure and impacts

Past/present

In Trentino the Vaia storm affected approximately 20,000 hectares of forested land, with an estimated 4 million cubic metres of uprooted or broken trees. Areas impacted either completely or significantly (with more than 50 % damage) make up a substantial portion of the total damaged area, totalling nearly 12,800 hectares. Two people died during the event, and three more in the following months due to incidents mainly related to collapses caused by the storm. There were significant damages to the road infrastructure as well as avalanche and rockfall barriers. The storm caused damage to buildings and power infrastructure. The flood caused some damages to vehicles (Table 9).

Table 9: Vaia Storm: Exposure and impacts across sectors in Val di Fassa and Val di Fiemme

Exposure element	Exposure description and elements affected by the past event
People	The storm affected residents and visitors, with some fatalities and injuries linked to storm-related incidents, especially from collapses.
Roads and Bridges	Roads, cycling paths, pedestrian networks, and railways were significantly impacted. The destruction of avalanche and rockfall barriers also posed a major risk. The loss of these protective measures could increase the vulnerability of areas to natural disasters.
Buildings	Many private homes, vehicles, and urban properties suffered damage, with widespread destruction from the storm's winds, including uprooted trees and damaged infrastructure. The accessibility of properties also became a concern, especially in remote areas.
Infrastructure and Energy Supply	Some power poles were knocked down.
Tourism and Recreation	Areas involved in productive activities, especially in Primiero, Fiemme, and Val di Sole, saw interruptions to their operations, affecting livelihoods and the economy.
Agricultural Land	Agricultural lands and livestock farming were affected, particularly in Valsugana, Primiero, and Val di Non, impacting local food production.
Forest	Vast forested areas were impacted, though assessing the full extent of the damage is challenging due to inaccessibility. The loss of trees could have long-term ecological consequences, especially for wildlife. The storm disrupted wildlife habitats, although precise assessments are not yet available due to the inaccessibility of affected areas. Similar past storms have shown that wildlife populations can suffer significantly in the aftermath.

The exposed elements discussed can be impacted directly or indirectly by hazards. Below are the potential indirect consequences:

- <u>People and Villages:</u> Road damage by fallen trees and flooding or debris flows can isolate villages and disrupt mobility, indirectly affecting people during road closures for cleanup. In Trentino waste management and the safety of workers, residents, and tourists in affected areas also became pressing concerns.
- <u>Tourism:</u> Indirect impacts include damage to tourist accommodations (e.g., hotels, agritourism) and to roads or hiking trails. While trail damage may be resolved within hours (but it is a low-urgency intervention in such a scenario), rebuilding accommodations can take months, and this could affect negatively the touristic offer in the longer term. The deep modification of the landscape could also have negative consequences on tourism and attractiveness. The tourism sector, which relies on safe access to trails and natural environments, faced potential setbacks.
- <u>Economic Activities</u>: Damage to energy infrastructure disrupts businesses, particularly those reliant on cooling systems (e.g., livestock and food supply). Forestry-related activities are also impacted in the long-term by long-lasting consequences of direct damage to forested areas, i.e. the timber market was impacted due to downed trees, and increased avalanche and landslide risks due to the loss of natural barriers.

Potential future developments

Tourist numbers in Trentino have steadily increased over time, with a slower growth in recent years that quickly rebounded after the COVID decline. Due to rising temperatures in tourists' home countries, a continued rise in visitors is expected, potentially exacerbating overtourism in areas like Val di Fassa. As tourist numbers rise, the presence of outsiders, who are more vulnerable to risks, will also increase. Restrictions on overtourism may be applied to specific areas but are unlikely to significantly impact overall numbers.

Trentino's population is younger than the national average, with an average age of 45.5 in 2022, compared to Italy's 46.4. However, the population is aging, with the percentage of people over 65 expected to rise to around 28 % by 2050. Over the past century, the population has grown by 25 %, with some areas like the Adige Valley seeing over 35 % growth. Projections suggest a modest increase of about 14,000 people (2.5 %) by 2050, but future population shifts, especially in the two valleys analysed, remain uncertain.

More than half of Trentino's population (51 %) lives in valley bottoms (altitudes between 0-250 m), and only 6 % live above 1,000 m. While overall population exposure to climate risks is expected to remain stable, the concentration of people in lower-altitude areas will likely increase their vulnerability to risks like heatwaves and floods. Urbanization trends in the Alpine region may further concentrate the population in these vulnerable areas.

Regarding floods and torrential phenomena in the future, higher temperatures and changes in rainfall patterns are likely to increase the frequency and intensity of debris flows, raising flood and torrential event risks. This will lead to more injuries, fatalities, and damage to buildings, infrastructure, and industrial areas. Strategic structures and cultural heritage sites will also face greater exposure to flooding, with direct and indirect effects, such as damage or accelerated deterioration. Ecologically, torrential events cause immediate harm to aquatic habitats and species, while longer-term effects may lead to biodiversity loss. However, sediment deposition can also create diverse habitats. This scenario highlights the need for increased maintenance and revised mitigation strategies.

Considering wind-induced forest collapses, bark beetles, forest fires, and avalanches rising temperatures and increased rainfall are expected to heighten the likelihood of wind-induced forest collapses, especially in areas with weaker root systems like spruce forests. These events, along with bark beetle infestations and wildfires, could reduce forest cover, which serves as protection against mass movements and avalanches, particularly on steeper slopes. Wildfires will cause direct damage to structures and agricultural areas, while also disrupting services like electricity and water. Avalanches, while affecting higher altitudes, will present a lower overall risk.

3.6.2. Vulnerability

Regarding floods and torrential phenomena increased rainfall intensity, frequency, and land use changes will heighten flood and torrential event risks in Trentino, increasing exposure. Understanding land vulnerability to flooding is challenging but essential for improving community resilience. Vulnerability depends on socio-economic factors, infrastructure, and event characteristics, such as water depth and velocity. Since detailed data is lacking, maximum vulnerability is assumed in flood risk assessments, as outlined in the Trentino Public Water Use Plan (PGUAP). Vulnerabilities also include inadequate drainage systems, urban impermeability, and transportation routes in valley floors near rivers.

Concerning wind-induced forest collapses, bark beetles, forest fires, and avalanches Trentino's forests, particularly monoculture spruce stands, are vulnerable to windstorms, as seen during the Vaia storm. Simultaneous threats, such as drought, increase vulnerability to bark beetle infestations. The loss of protective forests also heightens risks to infrastructure and increases hydro-geological hazards in areas once considered lower-risk.

Past/present

Quantifying vulnerability is complex. Physical factors, such as hazard intensity and territorial features, change over time. Asset values and characteristics also evolve, making future predictions challenging. Social vulnerability depends on factors like risk awareness and the efficiency of emergency communication. In the analysis the vulnerability is set to 1 to represent worst-case scenarios.

In Trentino for the Vaia case study, the main sources of vulnerability are the lack of risk management practices for handling multiple hazards and the inability to cope with events that exceed existing mitigation measures. Other important vulnerabilities include shortcomings in forest planning, which is not resilient to windthrow, as well as gaps in population preparedness and education. Additional relevant vulnerabilities can be categorised under physical vulnerability, which considers the characteristics of exposed assets, such as the construction, age, maintenance level, and potential damage to buildings, roads, and infrastructure. This depends on the type, intensity, and duration of the hazard.

Social vulnerability is influenced by factors such as age, physical condition, risk perception, preparedness, education level, and the quality of communication with risk managers during emergencies. Population growth can increase residential density in risk-prone areas, raising overall vulnerability. An increase in tourism in the pilot area could also heighten vulnerability, as tourists may lack in-depth knowledge of local hazards and the territory.

In conclusion, it was not possible to define a single vulnerability value at the provincial level, as vulnerability depends on various factors, primarily physical and social. It is complex to evaluate each exposed asset and assign a single vulnerability value. Therefore, for flood and torrent hazards, the maximum vulnerability value (1) is assumed. For other exposed assets, no unique value has been defined at the provincial level, but once the general risk map is established, it will be used to assess vulnerability, among other factors.

Although a quantitative approach to vulnerability assessment is not feasible at this time, the qualitative discussion of vulnerability factors is crucial for identifying the most appropriate adaptation responses to reduce overall system vulnerability.

Potential future developments

The loss of protection forests in damaged areas has increased vulnerability, e.g., for hazards like avalanches, necessitating the use of protective structures in high-risk zones. This vulnerability will decrease as forests regenerate.

Other predisposing factors depend on land use and territorial changes, such as glacier melt increasing sediment availability or improved forest management reducing deadwood in channels.

Risk management is evolving, with a greater focus on compound and cascading events, increased awareness of climate-driven hazard intensification, and heightened public risk awareness, all contributing to reduced vulnerability.

3.6.3. Risk Management

This chapter outlines risk management measures across the four phases: prevention, preparedness, response, and recovery.

- **Prevention Measures:** Structural prevention in Trentino includes weirs, embankments, snow retention structures, and valley bottom works to mitigate flood, landslide, and avalanche risks. A mapping project is underway to identify existing structures. New infrastructures are being developed with innovative materials to improve resilience, such as a traffic light system in Veneto for roads prone to landslides and debris flows. Additionally, buffer zones around roads are required by regulations for tree planting to reduce risks. Riverbank and unstable slope re-naturalisation projects, like Trentino's Life+ T.E.N. "Trentino Ecological Network," aim to improve water absorption and reduce landslide risk. Forest management, including tree planting and maintenance, helps prevent slope destabilisation. Non-structural prevention is achieved through planning tools like the Hazard Synthesis Map, which assesses risks like mass movements, floods, and wildfires, and classifies areas by vulnerability. This map guides land use regulations under the Provincial Urban Plan (PUP).
- **Preparedness Measures:** The Provincial Alert System (SAP) coordinates the monitoring, forecasting, and response to risks such as floods, landslides, and wildfires. It includes three phases: forecasting (daily meteorological predictions), evaluation (assessing potential impacts), and alerting (issuing warnings and activating emergency plans). Nowcasting provides real-time forecasting to support evacuations and emergency actions. Future enhancements will improve alert accuracy and timeliness. Civil protection plans, which include evacuation strategies, should be updated to address the compounded effects of climate change. It's crucial that both municipal authorities and the public are familiar with these plans.
- **Response Phase:** The Civil Protection Plan manages emergencies by protecting people, assets, and services. Each municipality in Trentino has a tailored plan with clear instructions for responding to critical situations. Rapid response teams, including firefighters, civil protection volunteers, and medical personnel, are trained to act quickly. In flood events, the Civil Protection Department forecasts and activates the Flood Service, coordinating operations through the 24-hour Operations Room. A key area for improvement, highlighted during a workshop, is the communication between emergency management teams and the public. Clearer communication channels and public education on emergency management are needed.
- **Recovery Phase:** After a disaster, financial support is provided for reconstruction. However, while the Vaia emergency received quick resources, the long-term effects, like the increase in bark beetle populations affecting the timber industry, were not sufficiently addressed. Future recovery efforts should take a medium-term perspective to consider these impacts. Debriefing sessions with all stakeholders involved in the emergency response will help identify strengths and areas for improvement in future disaster management.

3.7. Arly River Catchment, France

The Arly River Catchment is located in northeastern France, in the western Alps. The risk assessment focused on compound storm and heavy rain events. The impact chain and hazard analysis are presented in D 2.1.1. The following chapters describe the analyses conducted and the results achieved for the risk components: exposure and impacts, vulnerability, and risk management in both past and future contexts.

3.7.1. Exposure and impacts

The Arly River Catchment area comprises 26 municipalities, with Ugine and Albertville serving as urban centres in the southern part of the valley.

Past/present

Population: In 2021 the study area had approximately 50,000 residents, with about 50 % living in the urban centre of Ugine (7,000 inhabitants) and Albertville (17,000 inhabitants). In winter, the number of tourists visiting the ski resorts increases the catchment's permanent population by 2.5 times, and locally by a factor of 7 at the head of the catchment.

Settlements: Built-up areas exposed to natural hazards are identified in Risk Prevention Plans (‘Plans de Prévention des Risques’ - PPR) and are addressed in Municipal Information Documents on Major Risks (‘Documents d'Information Communaux sur les Risques Majeurs’ - DICRIM), which provide preventive information.

Several homes and built assets are exposed to avalanche risk. Built-up areas are also frequently affected by shallow landslides. For example, following Storm Eleanor, a landslide destroyed two tourist chalets. Some built-up areas are highly exposed to the risk of flooding and mudslides.

The GASPAR database lists the events for which natural disaster decrees have been requested by communes to benefit from the CatNat compensation procedure following damage to insured private property. In the communes of the Arly River Catchment, there were more than 150 natural catastrophe decrees for the period 1982-2024.

Roads: Roads in the Arly River Catchment are frequently affected by avalanches, landslides, rockfalls, and torrential flooding (see D 2.1.1), leading to regular traffic disruptions and costly road repairs. Following the passage of storm Eleanor on 4th January 2018, several roads in the Arly River Catchment were closed due to mudslides and snow slides.

In the Arly Gorges, rockfalls, avalanches, falling ice sheets, floods, scouring, and landslides have caused numerous accidents and led to frequent road closures for repairs. The cliffs and slopes above the road are frequent sources of landslides, involving several thousand cubic meters of material. Since the 1970s, rockfall protection works, including galleries and boulder barriers, have been implemented. In 2000, the Savoie Departmental Council launched a €21 million, ten-year rockfall protection program. However, not all rock hazards have been addressed. Recent events lead to increased mobilization of so-called “emergency” budgets, which have risen from around €2m per year on average to €4m since 2014, and even more in exceptional years: €6.8m in 2018 and over €9m in 2015.

Socio-economic activities: Characterised by a predominance of rural and forested areas, this mountain region has based its activity on summer and winter tourism around the tourist centres at the head of the catchment area. The watershed's economic activities are also closely linked to the use of water resources: tourism, snowmaking for ski resorts, hydroelectricity (with strategic production facilities at peak periods) and industry.

Tourism is a key economic driver for the region, supported by both summer and winter activities and major facilities. The basin has tourist beds, double its permanent population, including a significant number of second homes.

Agriculture: As the second most important activity in the catchment area after tourism, agriculture plays a strategic role both economically and in terms of land use.

Hydroelectric production: The use of water resources has historically been at the heart of the economic development of the Arly catchment area.

Other exposed sectors are industry and craft businesses and ecosystems.

Indirect impacts: The loss of accessibility due to frequent road closures from natural hazards is likely to impact all socio-economic activities in the basin, particularly access to resorts. When these closures occur during peak tourist periods, especially in winter, additional resources are required to assist stranded travellers.

Potential future developments

Forest cover will become more vulnerable due to increased disruptive events (droughts, storms, pests, fires, etc.). Foresters face uncertainties in choosing resilient tree species for the future climate. Tools like the ClimEssences model can simulate future species distribution under various climate scenarios, guiding species selection. The range of species like spruce is expected to shrink, requiring consideration of assisted migration for certain species. Efforts are underway to create management plans for forest species and anticipate fire risks (MOSAIC project).

The new climate regime could increase pressure on natural and man-made ecosystems. The timber industry and farmers are particularly affected by droughts, which threaten fodder supplies, promote parasites, and dry out forests, landscapes at risk, biodiversity, and local industries. Alpine pastures and forests, already impacted by heavy visitor numbers, must meet growing demands such as biodiversity preservation, carbon storage, slope stabilisation, water filtration, heritage, tourism, and health. Weakened, they struggle to survive amid urban populations and tourists seeking nature and outdoor activities.

3.7.2. Vulnerability

Past/present

Based on the example of storm Eleanor on 3rd and 4th January 2018, which was followed by another episode of thaw and heavy rainfall on 22nd January, it is possible to specify the vulnerability of the area. Two events close together in the Arly catchment generated a second flood - aggravating the damage caused by the first flood. The same phenomenon was repeated in 2023 with the same effects.

Intense precipitation in conditions of high temperatures (in other words, a high rain-snow line and rain on snow) led to wet avalanches, torrential flooding, landslides and flooding. Through a cascade effect, these events destabilized the land and banks of watercourses and encouraged the occurrence of new events. Certain infrastructures (roads, bridges, etc.) and buildings were damaged, limiting access to villages and generating economic costs for restoration work.

The fire brigade responded to a large number of flooding incidents, mainly in Ugine. These floods caused damage to private homes. The fire brigade also responded to falling trees in Flumet, avalanches and landslides in La Giettaz and preventive beaconing in Marthod. In Ugine, the Gorges de l'Arly road (RD1212) remained closed together with two other secondary roads for one month due to numerous landslides.

Floods and landslides caused damage and post-flood work was required due to filled storage areas, overflowing torrents, broken culverts, flooding and impact on protective structures. Numerous emergency and post-flood restoration operations have therefore been undertaken by the communes and Arlysère, as part of the GEMAPI remit. In the catchment area, almost 20 sectors have been the subject of emergency work or repairs, at a cost of almost €190,000 (GEMAPI, excluding roads).

For the SMBVA technical team, providing technical support to local authorities for the implementation of restoration work (files / work) required almost 2 months of full-time work.

The communes of the Arly River Catchment also applied for recognition of the state of natural disaster (CatNat guarantee) in order to obtain compensation for the restoration of damage.

Potential future developments

Were an event of this type to occur again – and as reflected by local actors as part of the construction of the climate risk storyline – the main road could be cut off in several places by landslides, and several hundred meters could be washed away by bank erosion. Flooding in the alluvial plain could cut off the freeway and affect small manufacturing zones and numerous homes.

The Ugitech steel mill would flood and up to 200 people would likely be trapped on the site. They would have to be evacuated as a matter of urgency, due to the risk of water intrusion into the molten furnace, although this is less likely.

It is possible that hundreds of tourists would be blocked for several days in the resorts of Arêches-Beaufort, Crest-Voland and the area between Saint-Nicolas and Flumet. Villages could remain isolated for several weeks to months.

Following this sort of event, the local authority would possibly decide not to reopen the Arly River Catchment road, due to the exponential increase in its road maintenance budget. As a result of the damage caused to the forests in the catchment, torrential erosion and rock falls would be expected to increase further over the following decades.

3.7.3. Risk Management

Past/present

State services organise risk prevention and emergency response. The "Dossier Départemental sur les Risques Majeurs" (DDRM), created by the Prefect, is a document to raise citizen awareness of major risks. It includes information on foreseeable risks and planned measures to limit their effects. The Savoy DDRM, approved on 7th December 2020, lists municipalities at risk where preventive information must be provided (Préfecture de la Savoie, 2021).

Flood risk prevention includes risk knowledge, implementation of the European Flood Directive, Flood Prevention Action Programmes (PAPI), Flood Risk Prevention Plans (PPRI), protection and vulnerability-reduction measures, forecasting, and emergency organisation.

A specific prevention policy is in place to deal with natural hazards in the mountains.

At the municipal level, natural risks are addressed through Risk Prevention Plans (PPR), which are incorporated into Local Town Planning Plans (PLU) to regulate construction and define prevention, protection, and safeguard measures. PPRs identify risk-exposed areas and those where stakes (buildings, structures, activities) may exacerbate or create risks. They outline measures for prevention and protection, as well as guidelines for existing developments. Another prevention plan used in Savoie is the Plan d'Indexation en Z (PIZ), a summary of the PPR, combining zoning and risk information on a single graphic document with regulation sheets. Several PIZs have been updated since 2012 in the Arly basin.

The Municipal Safeguard Plan (PCS) defines, under the authority of the mayor, the organisation planned by the municipality to ensure that the population is alerted, informed, protected and supported in the face of known risks. It draws up an inventory and analysis of risks throughout the municipality. It integrates and completes the information documents drawn up for prevention purposes, including the Municipal Information Document on Major Risks (DICRIM). This plan is compulsory in communes with an approved PPR or in communes within the scope of a special intervention plan (PPI). PCS is strongly recommended for all other communes. Civil protection training and exercises are compulsory since 2022. The mayor must therefore carry out exercises (at least 1 every 5 years) to test the communal crisis organisation. The intermunicipal authorities can provide support through their Intercommunal Safeguard Plan (PICS).

The Syndicat Mixte du Bassin Versant de l'Arly (SMBVA) consists of 26 municipalities across 3 communities of communes and 1 community of agglomerations, focusing on managing the larger Arly watershed. SMBVA handles aquatic environment management and flood prevention (GEMAPI). It assists local stakeholders with river management and flood prevention projects.

Actions taken by the Savoie department

Departmental Road management: The Département de la Savoie is responsible for managing and deciding on the opening and closing of departmental roads.

Potential future developments

The local feedback meeting for the MIROIR project on the Arly, held on 28th September 2023 in Ugine with support from the SMBVA and Ugine town council, discussed proposed actions based on the project's findings. Two main actions were considered (BRGM, 2024):

- Slope monitoring: Shared by the Savoie Departmental Council and local partners (communes, Arlysère agglomeration, SMBVA) to enable synergies and cost control.
- Torrential risk study: Consolidating economic components downstream and improving scenarios of slope contributions to the river as part of the SMBVA's PAPI program.

In addition to current flood prevention measures in the PAPI program, the SMBVA, with the PARN (Alpine Institute on Natural Risks), is developing a future Integrated Natural Risk Management (INRM) action program. This multi-risk strategy, part of the ERDF "Massif des Alpes" program (2021-2027), will benefit from the INRM Alpine Territory network, pooling expertise since 2009.

4. Synthesis

4.1. Evidence from past events

4.1.1. Risk insights from the pilot analyses

A comparison of the pilot level analyses yields several insights and commonalities that might be of interest across the Alpine Space. The observations related to the methodologies of analysing past events are discussed here. We also evaluate possible implications these results might have for improving preparedness for the future risk situations.

Based on event documentation and registries, the pilot studies report damages that have been observed in different exposure categories. The event documentations vary in length of data records, the types of events that are included and the detail in which the impacts are recorded (see also D 2.1.1). The focus is on direct damages, covering common exposure types, such as affected buildings, roads and critical infrastructure, forests and agricultural lands. The damages are generally quantified and sometimes monetized. Indirect damages (also known as cascading damages) are usually described qualitatively. Damages are in many cases reported for major events only. Examples of this include Garmisch-Partenkirchen, where a detailed event documentation exists only for major hydrological events that were declared a disaster with the county administration, or in Gorenjska, where drought damages are only collected if it is declared a national disaster. The cost of smaller and more frequent impacts is generally neglected. Consequently, there is less data available for the development and validation of models, such as risk or vulnerability models. Multiple pilots (e.g., Gorenjska and Wipptal/Stubaital) point out the lack of local quantitative vulnerability information that can be used to assess future scenarios. Another effect of incomplete documentation is that it is almost impossible to analyse the overall costs, i.e., cumulative impacts, of slow changes in climate or predisposition, which can manifest in more frequent but not necessarily more intense hazard events. An example of this can be the loss of protective forest that will increase the susceptibility to landslides and flow events.

Several pilot studies make use of official hazard or risk maps in their investigations. While risk maps usually include information beyond the hazard, e.g., including information on exposure or vulnerability, there is no consistent definition for these maps, and they can vary largely depending on the intended purpose of the maps. For the Wipptal area it is described that the local risk map reflects the exposure at the time of map creation and is not continuously updated. Its intended use is primarily to serve as an indicator for high-risk areas that should be prioritized in mitigation projects but not as a tool for design or evaluation of measures in the planning process.

Several limitations of these maps are mentioned. Regarding the accuracy of hazard maps in past events, deviations between actual hazard areas and those outlined in hazard or risk maps were observed, particularly when events resulted from compound or cascading hazards. In most cases, the maps do not convey complex scenarios but focus on single hazards and their direct impacts. With regard to the emerging risk landscape, it is also noted that risk management tools available to risk managers rarely account for future conditions, failing to reflect changes in hazard frequency, magnitude or exposure. While climate trends are often addressed through extrapolations or what-if scenarios, similar approaches to other factors influencing future risk are less common.

4.1.2. Synthesis of results from the Alpine-wide mass movement impact model

Drivers of slide-type mass movement impact events

In contrast to D 2.1.1, which focused only on the hazard components of the impact models, the results presented here include the variables describing the potentially exposed infrastructure within the PPA. The variable importance plot shows that the number of buildings (log scale) in the process path area is the fifth most important variable in the impact model (Figure 5). The partial effect plot also shows a linear relationship (log scale), i.e., the greater the number of buildings in a half-basin that are potentially exposed to slide-type mass movements, the more likely it is that an impact event will occur (or be recorded). The other difference from the hazard focus in the previous report is the inclusion of the proportion of roads in the PPA, albeit with a less significant contribution as an explanatory variable.

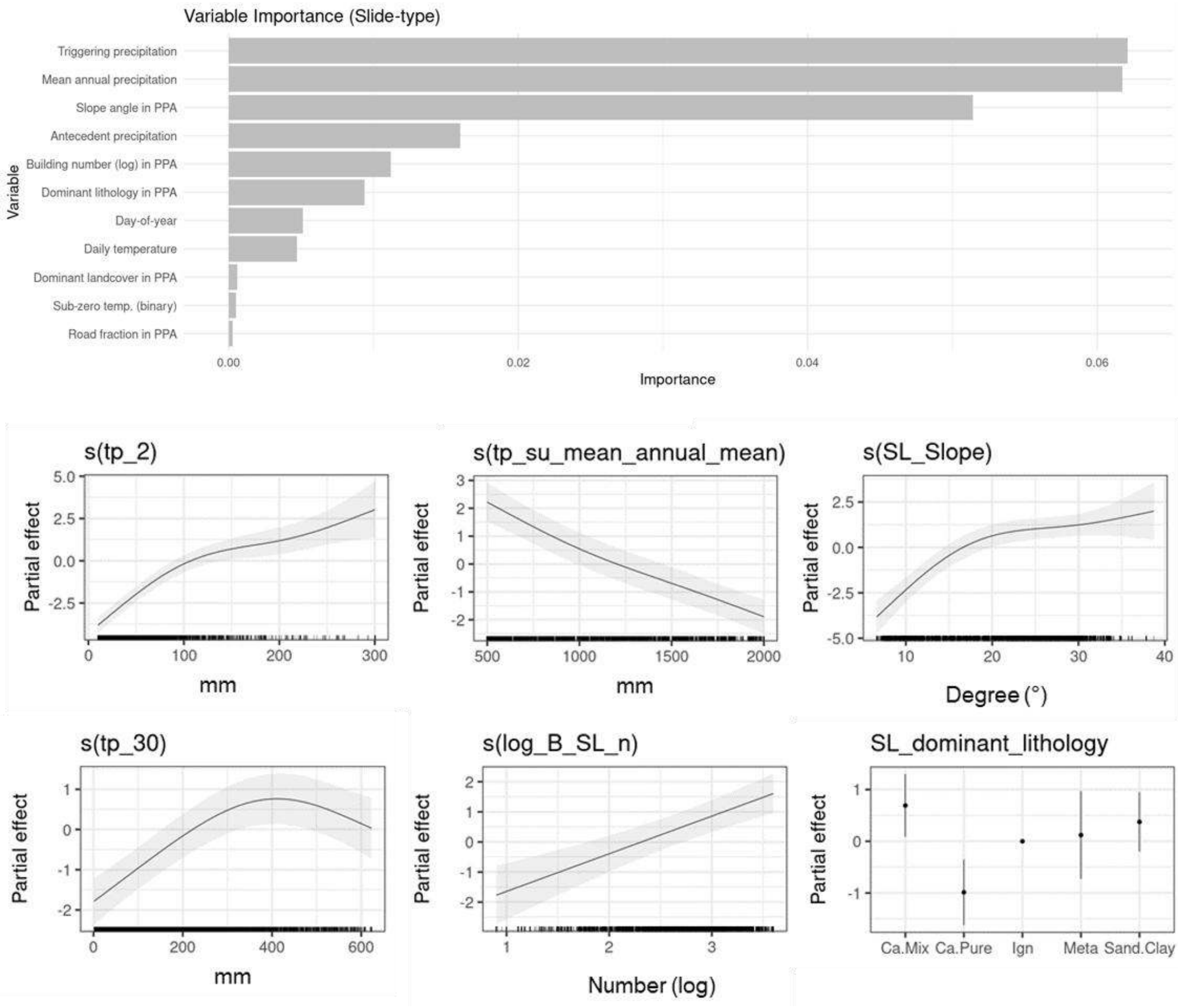

Figure 5: Permutation-based variable importance for the slide-type impact model computed using 100 iterations. Note, only the most important explanatory variables are shown and partial effect smooth functions for the six most important variables.

Drivers of flow-type mass movement impact events

The variable importance plot for the flow-type shows similar tendencies to the slide-type plot, with slightly less importance attributed to the infrastructure variables (Figure 6). In fact, the proportion of half-basins occupied by roads was not included in the variable selection process. The impact events due to flow-type mass movements are therefore predominantly driven by climatic variables alone (triggering and annual precipitation as well as the mean daily temperature). These explanatory variables are followed in importance by the average slope of the PPA and the 21-day antecedent precipitation.

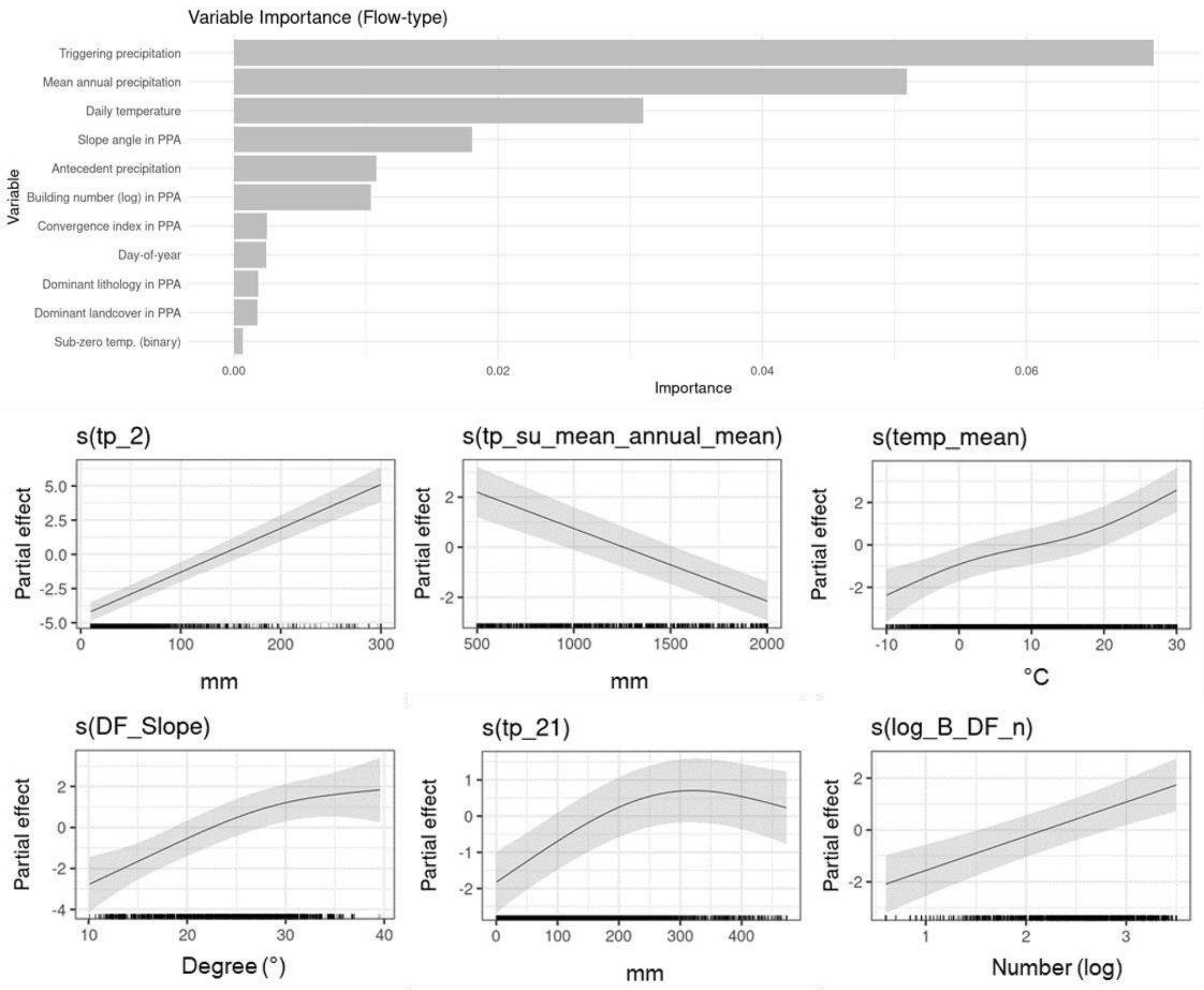

Figure 6: Permutation-based variable importance for the flow-type impact model computed using 100 iterations. Note, only the most important explanatory variables are shown and partial effect smooth functions for the six most important variables.

Drivers of rockfall mass movement impact events

The rockfall impact model is in stark contrast to the slide and flow impact models in that the most important variables determining impact events are the two infrastructure variables, number of buildings and proportion of roads per half basin (Figure 7). The main driver of rockfall events is exposed number of buildings, and the relationship is linear on the log scale - as shown in the partial effect plot. The partial effect plot for roads shows that the probability of a rockfall event increases as the fraction of roads increases, and plateaus when approximately 10 % of the PPA within the half-basin is occupied by roads. As the next four most important variables after the infrastructure variables are static environmental variables, the meteorological and climatic explanatory variables have comparatively little influence on the predicted probabilities of occurrence. Thus, changes in precipitation triggering events will have a limited effect on the predicted probabilities. Therefore, the rockfall mass movement model suggests that the recorded rockfall events are less dependent on precipitation as the triggering mechanism. For this reason, the resulting predictions show where rockfall impacts are possible, based primarily on the exposure of infrastructure within a landscape that is predisposed to rockfall due to its lithological and morphological characteristics.

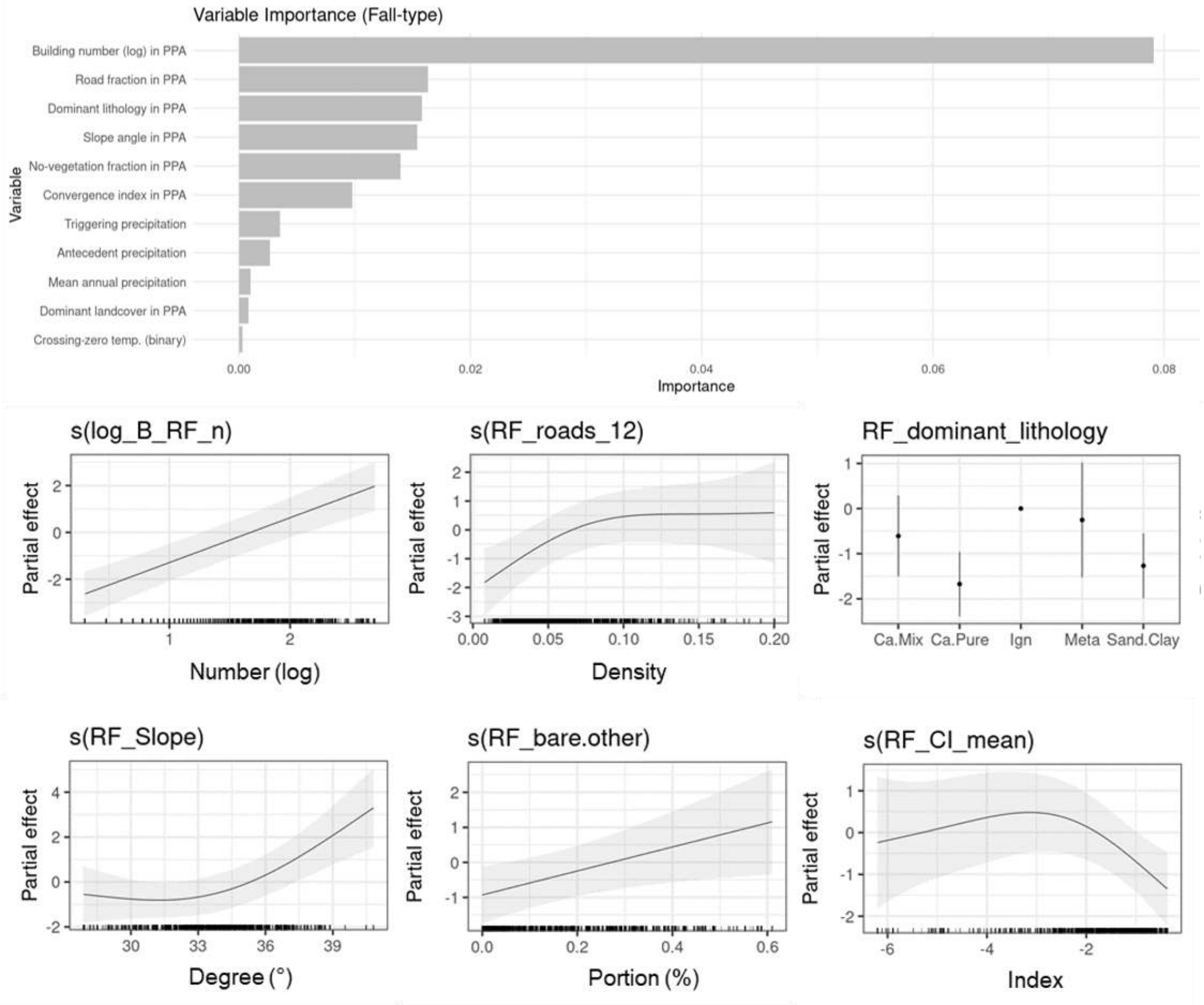

Figure 7: Permutation-based variable importance for the rockfall impact model computed using 100 iterations. Note, only the most important explanatory variables are shown and partial effect smooth functions for the six most important variables.

Hindcasting recent mass-movement triggering large storm: Eleanor and Vaia

To illustrate the utility of the impact models and assess their spatial transferability, predictions and hindcasts were computed for two recent storm events: the Eleanor and Vaia storms (Figure 8). While these storms lasted for more than one day, conditions on 3rd January 2018 were used to hindcast the Eleanor storm and those on 29th October 2018 for the Vaia storm. The Vaia storm proved to be significantly more severe in terms of spatial extent and probability values of all mass movement types, affecting large parts of the Eastern Alps, especially Austria and northern Italy. In contrast, the Eleanor storm mainly affected the western Alps, with its centre over the French Alps and impacts extending into the southern Swiss Alps. Although precipitation was not a key driver in the rockfall model, significant differences in the hindcasts highlight the influence of climatic and meteorological conditions on the results.

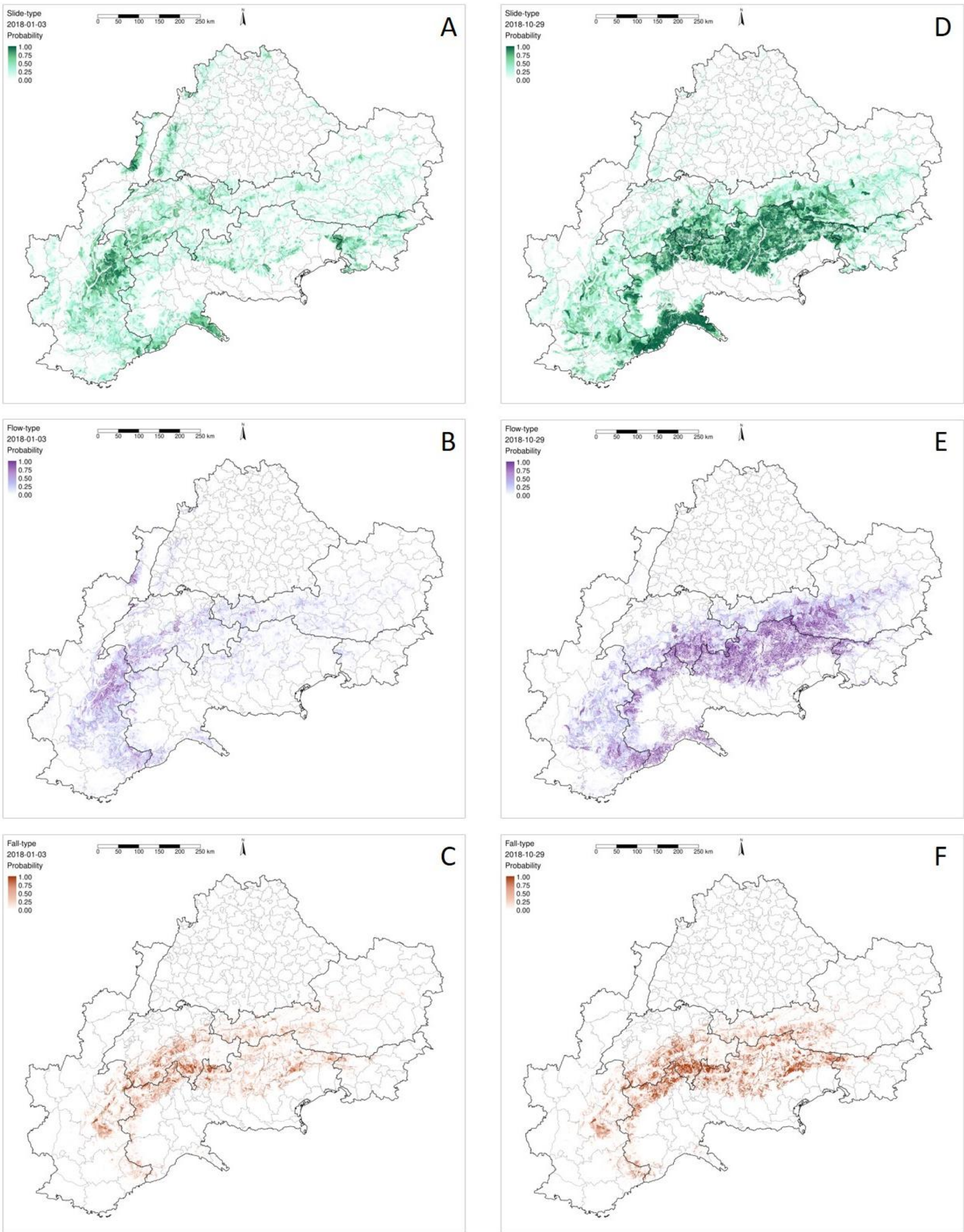

Figure 8: Predictions of slide-type, flow-type and rockfall impact models for the recent impact events of Eleanor storm in January 2018 (Insets A-C) and Vaia storm in October 2018 (Insets D-F).

4.2. Preparing for future risk

4.2.1. Risk insights from the pilot analyses

The results of the pilot level analyses yield several insights and commonalities, both related to risk factors and management methods, regarding preparing for future risk that might be of interest across the Alpine Apace. We discuss these here.

A major challenge lies in the continuous socio-economic growth of the Alpine Space. Most of the pilot areas of X-RISK-CC report expected increases in population and tourism that also require the development of additional structures. Due to the confined topography in many alpine valleys, areas for expansion of settlements and infrastructure are limited and are likely to result in an increase of exposure to natural hazards. The Wipptal study shows that none of the currently dedicated expansion zones are in the most critical hazard zone (very high risk) but mainly located in other zones. Under future climate conditions it is nonetheless possible that due to the increases in magnitudes and frequency of certain hazards these zones could be affected more frequently and more intensely, resulting in a similar risk as currently in very high-risk zone. Some of the pilot areas, such as Garmisch-Partenkirchen and Gorenjska, give examples of infrastructure projects that will reduce exposure, e.g., by relocating traffic. The feasibility of such measures is generally dictated by the spatial confines of a region. Because of spatial limitations on new development of touristic infrastructure, in Wipptal it is concluded that tourism is unlikely to increase significantly.

Multiple pilot studies, e.g., in Stubaital/Wipptal and Trentino/South Tyrol, report that risk managers and decision makers are increasingly aware of the complexity and interconnectedness of the environments they operate in. Growing awareness about the effects of climate change on the occurrence of hazards and attention to the compound and cascading impacts that follow, will lead to better risk management that hopefully will be able to compensate for some of the adverse effects of climate change. However, when it comes to assessing the effect of future changes in risk management some challenges are pointed out. There is uncertainty about the effect that ageing risk mitigation systems will add to risk. Because risk mitigation structures were designed and built based on outdated protection standards or design values these systems might not be sufficient in the future. As a result, exposure to some hazards could possibly increase. Ageing infrastructure is also more likely to fail during events. The residual risk stemming from overload or failure of these structures is rarely addressed in the tools, e.g., hazard or risk maps, commonly employed to inform about the risk situation. Multiple pilot studies observe a lack of risk management measures that specifically aim at coping with multi-risk events, as these are rarely addressed in the tools and information available to risk managers. They stress that there is a need for the development of tools and methods that help increase preparedness for coping with such unexpected events.

Only a single pilot study, in the Gorenjska region (Slovenia), reports drought as a relevant hazard in current climate. Other pilot studies, e.g., in Stubaital, Arly River basin and Garmisch-Partenkirchen, point out that drought could be of importance in the future and has the potential to adversely affect the preconditions for other hazards to occur. In Slovenia, the sectors most affected by drought conditions in the past include agriculture, forestry and public water supply. The largest impacts were recorded in the agricultural sector where crop growth and livestock care are impacted. Increasing irrigation cost as well as increasing plant and animal disease strain finances of agricultural businesses. State subsidies had to be put in place. Forests were quite resilient in dealing with water scarcity, but they became increasingly vulnerable to pests. In combination with higher average temperatures the conditions for both cultivated forest and protective forest are expected to change and adaptation measures will be necessary to maintain healthy and resilient forests. Additional hazards, such as wildfires, can arise during drought periods, possibly affecting forests in higher altitudes with new impacts on sensitive ecosystems. Water demand is even higher when drought coincides with heatwaves. The demand reflects increased freshwater demand for population and livestock, irrigation demand, and possibly demand for firefighting efforts. The capacity to cope with prolonged drought conditions depends on the availability of backup sources in the supply system. In Gorenjska, small supply systems had to be supplemented through emergency water deliveries.

4.2.2. What-if Alpine-wide scenarios of mass movement impact events

The Alpine-wide mass movement impact models can be used to prepare for and mitigate future risks across the Alpine Space. One example of this is to use the models to quantify the contribution of key variables on mass movement impacts, such as the exposed infrastructure variables. This information can serve as an entry point for determining areas where mitigation measures are most effective. In Figure 9, a hypothetical scenario with fixed values for triggering (100 mm) and antecedent (50 mm) precipitation is used to quantify the effect of the exposed infrastructure variables. By applying fixed values to the infrastructure variables (based on average values across the Alpine Space) and comparing to predictions using the actual values, the degree to which exposure contributes to the probability score is shown. The difference maps (Insets C, F, I) show the extent to which exposed infrastructure increases or decreases the likelihood of mass movement impact events, with positive values representing increased risk and negative values representing a reduction in risk due to the lack of exposed infrastructure. For example, for the slide-type, the probability values in eastern Switzerland are relatively low (Inset A) and increase significantly with average exposure (Inset B), as shown by the blue values in Inset C. This means that despite the steep topography in this part of the Alps, the probability of an impact event in this scenario is relatively low due to the lack of exposed infrastructure in the PPAs. The rockfall maps are also interesting because the difference map (Inset I) shows many areas with negative values. This means that there are large areas of rockfall hazard that currently have little exposed infrastructure. However, risk levels could change drastically with increases in infrastructure within PPA.

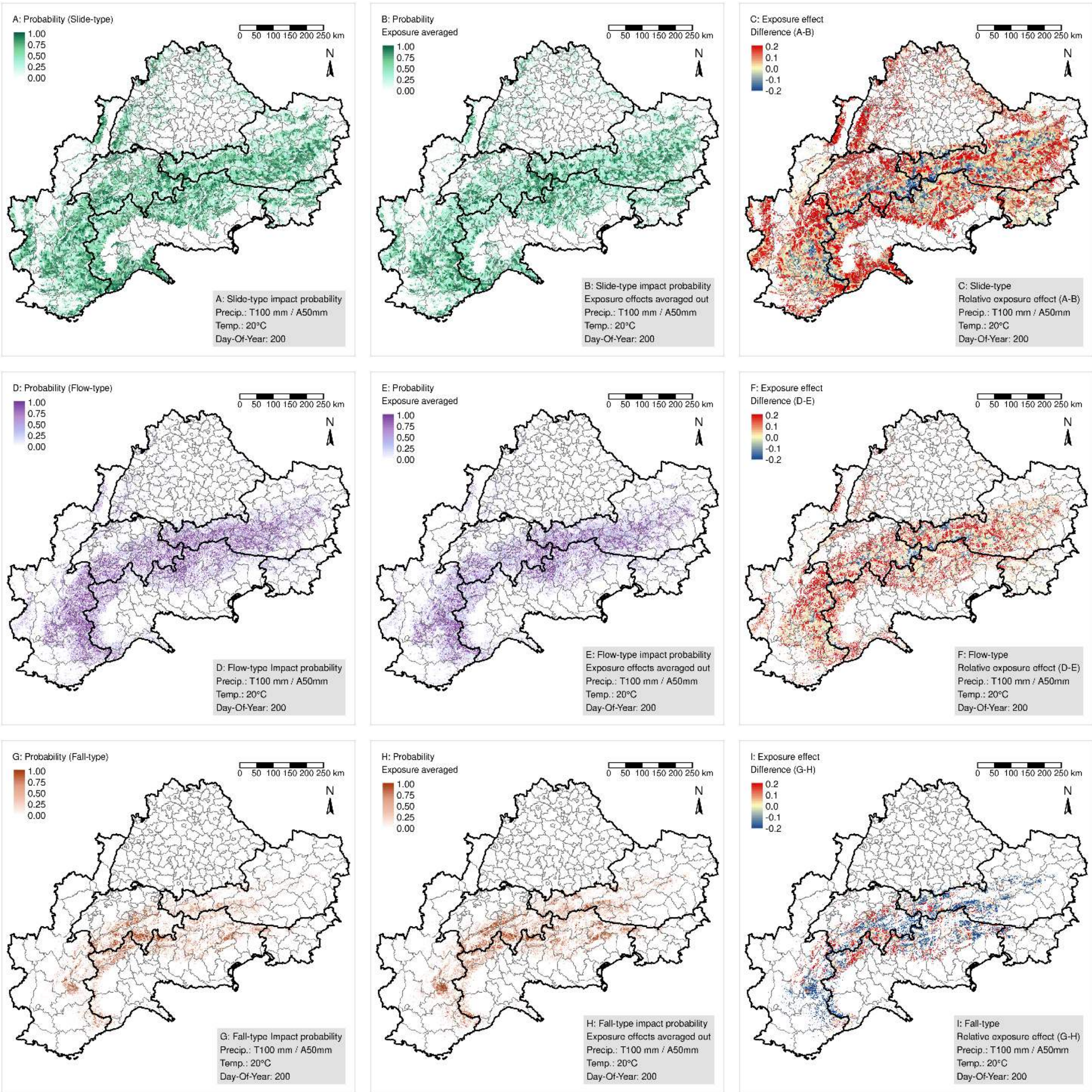

Figure 9: Comparing hypothetical scenarios with exposure variables included and averaged out. The difference in the predictions indicates the spatial variability in the importance of exposed infrastructure in determining expected impacts.

The impact models can also generate predictions of mass movement impact events for spatially uniform precipitation scenarios. An example of such scenarios is shown in Figure 10, which displays predictions using a triggering rainfall of 150 mm and antecedent rainfall of 200 mm for a typical summer day. The higher the probability value, the more likely it is that impact events will occur within the extent of the half-basin's PPA.

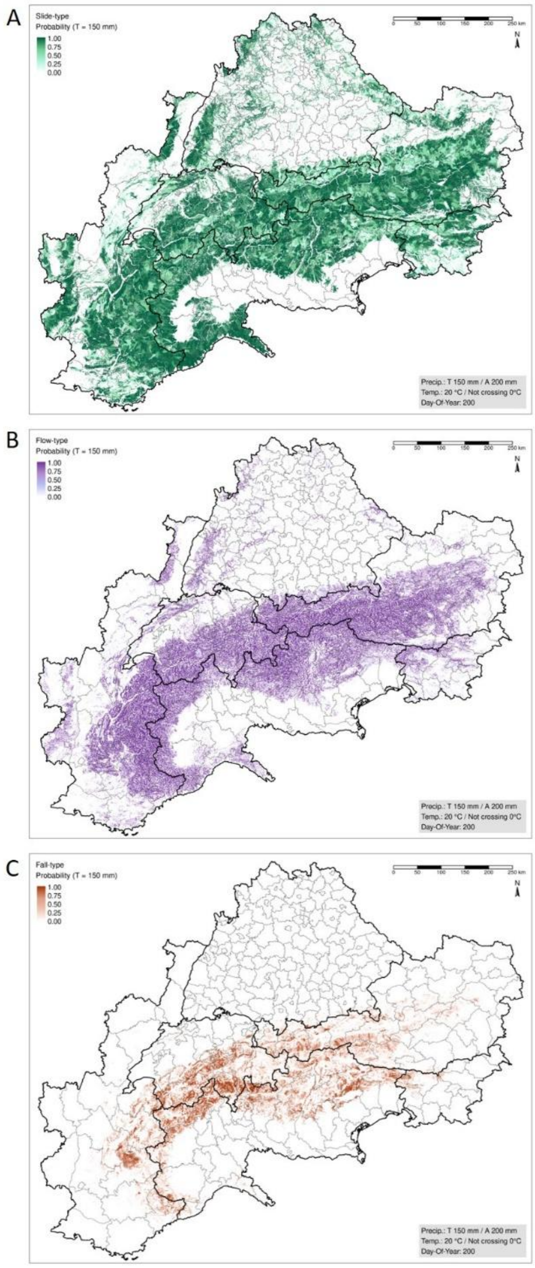

Figure 10: What-if scenarios using spatially uniform precipitation values.

5. Conclusions

The activities of Work Package 2 aimed to investigate the factors contributing to impacts and risks in the pilot areas due to weather extremes under climate change. This was achieved by analysing climate extremes, hazards, exposure, vulnerability, and risk management for both past events and future scenarios. Chapter 2 introduced multiple methods that were applied in five pilot areas and their sub-regions in the Alps and provided complementary information for assessing local risks. Conclusive remarks on the overall approach and main limitations are discussed here.

To build on the understanding of past events gained from developing sequential impact chains (see D 2.1.1), we suggested a structured investigation into the main contributors of risk (i.e., hazard, exposure, vulnerability and capacity) through a questionnaire. This approach was chosen to accommodate the diverse meteorological events and hazards at the centre of the pilot areas and the variety of studies, models and data available at local level.

While recommendations were made regarding the tools through which to investigate different contributing factors of risk, local partners were encouraged to use local models and refer to local studies whenever available. As a result, the risk questionnaires yield a broad variety of answers that are not immediately comparable across pilot level analyses. This is compounded by the fact that each local partner may choose to focus on aspects more relevant to their area of responsibility, where they have the greatest impact. To make the most of the risk questionnaire, it is recommended that these considerations are discussed with a group of local risk managers and decision makers from diverse areas of expertise.

Some partners opted to conduct quantitative investigations of risk for selected hazards in the pilot areas. However, there is a lack of quantitative approaches that cover multiple hazards and/or multi-risks, as most do not consider interactions and cascading effects. Moreover, existing approaches tend to require vast amounts of data. Since the focus of X-RISK-CC is on cascading and compound impacts and risks, the quantitative analyses performed in X-RISK-CC must be evaluated within the context of the compound and cascading effects that were described qualitatively.

The risk questionnaire asks local partners to make statements about the future developments, e.g., trends in population increases or tourism, in their respective region. In most cases, these were derived by extrapolating trends that were obtained from recent data. While it is common by now to think about the influence of climate change on our future living conditions in terms of scenarios (e.g., future conditions under different global warming levels), the possible influence of other trends, such as changes in exposure or vulnerability, are less likely to be treated in a similar manner. One of the reasons could be that it is difficult to make statements about some of the future developments e.g., effectiveness of future risk management or new building/zoning regulations. Nevertheless, it is reasonable to assume that some local developments will counteract the adverse effects of climate change on impacts and risks of extreme weather events.

Based on the knowledge collected from the risk questionnaires, climate risk storylines were developed as a tool to communicate a future plausible scenario. Their primary purpose is to facilitate discussions with local stakeholders about their capacities to mitigate, prepare for, respond to and recover from an extreme future weather event and its compound and cascading impacts and risks. The climate risk storylines, tailored to each pilot area and sub-region, were used in the local stakeholder workshops as part of X-RISK-CC Work Package 3, aiming to identify entry points for improving future local risk management practices.

Three impact-based models were developed to predict the impacts of extreme weather-induced mass movements (landslides, debris flows, and rockfalls) across the Alps, based on inventories from Austria and South Tyrol (2005–2021). Using a risk framework, hierarchical generalised additive mixed models (GAMMs) integrate meteorological, geological, hydrological, and land-use data with asset exposure. The models identify key societal and environmental drivers, supporting risk reduction across the Alpine region. Developed at a half-basin scale (17,872 units), they focus on process-relevant areas, including release zones and runout paths.

There is considerable potential for such impact models to be used in the context of impact-based early warning and preparedness planning. However, further research is required to identify and test the use of probability thresholds for warning purposes. The GAM models used here are classifiers that aim to predict the probability of class assignment. That is, on a given day and for a given spatial unit, what is the probability that the environmental, meteorological and societal conditions are such that they resemble those conditions where known (sampled) impact events have occurred in the past? Thus, future research is needed to identify appropriate thresholds for warnings and to translate class probabilities into actual occurrence probabilities, to facilitate with the interpretation of the maps.

The methods developed in Work Package 2 and documented in D 2.1.1 and D 2.2.1 will be included in the X-RISK-CC Manual, which comprises a conceptual framework to assess and manage risk across the Alpine Space and to derive rules for translating the newly generated knowledge on impacts/risks into concrete management practices.

Appendices

A. Risk Questionnaires
B. Climate Risk Storylines
C. Method description of Alpine-wide mass movement models

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Appendix A

Risk Questionnaires

1. Gorenjska, Slovenia

Interreg
Co-funded by the European Union
Alpine Space
X-RISK-CC

RISK QUESTIONNAIRE

SORA CATCHMENT - DROUGHT

(MULTI-) HAZARD ANALYSIS

Prepared by Slovenian Environment Agency with the support of Mihael Brenčič Ph. D. and Nives Vidmar, University of Ljubljana, Faculty of Natural Science and Engineering, Department of Geology

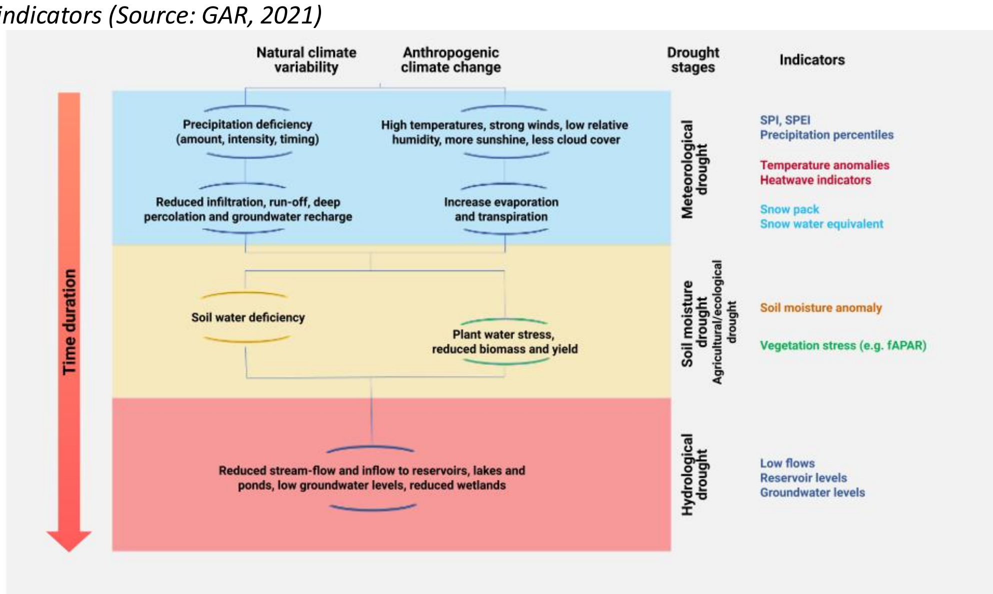
September 2024

Introduction to drought

(Extracted from Global Assessment Report on Disaster Risk Reduction, Special Report on Drought 2021, *italic letters – citations*; same understanding of the term "drought" in the project X-RISK-CC)

- **Definition**: *The Intergovernmental Panel on Climate Change (IPCC) defines drought as "a period of abnormally dry weather long enough to cause a serious hydrological imbalance" (IPCC, 2012). It results from a shortfall of precipitation over a certain period, from the inadequate timing or the ineffectiveness of the precipitation, and/or from a negative water balance due to an increased atmospheric water demand following high temperatures or strong winds* (higher evapotranspiration)*. Furthermore, a lack of snow- or glacier-melt following a drop in winter precipitation can cause or exacerbate drought* (GAR, 2021, p.26).
- **Duration, stages/types of drought**: *Droughts are slow-onset events that can last from weeks to years. They are often defined as meteorological, soil moisture (i.e. agricultural and ecological) or hydrological droughts* in surface waters and groundwaters*. In reality, these are progressive manifestations (or stages) of the same drought propagating through the hydrological cycle. A drought will likely have more-severe impacts as the propagation in the hydrological cycle advances* (GAR, 2021, p.26 -28).
- Because drought is a phenomenon whose start cannot be exactly defined and also propagate from one part of the hydrological cycle to another (from atmospheric water in precipitation system to soil water, and to recharge of surface water to groundwater) it is a creeping phenomenon (interpretation of drought first introduced by American meteorologist Tannehill in 1947) (Brenčič and Vidmar, 2024).

Figure 1: Schematic representation of drought propagation through the hydrological cycle, related drought stages and key indicators (Source: GAR, 2021)



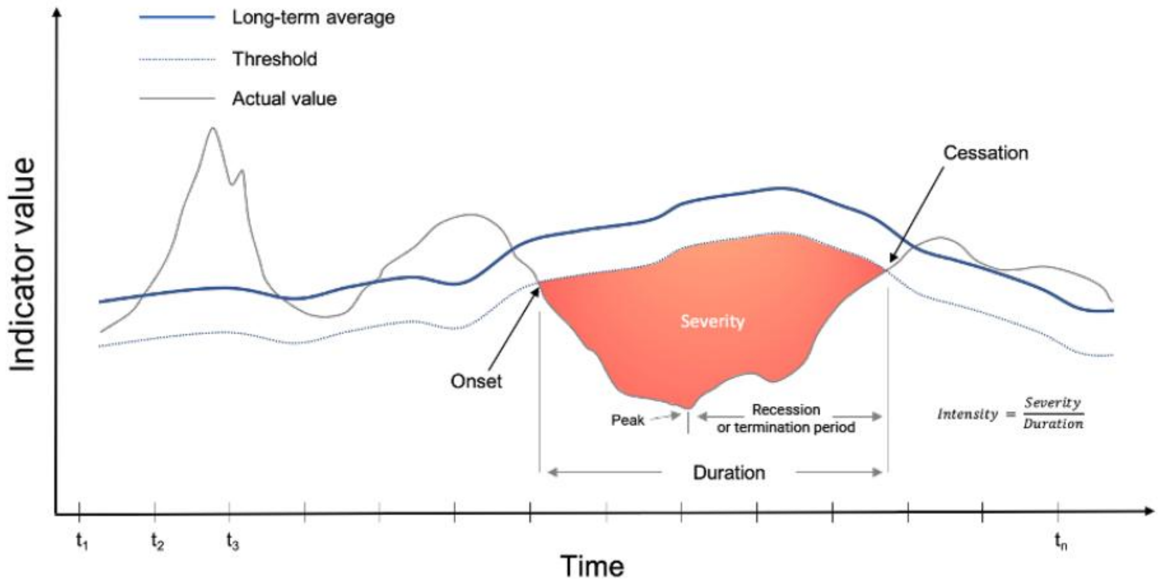
Note: fAPAR: fraction of absorbed photosynthetically active radiation; SPEI: standardized precipitation evapotranspiration index; SPI: standardized precipitation index.

Sources: Adapted from the National Drought Mitigation Centre, United States of America; Wilhite et al. (2014)

- **Flash droughts**: *Exceptions from the rule "*more-severe impacts as the propagation in the hydrological cycle advances" *are flash droughts, the concept of that recently emerged and describing quick-onset, severe events of water stress due to high temperatures and a high evaporative demand. Flash droughts" are short periods, usually less than 3 months, of high temperatures and/or strong winds, resulting in increased evapotranspiration and a fast depletion of soil moisture that can lead to major impacts, especially in the agricultural sector* (Mo and Lettenmaier, 2016; in GAR, 2021, p.26 -28).
- **Monitoring, drought detection**: *Droughts are usually monitored based on a series of hydrometeorological and land-surface indicators. A drought event is detected when one or several indicators fall below a given threshold for a defined period (e.g. 1 or 2 months). The threshold is often defined as a negative deviation in units of standard deviation from the long-term average or as a*

percentile. This threshold is variable during the year and depends on the indicator(s) monitored (GAR, 2021, p.26).

Figure 2: Schematic representation of selected key drought parameters (Source: GAR, 2021)



- **Detection and drought impacts**: *The use of several indicators allows for consideration of drought propagation through the hydrological cycle and for monitoring impacts in different economic sectors and on the environment. Drought impacts may linger for a significant time period, even after the hydrometeorological indicators return to normal. Defining discrete drought events is important for quantifying loss and damage from extreme climatic events and for policy implementation* (GAR, 2021, p.xii).
- **Drought as a disaster:** *Not all droughts result in disasters. A drought becomes hazardous when water demands are no longer met and becomes a risk when there is a diminishing capacity to cope with the lack of water. This risk can result in dangerous consequences for people's livelihoods, the economy, ecosystems' health, and even the lives of humans and animals* (GAR, 2021, p.xiv).

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

In this report **drought** is considered **as weather extreme and hazard,** which is observed via drought indices that were used for detection of past droughts and their severity (see WP1 pilot report).
In the frame of the project, following weather extremes / hazards were thoroughly studied in the pilot area:

- Top-soil drought
- Heatwaves
- Compound drought and heatwave events
- Groundwater drought

Additionally, also drought in surface waters was observed in the pilot area via drought index based on river discharge and anomalies (1993, 2003, 2012, 2022) (Cvelfer Domadenik et al, 2023), but no major impacts were recorded. Due to the fact, it was decided that surface water drought will not be analysed in the frame of the project.

a) Past/present weather extremes

Top-soil droughts and heatwaves, compound events:
Top-soil drought in growing season months resulted from **extended periods of below average precipitation,** while some developed and intensified rapidly due to **co-occurrence with heatwaves/high temperatures (flash droughts**). Several compound drought and heatwave events have also been observed in recent years.

The three most severe drought events recorded in the area in the last 20 years exhibited severely to extremely dry conditions based on the SPEI, in the years 2003, 2013 and the most recent in the growing season 2022. The most extreme of those was in 2022 and it has an estimated return period of approximately 60 years with a 90 % confidence interval.

The intensity of drought conditions on shorter timescales (1 to 2 months) has been slightly increasing with time since 1970. On average, the number of dry months and severely dry months has also increased in the last few decades in the region.

The number of heatwaves, the number of heatwave days and the maximum heatwave magnitude have been increasing across the case study area since 1950.

- The average highest number of heatwaves and the highest average number of heatwave days occurred in 2003 with 7 or more heatwaves, the longest lasting 10-23 days and between 34-46 heatwave days.
- 2013 saw the highest average maximum magnitude of a heatwave since 1950 which was between 43-55 and over 50 on half of the stations in the Sora River catchment. The return period of this magnitude is estimated at 22-38 years. The maximum magnitudes of heatwaves with return periods 25, 50, and 100 years are estimated to be 42-49, 48-60, and 55-73, respectively.

Several compound drought and heatwave events have also been observed in recent years; the number and the magnitude of those compound events also show an increase at certain locations.

Summary of trends: Historical data shows an increase in frequency of occurrence of circulation patterns that reinforce drought. Comparing two consecutive 30-year periods, the number of dry and severely dry months shows an increase. The growing season minimum SPEI value is showing a negative trend, anticipating a higher intensity topsoil drought in the future. Occurrence and magnitude of heatwaves has also been increasing since 1950-2023.

Groundwater drought:

Aquifer in the lower flat part of the area - Kranj-Sora alluvial aquifer; in the pilot area only part of this alluvial): Using the *Standardized Groundwater Index (SGI)* and the average monthly groundwater level to analyse the groundwater level data at the Sveti Duh station between 1981-2023, there is a statistically significant decrease between April and July. The SGI also shows a decrease for the entire analysed period. The calculation of SGI at 10 locations of stations from 1986-2010 in the same aquifer, the most recent extreme groundwater droughts with the SGI below the value of -2 since the effect of decreasing groundwater level due to the river dam has been slowed down were in 2002, 2003, 2005, 2006, 2009 and 2010 (Brenčič and Vidmar, 2024). The same analysis showed a decreasing average SGI value for the Sora alluvial aquifer comparing three consecutive 30-year periods as well as most other alluvial aquifers in Slovenia, and an increasing number of months with SGI values under -1.

Situation on 4 control points (mountainous area, small recharge watershed) – information on locations and detailed analysis see Pilot report in X-RISK-CC Digital Library):
In the period 1971–2023, according to the data of *groundwater recharge*, there were severe droughts (95th percentile) between March and August in the years 1993 and 2022. In the same time span, the following years had moderate droughts (75th percentile): 1997, 2003, 2011, 2012, 2015, and 2017.

A comparison of the *soil water deficit index* (SWD) for two 30-year periods, 1971-2000 and 1991-2020, shows that there were more drought days and more consecutive drought days in the period 1991-2020. The years 1992, 1993, 2003 and 2022 stand out as the years with the most drought days (ndSWD60), especially the years 1993 and 2023.

In the period 1971–2023, according to the data of *groundwater recharge (Qrn),* there were severe droughts (95th percentile) between March and August in the years 1993 and 2022. In the same time span, the following years had moderate droughts (75th percentile): 1997, 2003, 2011, 2012, 2015, and 2017.

b) Potential future weather extremes

Top-soil drought, heatwaves, compound

In the future, both droughts and heatwaves are expected to become more severe and more frequent under all global warming levels. The **frequency** of compound drought and heatwave events is expected to increase by between 1 to 5 events annually under global warming level of 3 to 4 °C, corresponding to a relative increase from 15 to over 100 %. Regardless of the global warming level, the intensity of future events is expected to increase by 40 % to 150 %.

The **probability of occurrence** of individual drought and heatwave events, as well as the occurrence of compound drought and heatwave events are expected to increase in the future. A compound drought and heatwave event as extreme as the 1-in-50-year event in 1991–2020 is projected to become up to 6–8 times as likely under global warming level of 3 °C and up to 12–13.5 times as likely under global warming level of 4 °C.

Groundwater drought

In the future, net groundwater recharge (Qrn) in the period from March to August is expected to remain similar to the median values in the reference period 1991–2020, mainly due to winter and spring precipitation. Other indices have not yet been evaluated. Return periods have not been calculated either for groundwater levels or for the values derived from them, as this is not a commonly used methodology in hydrogeology.

II. Which hazard processes can be triggered by current and future weather extremes?

Drought in combination with heatwaves as weather extreme and hazard, and also groundwater drought, are described in previous chapter I with the focus on the specific events, their trends in the past and for the future. In this chapter the focus is on cascading hazards or impacts in the natural environment.
In drought conditions, especially in combination with heatwaves, other hazards can be triggered as a cascading effect in the pilot area:

- → **wildfires, forest fires** and related **air pollution**
- → **animal and plant diseases** (e.g. bark beetle)

While droughts are not usually thought to **contribute to the occurrence of floods** due to depleted water storage, they can <u>change the runoff processes</u> by changes in vegetation and infiltration process that also depend on the process of drought recovery, climate, soil characteristics, human activities and other.

Similarly, other events, such as **wildfires after droughts**, **floods after wildfires**, **landslides after wildfires** are possible and can occur, triggering a sort of a hazard chain of events.

A case when one event/hazard follow by another from the past
In the past, it was not the case in the pilot area that one extreme event would follow by other. There were some years when flood (in autumn) followed drought (in summer). Such years were 2007 and 2022, but only one of the events was extreme according to its impacts.
Y. 2007: the flood in autumn was really extreme. But the drought in summer before was relatively mild with impacts that were not strong enough to be relevant for later flood impacts.
Y. 2022: there was an exceptional drought (according to statistics and reported impacts)
- in top-soil (declared natural disaster on national level due to impacts in agriculture; additionally impacts in forests, wildfires (5 ha in 2022)),
- in groundwater aquifers (lack of water in local water supply systems - help of fire brigades, also restrictions in water supply systems fed from larger and deeper aquifers),
- in surface water according to the percentile analysis of river flow (we have not studied impacts yet, nothing dramatic according to brief check of available reports)
After the 2022 drought, September brought strong and long-lasting downpours which caused high water flows and flooding in the Sora River catchment, reaching even the 2nd highest discharge since 1950 on the Poljanska Sora River in Žiri with a return period estimated between 20-50 years (Brenčič and Vidmar, 2024), but impacts were not as extreme as in the year 2007 in Selška Sora catchment.

III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

Past/present and potential future frequencies and magnitudes

Past/present and potential future frequencies and magnitudes related top-soil drought, heatwaves and groundwater drought are described more in detail **in Chapter 1 related to weather extremes.**

Table 1: Trends in frequency and intensity of different hazards detected in the Sora catchment pilot area in the past and for the future.

	Past		Future (under GWL 2°C, 3°C or 4°C)	
	Frequency	Intensity	Frequency	Intensity
Top-soil drought (SPEI)	↗	↗	↗	↗
Heatwaves (HW)	↗	↗	↗	↗
Flash drought – Compound (CDHW)	↗ *	↗ *	↗	↗
Groundwater drought Standardized Groundwater Index SGI (larger, aluvial aquifer)	↗ April-July**	↗ April-July**	na	na
Soil Water Deficit (SWD) (small recharge watershed)	↗	↗	na	na
Groundwater recharge Qrn (small recharge watershed)	↗	↗	→ ***	→ ***

*at certain locations

** Statically significant only for those months

*** Groundwater – explanation: The mGROWA water balance model is distributed raster model. We estimate small local watershed recharge as modelled groundwater recharge. Information on groundwater recharge is especially important for smaller local water supply watersheds, because these are more susceptible to water shortages due to small aquifer yields. For bigger aquifers the issues are not expected as these are more resilient. The mGROWA water balance results are based on climate change scenarios and are the results of expected future impacts on water balance. The results of annual groundwater recharge are in general showing slightly increasing trend, but the significancy of the results is low due to small expected changes. The situation could be different dry summer periods in the future, but the scenarios for that are even more disperse.

↗ more intensive, more frequent

→ no significant changes

↘ less intensive, less frequent

As seen in the table above, the frequency and intensity of individual drought and heatwave events, as well as the occurrence of compound drought and heatwave events are expected to increase in the future and in relation to that there is high likelihood of **increase of other related cascading hazards in the future**:

- **Wildfires**
- **Animal and plant diseases, pests** (e.g. bark beetle)

In case of heavy precipitation followed by wildfires and damaged forests due to diseases or pests, the landscape would be also more exposed to **landslides and debris flows**.

Additional data on **Wildfires** in the Sora catchment

Data on wildfires are available since the year 2005, when the information on interventions of fire brigades is systematically collected and entered into the national application SOS SPIN.

Table 2: Wildfires in the Sora catchment in the years 2005 – 2023.

Year	**Number of fires**	**Affected area** in ha	**Damage** in eur
2005	17	5	0
2006	21	1,16	2000
2007	22	4,75	10000
2008	10	0,31	0
2009	13	0,07	0
2010	14	1,86	0
2011	16	33,06	12000
2012	22	32,61	0
2013	25	4,59	2000
2014	8	0	2000
2015	22	1,51	6000
2016	8	2,12	2000
2017	39	11,84	18000
2018	7	2	0
2019	11	2,04	2000
2020	19	5,32	4000
2021	9	0,28	2000
2022	32	5,27	10000
2023	7	0	2000

**Source: https://spin3.sos112.si/javno/porocilo (Poročilo > Požari (fires) > Select Občine (Municipality))*

According to the short dataset above and the opinion of the forestry expert from Slovenia Forest Service, drought and the occurrence of wildfires (number, extent) was not correlated in the past in the pilot area. The forests in the area are not highly vulnerable to drought. Because of the expected increase of frequency and magnitude of droughts and heatwaves for the area, it is expected in the future at least a slight increase in number and extent of the wildfires/forest fires.

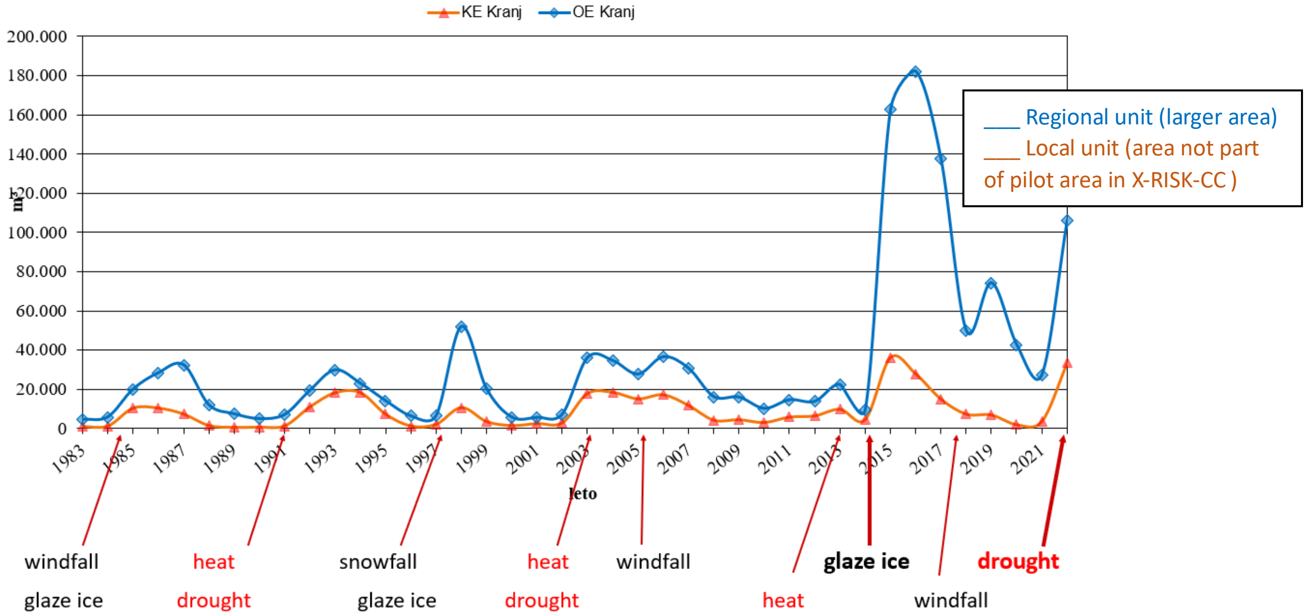
Animal, plant diseases, pests

Prolonged droughts in coniferous forests can cause direct physiological damage and increase the susceptibility of pines to fungal diseases. Droughts can cause widespread tree mortality due to failure of the plant hydraulic system (Choat et al., 2018). Drought stress can promote outbreaks of plant-eating fungi and insects. Agriculture and forestry can be seriously damaged as droughts favour the proliferation of pests (GAR, 2021, p. 49,50)

In the pilot area, Forestry service monitor (and manage) different diseases and pests in the forests, which covers 71 % of the pilot area. Because of the complexity of the forest ecosystems, the factors that contribute to the occurrence of the diseases and pests could not be monitored separately i.e. drought, heat, windfall, glaze, snow-breaks.

Figure 3 shows trend in the number of affected trees due to bark beetles in the nineteen years. In the bottom of graph an occurrence of different natural disasters/weather extremes are marked. It can be seen, that after each weather extreme affecting forests/trees the occurrence of bark beetle increase.

Figure 3: Number of affected trees due to bark beetles in the years 1983 – 2022 taking into account information of different natural disasters/weather extremes which contribute to the occurrence of bark beetle.



Source: Slovenia Forest Service, Regional unit Kranj, 2023 (internal documents)

In the future it is expected increase the occurrence of barkbeetles in the forests with high percentage of coniferous.

IDENTIFICATION OF KEY HAZARDS

Table 3: Identified hazard processes (observed and novel) in the Sora catchment.

Event	Event type (Cascading, Compound, Single)	Observed/ potential	Likelihood (low, medium, high)	Adverse consequences (taking into account past events in the area) (low, moderate, high) linked to that hazard process, considering the spatial extent of the hazard and the types of elements that may be affected	Irreversibility of consequences	Potential cascading effects (e.g. based on time-space-coincidence of hazard processes)	Dependence on risk management measures for coping with the event (mitigation, preparedness)
Top-soil drought	single	Observed	high	Medium (Agriculture, Forestry)	In Agriculture – Drought damage to crop yield is irreversible within a particular growth season, Forestry – growth of wood; usually forest recovers under a certain time frame	Wildfires Animal, plant diseases	Agriculture – irrigation systems, selection of crops less vulnerable to drought Forestry: sustainable forest management
Heatwaves	single	Observed	high	Medium (Agriculture, Forestry)	Impacts on Agriculture, Forestry	Wildfires Animal, plant diseases	Agriculture- ?? Forestry – in case of afforestation, selection of more resistant species
Flash drought Compound	compound	Observed	high	Medium (Agriculture, Forestry)	Agriculture, Forestry – annual yield	Wildfires Animal, plant diseases	Above- D & HW
Groundwater drought	single	Observed	medium	Medium (Water supply)	Deterioration of water quality, loss of recharge capacity	Groundwater in aquifers related to surface waters/ecosystems: - Reduced surface water availability- lower streamflow - surface water scarcity, - loss of aquatic and riparian ecosystems- shrinking wetlands,	Measures related to water supply Measures related to reducing pollution
Wildfires	cascading (followed by drought)	Observed	medium	Low (Forestry, ecosystems)	Forest recovery takes decades	Air pollution Extreme precipitation followed by wildfires >	Measures related to forest management

Event	Event type (Cascading, Compound, Single)	Observed/ potential	Likelihood (low, medium, high)	Adverse consequences (taking into account past events in the area) (low, moderate, high) linked to that hazard process, considering the spatial extent of the hazard and the types of elements that may be affected	Irreversibility of consequences	Potential cascading effects (e.g. based on time-space-coincidence of hazard processes)	Dependence on risk management measures for coping with the event (mitigation, preparedness)
						floods and debris flow, landslides	
Animal, plat diseases (barkbeetle)	cascading (followed by drought and other)	Observed	medium	Medium (Forestry, ecosystems…	Forest recovery takes decades		Extent of impacts depends on implementation of sustainable forest management
Extreme precipitation followed by wildfires > floods and debris flow, landslides	cascading	Potential for the case of one extreme followed by another		Settlements: infrastructure, buildings > see Risk q. on floods			

* In the Sora catchment, all types of drought were observed in the past according to meteorological and hydrological drought indices (based on deviations from reference periods), but drought impacts were more evident in sectors related to topsoil drought and hydrological drought in groundwater - drought in surface waters not part of the analysis

Depending on severity, magnitude and return period, drought can have several, variegated and adverse consequences. They can be related to different sectors in the region. For Sora River catchment, in the past adverse consequences occurred in the following sectors: agriculture, forestry and water supply. For the future there is possibility for additional potential consequences in public health, built environment and infrastructure, tourism, other land uses and civil protection systems.

Irreversibility level of drought consequences depends on the duration of drought and the time frame inside of which irreversibility is defined. This can be illustrated by the crop yield. Drought damage to crop yield is irreversible within a particular growth season. If drought has a multi seasonal length of several years, irreversibility can exist for longer time periods. Similar considerations can be presented for the forestry sector, since drying and recovering of the forest depends on the drought characteristics, usually forest recovers under a certain time frame. In the case of cascading events where fire occurs as a drought consequence, the recovery and irreversibility time frame can be much longer. At the present climatic conditions in the Sora catchment area, multi seasonal droughts have a low realisation probability, however in the future, the probability of their realisation is higher (Brenčič and Vidmar, 2024).

ANALYSIS OF KEY RISK PATHWAYS

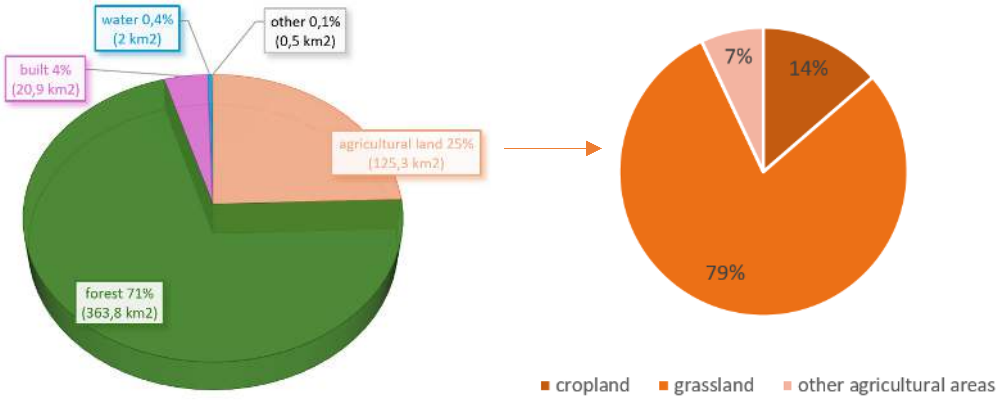
IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

a) Past/present exposure and impacts

i. Directly exposed elements.

In the event of drought, the entire pilot area is exposed to drought. **The pilot area measures 512,5 km2 and the population was 43276** in y. 2024 (Source: SURS, 2024)
. The type of land use is related to some specific impacts and impacted sectors – **on agriculture, forestry, (ecosystems)**.

Figure 4: Land use structure in the pilot area – <u>potentially exposed</u> agricultural and forest to drought areas (see also the land use map in appendix).



Source: MKGP, 2024

<u>Agriculture</u>:
Agriculture can be adversely affected if a drought damage crops and other related losses. Farmers may spend more money due to increasing irrigation costs, or feeding and providing water to their animals (GAR, 2021, p.45)

As shown in the Figure 4, agricultural land covers 25% of the pilot area (125,3 km^2). The largest share of agricultural land is grassland and pastures, 14% is cropland with arable fields, gardens, permanent crops such as orchards and vineyards, and 7% is other agricultural land.
From society perspective, farmers or agricultural holdings are most directly exposed to droughts and other natural disasters affecting agriculture production. In the pilot area there were 1627 of agricultural holdings in y. 2010 and 1491 in y. 2020 (Source: SURS, 2024) – their number is declining.

In Slovenia (and on the pilot area) drought impacts or damage in agriculture are systematically collected only in case drought is declared as a natural disaster on national level. The condition for this declaration is that the final assessment of damage to agricultural products exceeds 0,3 ‰ GDP taking into account the areas where agricultural production is reduced by more than 30% of normal annual production due to drought. Impacts are entered into national AJDA system since the year 2005 (and available for analysis).

In the last 2 decades, there were 4 droughts declared as natural disaster and that affected pilot area – years 2001, 2003, 2013 and 2022. Impact data are available for the y. 2013 and 2022. (Table 4).

Table 4: Impacts in agriculture in the year 2013 and 2022 (drought declared as natural disaster) in the pilot area (municipalities Škofja Loka, Gorenja vas-Poljane, Železniki, Žiri).

Year	**2022**	**2013**
Affected area	55 km^2 (44% of all agricultural area)	19,4 km^2
Damage (in eur)	2.017.892,76 eur	536.835,25 eur
Affected agricultural holdings - No. of for reimbursement)	610 (cca 40% of all agri. holdings)	220 (cca 14% of all agri. holdings)
Most affected crops (% of crops damaged)	- Permanent grassland and pastures (50%) - Silage maize (50%), - Meadow orchards (40%) - and others (less)	- Permanent grassland (35%), - Silage maize (45%) - others (less)

(Source: AJDA system, URSZR, 2023; RS Statistical Office https://www.stat.si/StatWeb

Forestry (forests, ecosystems):

Forests covers forth fifths of the area (71%) and if taking into account the size criteria, this is the most directly exposed element. According to the forest expert (Slovenia Forest Service, reg. unit Kranj), the forests in the pilot area are not highly vulnerable to drought. Usually, on the pilot area, the damage is only temporary and the habitat return to normal when the drought is over, in more extreme drought conditions and cascading effect of plant diseases, a recovery to normal conditions takes several years.

More vulnerable to bark beetle attack are conifers, which represents 60 % of the wood stock in the pilot area (ZGS, Forest management plans of forestry units, 2023).

In case of severe/extreme drought, forestry is affected by reduced fibre production and increased vulnerability to pests and insect attacks (e.g. bark beetle).

Public water supply:

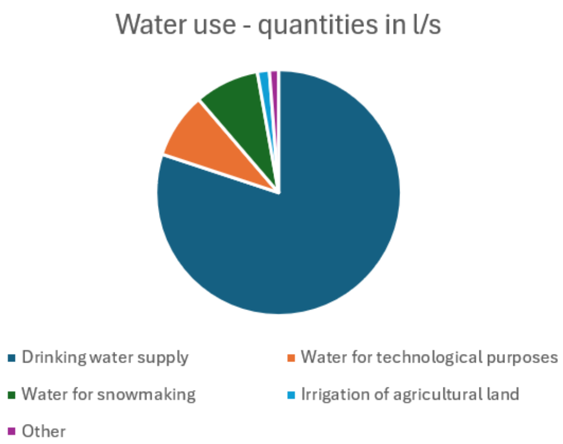
Drought conditions decrease water supply and increase demand for various uses (e.g. industrial, agriculture, residential, sanitation and wastewater management). Co-occurrence with heatwaves can aggravate impacts due to increased demand. Reductions in the available quantity of water can have secondary effects on water quality due to reduced dilution of pollutants (GAR, 2021, p.45)

In the Sora catchment, the settlements are relatively dispersed, except in larger municipality centres (Železniki, Žiri, Gorenja vas) and in the city of Škofja Loka. The existing settlement pattern influences the communal infrastructure with water supply systems. Outside of the concentrated settlements, there are relatively many smaller water-supply systems which are more vulnerable to droughts and heatwaves.

In the pilot area there are two bigger public water supply systems managed by utility company Škofja Loka and several smaller supply systems connected to local water sources. Systems with less than 50 consumers are privately owned, and part of the tasks are covered by the municipality of Škofja Loka. Bigger public supply systems are designed to have multiple water sources and multiple backup water sources, which are dispersed. One of the important backup water sources is located at Visoko (Poljanska Sora catchment) and the other Kranj-Sora alluvial aquifer, which is abundant water source, although not very good quality. In the areas of smaller water supply systems there were increased number of water deliveries in drought years as shown in Table 6.

Table 5/ Figure 5: Exposed elements related to the water use.

	Quantity l/s	%
Drinking water supply	770,85	80,1
Water for technological purposes	83,22	8,6
Water for snowmaking	81,90	8,5
Irrigation of agricultural land	15,20	1,6
Other	11,62	1,2
TOTAL	962,80	100,0



*Water for small hydropower, mills and sawmills, heat generation, fish farming and ponds not included (return flows, equal discharges)
Source: Brenčič and Vidmar 2024; Water book, 2024, https://podatki.gov.si/dataset/vodna-knjiga

In case of water shortage or contamination, the fire brigades as a part of civil protection delivers water to the residents. Data on water delivery by fire brigades are publicly available for the years 2019-2024. (SURS, 2024, https://spin3.sos112.si/javno/porocilo/oskrbanaselje). In this database all water deliveries by civil protection/firefighters are included regardless of the cause (water shortage, contamination). In non-drought years, number of deliveries varied from 10 to 40 and quantity of delivered water was from 60 to 150 m^3. In a drought year 2022, there was 129 deliveries and 835 m^3 of water delivered to the residents.
Data shows an increased water delivery needs during the 2022 drought. The number of deliveries rose 4-7 times than in the previous years and the total amount of delivered water increased by 5-10 times.

Table 6: Water delivery by fire brigades in pilot from 2019 to 2024.

Year	Number of water deliveries	Quantity of delivered water (m^3)
2019	19	92
2020	21	81
2021	31	155
2022	129	835
2023	13	66
2024	20	14

Source: SOS SPIN, 2024

Besides above mentioned directly exposed elements and impacts, there are probably also other impacts which were not recorded during the extreme drought events as impacts on other ecosystems in general (small lowland forests, water ecosystems - wetlands, small watercourses and fish mortality in case of dried-up stream beds).

ii. Indirectly exposed elements

There is no precise data on elements indirectly exposed by drought. These impacts can be estimated based on general knowledge of the area. Indirect impacts can occur on elements in different sectors: agriculture, forestry, public health, other land use, ecosystems and tourism. Currently, only minor impacts on infrastructure and building sector are expected.

For the Sora catchment, it is estimated that in past drought events, indirectly exposed elements were probably predominantly present in forestry and agriculture sector affecting the occurrence of plant and animal diseases. The damage to agriculture affected the economy of farmers and increased the pressure on the state to release funds (subsidies)

Tourism in the area generates lower revenue compared to some other regions in Gorenjska (e.g., Bled), but is more boutique, sustainable and focuses on small businesses in mountain valleys (promotion of local characteristics and specialties, outdoor activities) and the town Škofja Loka. There are no known reports of the impacts of past droughts on tourism, but it may be affected primarily by shortages in drinking water supplies. Heatwaves have probably affected the outdoor activities of tourists and the overall number of their visits to the region.
Additionally, there are also several smaller ski resorts in the area (Stari vrh, Soriška planina, Rudno), and all of them have possibility of snowmaking. As can be seen from Table 5, water use for snowmaking accounts for 8.5%, which could affect winter tourism in the event of temperatures too high for snowmaking (cases in the past) or in the event of winter drought in terms of water scarcity (could be concern for the future).

As the Sora area is at relatively high altitude, drought and heatwaves are generally expected to have little impact on the inhabitants' health. However, as there is some evidence at state level that heatwaves are already affecting public health, it is possible that there are impacts particularly in the lower parts of the area. However, there is no reliable data on this phenomenon.

b) Potential future exposure and impacts

i. Directly exposed elements.

According to the future projections, a general increase in intensity and numbers of drought events in the growing season is expected, also in combination with heatwaves. The increase will occur in any case, only its extent will vary depending on the realisation of the scenario.

Exposed population (in total): The population in the area is relatively stable with slight increase (SURS, 2024) and it is expected to stay stable in the future.

Agriculture and Forestry:
Exposed agricultural land and holdings: The strategic documents promote the development of the rural areas, the preservation of the agricultural landscape and agricultural land. The number of farmers/agricultural holdings in the area is declining, but there is a tendency to maintain farms through sub-strategies. It is therefore assumed that the number of exposed farms will not decrease significantly and the size of agricultural land will remain roughly the same.

Due to expected increase in number and intensity of events, it is expected that in agriculture and in forestry the total affected area and consequently economic damage will increase. With information and data currently available, it is not possible to estimate future impacts more in detail.

Water supply:
Due to the characteristics of the drinking water supply in the area with the increasing number of drought and heatwaves events, it is expected that the number and duration of incidents with interruption of water supply will increase. This will result in larger quantities of drinking water delivered by trucks/fire tankers (e.g. by fire brigades). This will also cause an increase in the number of truck transports as the water supply of the settlements in large parts of the area are dependent on small water resources vulnerable to drought and relatively widely dispersed. If the available empirical data on past drought events is reliable, the demand is expected to increase at least 4-times with each new drought event of a higher magnitude (Brenčič and Vidmar, 2024).
A problem could be also availability of water in a case of the wildfires or other fires.

ii. Indirectly exposed elements

Indirectly exposed elements in the future will depend on building the socio-economic resilience of society in general, at national and local level. If adaptation measures are implemented, the impacts will be smaller than without them. Therefore, it is crucial to develop future adaptation measures to climate change. Currently, there is no known programmes including concrete adaptation measures to future drought conditions outside the agricultural sector. Without them it is not possible to estimate impacts of directly and especially indirectly exposed elements to droughts (Brenčič and Vidmar, 2024).

It is expected that with the increasing number of droughts and heatwaves, and their increasing frequency and magnitude the following element will be more exposed:

- Public health system.
- Agriculture and forestry - more plant and animal diseases; occurrence of will be more invasive species will appear in both sectors as well as in natural ecosystems.
- Tourism can be also affected by increasing number of droughts and heatwaves, especially at lower parts of the area. At the same time, smaller touristic enterprises at higher altitudes can benefit due to more agreeable air temperatures compared to the lower parts.
- By compound drought and heatwave, elements in buildings and infrastructure can be exposed. Among them are the impacts on road pavement, rail embankments, structural elements of the bridges and energy transfer network which all are present in the area.

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

The vulnerability depends on many factors, mainly related to physical and social aspects.
The physical vulnerability i.e., the predisposing/preparatory factors, take into account for the specific features of the territory (i.e., morphology, presence/absence of forest, availability of sediments, glacier melt) and of the exposed asset (i.e., how buildings, roads and infrastructures are constructed, their age and maintenance status). It also considers the potential damage that the exposed assets can undertake, which in turn depends on the hazard type, intensity and duration.
The social vulnerability i.e., the pre-impact vulnerability factors, depends mainly on people i.e., their age, their risk perception and preparedness, their education level and the level of communication with risk managers during the emergency phase.

a) Current vulnerability factors (following directly exposed elements to drought and heat from the Q. IV)

The factors that contribute to the **physical vulnerability** (the predisposing/preparatory factors:
Public water supply:

- Higher vulnerability of people and agriculture (water for irrigation) in parts where water supply system is depended on shallow, small aquifers.

Agriculture:

- Agriculture production is more vulnerable to drought in the areas of gravelly soils (most of the lowlands in the pilot) and on the sunny slopes, where most of the agricultural land is located in the high altitudes.
- During periods of drought, the demand for irrigation water and for livestock farming is also higher. Where water supply systems are fed from shallow, small aquifers, there is a higher likelihood of water shortages.

Forestry (forests, ecosystems):

- Forests that have already been damaged by snowfall, windthrow or forest fires are more vulnerable to drought, heat waves, and cascading bark beetle infestation.

The factors that contribute to the **social vulnerability** (the pre-impact vulnerability factors)

- Missing coordinated drought management protocols at the local (and national) scale
- Analysis of current water permits (and related quantity of water) show that only 1,6 % of all registered water usage is for irrigation, which is a small share of renewable water quantities in the region.
- The vulnerability of agriculture is exacerbated by the fact that in the event of water scarcity, the use of drinking water takes precedence over other uses, such as irrigation. In the event of conflicts of interest, drinking water use has absolute priority, while other uses are not yet prioritised - this is not yet systemically regulated in Slovenia.
- Lack of adaptation measures for climate change in the operative level – missing vulnerability maps for different crops and introducing drought and heat-resistant crops, water retentions, potential new water resources…)
- Lack of impact – based forecasts

b) Potential future vulnerability factors

Among sectors, social vulnerability to drought is most profound in the public health system where the current impact of drought and heat waves is unknown. There are indicators (e.g. media reports) that they already have an impact on mortality rate as well as on the chronical diseases, but no exact data is available at the state level and consequently it is not possible to downscale them to the municipality level and on the area of the Sora catchment. Future impacts are dependent upon adaptive measures of public health system to climate change but based on the current development trends in this sector and aging structure of population, situation is not optimistic (Brenčič and Vidmar, 2024).

Social vulnerability is also relevant to the supply and demand of water. According to the evidence of water use permissions (water permissions and special use of water permissions) in the region of Sora catchment, their large part is represented by the drinking water supply. They are also relatively numerous which means that they are related to drinking water supplies of numerous people in individual houses or smaller settlements. At the same time, geological and hydrogeological conditions in their recharge area are not favourable to develop more extensive aquifers (shale and sandstone rocks are prevailing). A characteristic of these water resources is a relatively low yield and a relatively shallow recharge area which is very vulnerable to the impacts of higher air temperatures. On one side, air temperature influences yield and on the other, it has an impact on the temperature of the water which can cause sanitary and hygiene problems. In the case of severe drought occurrence, they can completely dry out. Such conditions have already been experienced in the region (see analysis above) (Brenčič and Vidmar, 2024).

The entire drinking water supply infrastructure (transport pipes, reservoirs) is also sensitive to heat waves. Existing water supply infrastructure in the area was constructed in the period when air temperatures were lower, and during winter months, snow was present for longer periods. Today and especially in the future, it is expected that snow will appear only occasionally. As a result, air temperature fluctuations are penetrating deeper, heating pipes in the ground. A similar situation is related to the water reservoirs (e.g. pressure compensation reservoirs, storage reservoirs) in the water supply network. Warming of drinking water inside of the water supply is not acceptable. In the presence of damages in the system, it can cause intrusion of various biological agencies (e.g. bacteria, viruses, parasites) which can harm the quality of drinking water, and it can have deleterious consequences on the water consumers. If this happens in the water supply systems supplying larger number of inhabitants, it can have larger socio-economic consequences (Brenčič and Vidmar, 2024).

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

a) Current risk management measures

One of the important measures in preparedness to droughts are available data and forecasts of drought time and spatial development which enables stakeholders to respond properly and in time. Slovenian Environment Agency – ARSO developed a web-based application called *Sušomer* ("Drought-meter") showing the current, archive and forecasted analysis of potential drought in topsoil, rivers and groundwater and offers information on current and expected drought conditions on a wider regional scale of Slovenia. This is an important and well-supported tool, very useful for decision making. However, a tool could be improved by development of impact-based forecasts, and this could be achieved in cooperation with or involvement of all sectors affected by drought.

In the case of a drought impacting the water supply and causing water shortage, water is delivered to residents, reserve water sources are activated and/or restrictions on water use are put into place. The drinking water shortages in the pilot area are local and affect mainly inhabitants supplied by small water sources.

The acting organizations identified in the case of drought management are drinking water supply operators which monitor the water quantity and quality and inform users. Civil protection and firefighters are always on stand-by to intervene in emergency situations (existing protocols within civil protection), such as water delivery, the government is involved in drought damage assessment and reimbursement through municipal, regional and national commissions of civil protection and disaster relief administration and through the Ministry for economy (Brenčič and Vidmar, 2024).

From the water supply point of view, according to the past experiences in the pilot area, they are well prepared for small-scale extreme events, in case of the extreme events as earthquake or extreme floods with landslides, the protocols are inadequate.

Current risk management related to general characteristics in Slovenia, agriculture and forestry, see document *X-RISK-CC-RRMA_All-Pilots-interpretation_25.5.24.docx*

b) (Potential) future risk management measures

Slovenian Environment Agency – ARSO will further maintain and develop web-based service *Sušomer*.
They will shortly include new data sets, additional meteorological stations.

Since the current use of water for irrigation in agriculture represents small share (1,6% of all usages), that potential for irrigation is high and at the present not exploited. In the future, development of irrigation systems can help to improve the resilience of agriculture to droughts. On the other hand, irrigation systems are applicable/feasible only in the areas of the large groundwater aquifers – lowlands.

In dispersed settlements with many smaller water supply systems the efforts will go in integration of water works into the interconnected water supply networks (in municipality plans). Despite that, due to economic reasons some areas will remain separate from these water supply networks. In such cases, resilience of water supply to droughts must be improved with additional reservoirs and improved intervention measures.

An important measure for drought consequences prevention can also be wastewater reuse.

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

Figure 6: Present compound/cascading events related to drought and heat in Sora catchment.

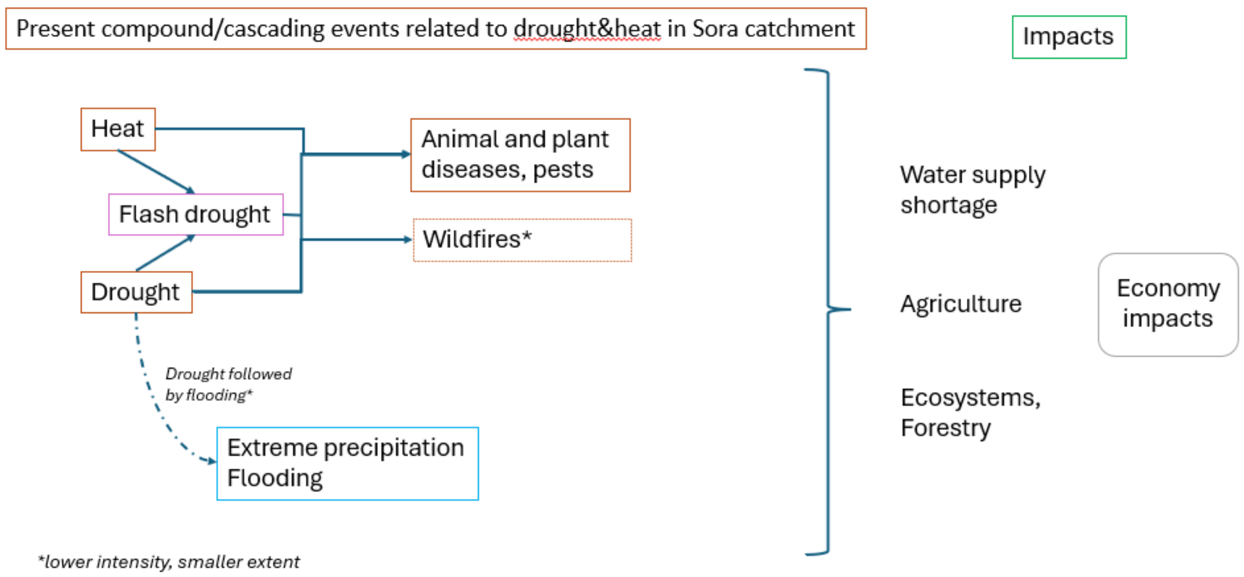
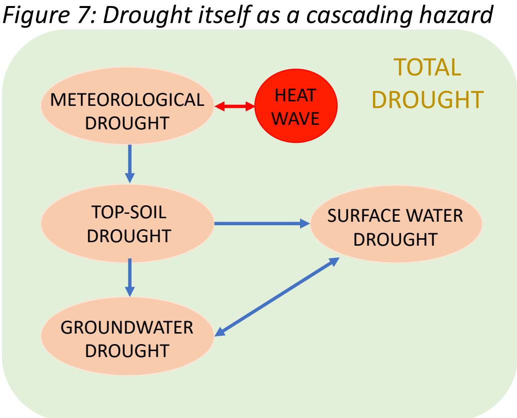


Figure 7: Drought itself as a cascading hazard



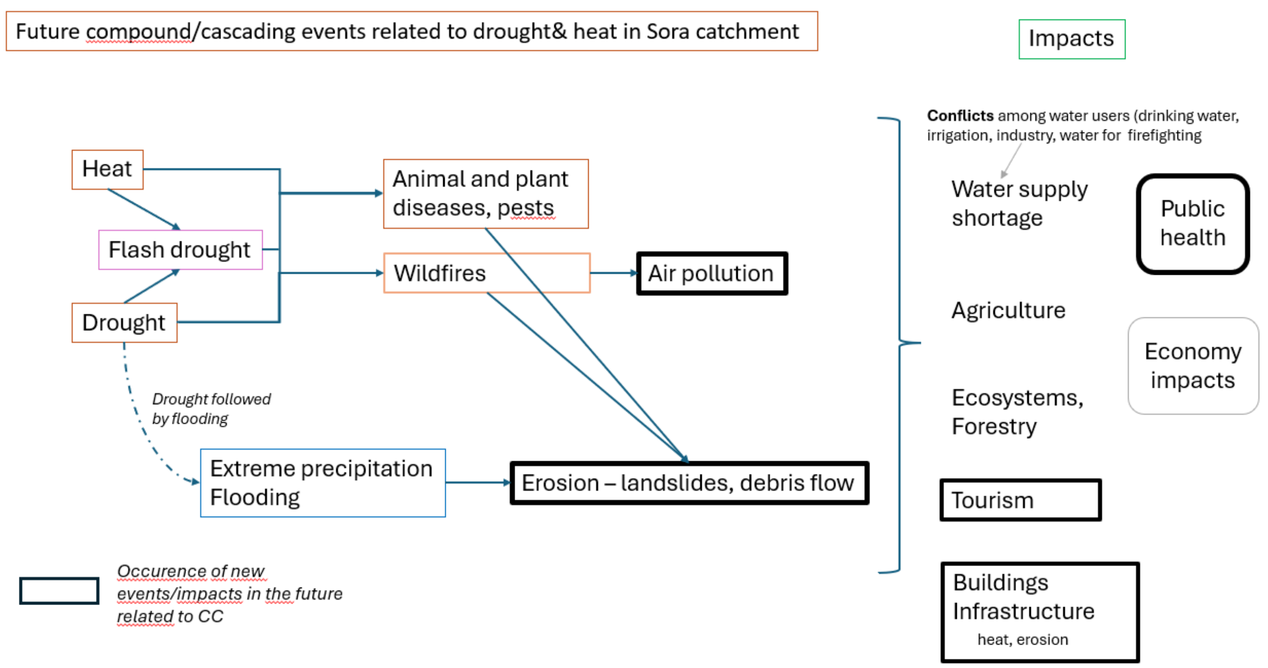
Source: Brenčič and Vidmar, 2024.

Drought is a compound/cascading hazard composed of interrelated types of droughts (meteorological drought, top-soil drought, surface water drought, groundwater drought). The severity and magnitude of drought depends on meteorological triggers and the extent to which the different drought types are realised. Meteorological/precipitation drought usually triggers occurrence of drought in topsoil, which is often intensified by heatwaves, that influence drought severity or magnitude. Dry air masses with the lack of atmospheric water also influence air temperatures and consequently relation between heatwave and meteorological drought can be considered as a return loop while both are forming a compound event – flash drought. Meteorological drought propagates or creeps "through" the hydrological cycle - from meteorological drought to top-soil drought and further to surface water and groundwater drought. Due to the interactions between the water in the soil, groundwater, and surface water, these drought types are interrelated, influencing each other in the return flow cycle (Figure 7). The relation between them depends on the conditions in the area (geology, relief, drainage network, land use etc.). In the upper parts of the catchment where the slopes are steep, groundwater drought will develop faster than in the lower, flatter parts. Surface water drought will also develop faster in the upper parts of the catchment area (Brenčič and Vidmar, 2024).

In the Sora catchment, drought, also in combination with heat, affects agriculture, forestry and water supply in a cascade of events. In the agriculture and forestry, the consequences of the drought are reflected in a decrease of crop yields and tree growth. There are indirect economic impacts, but these are not measured as direct impacts of drought, except in agriculture when drought is declared a natural disaster.

b) Potential future impacts of compound/cascading hazard events

Figure 8: Future compound/cascading events related to drought and heat in Sora catchment.



Current knowledge and monitoring show that there is a lack of dense meteorological monitoring system (evapotranspiration), impact – based forecasts, a link between drought monitoring and drought management, coordinated drought management protocols at the local level, and climate change adaptation measures. Impact chain of future drought events can only be carried out at a conceptual level (Brenčič and Vidmar, 2024).

When future drought events are realised, the cascade structure of current drought impacts will remain (Figure 6 and 8), only the magnitude of impacts will be greater. As air temperatures are expected to rise, drought events will be longer, more severe and more widespread. Under such conditions, additional hazards may occur. The occurrence of a greater number of fires and their extent (forest, grassland and urban fires) can also lead to air pollution. Fires can also influence runoff conditions, which can increase soil erosion, especially on steep slopes where the bedrock consists of dolomite or clastic rock (Brenčič and Vidmar, 2024).

As for water supply from aquifers from small watershed, which are more vulnerable to drought, it is to be expected that there will also be conflicts between the different water users, as water is needed for drinking, firefighting or irrigation – all necessary for the safety of the inhabitants.

Flooding is not a direct consequence of drought. It is indirectly related to the change in surface and soil conditions. t is to be expected that periods of drought in this area will be followed more frequently by intensive, short storms with extreme amount of precipitation. Heavy rain on dry soil leads to very rapid surface runoff with only minor infiltration. The probability for such events is much higher on the steep slopes than in the lower parts of the region. Such surface runoff also has an impact on soil and rock erosion (Brenčič and Vidmar, 2024).

Taking into account intensified or new related hazards (Figure 8), greater indirect impacts on public health, tourism and on economy in general are expected (Brenčič and Vidmar, 2024).

This impact chain highlights the need for integrated water management, and a need to consider drought mitigation measures in combination with heat and extreme hydrological events such as floods and landslides when planning adaptation measures (Brenčič and Vidmar, 2024).

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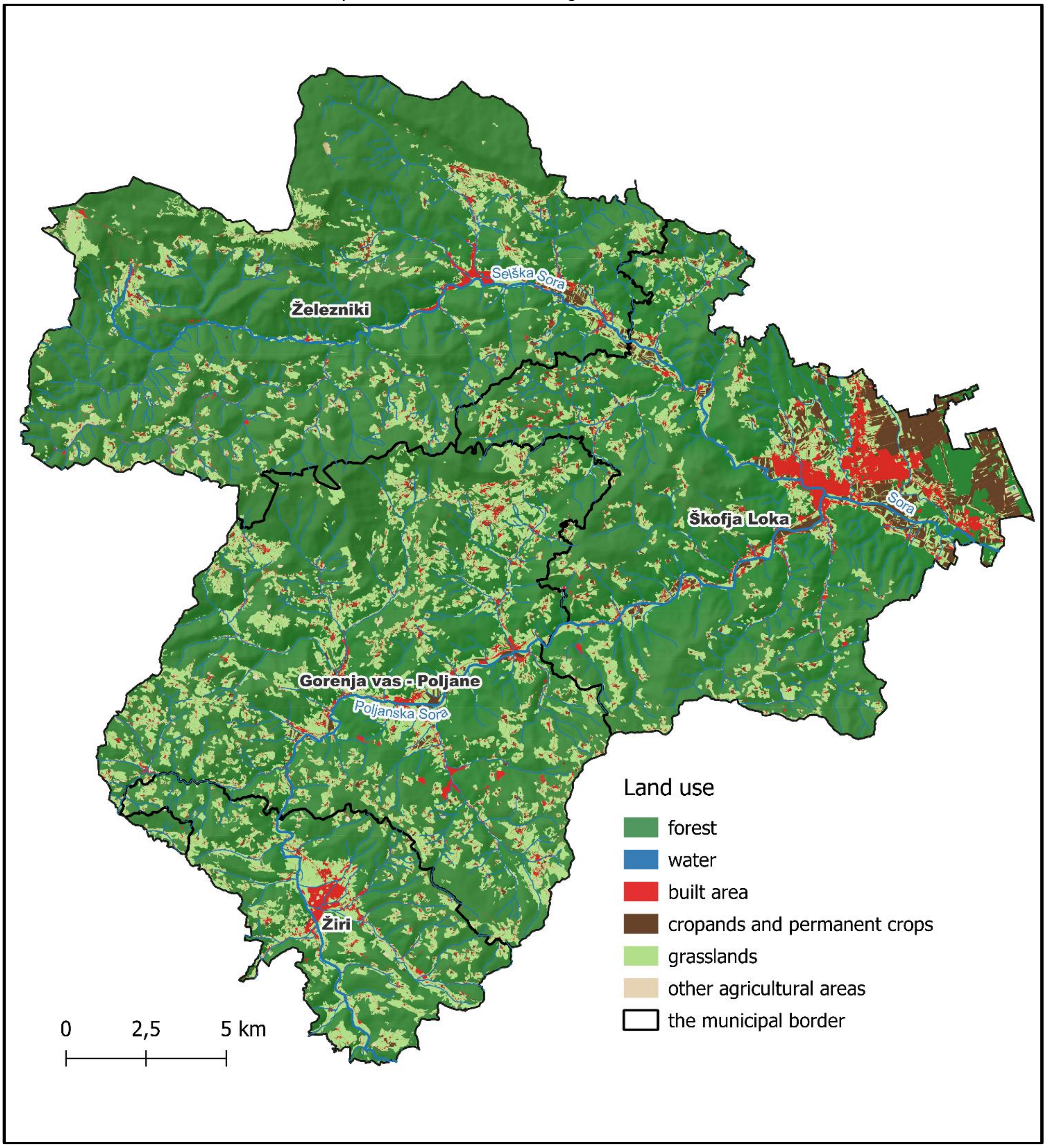
SURS, 2024. RS Statistical Office. URL: https://www.stat.si/StatWeb

Water Book, 2024. Ministry of Natural Resources and Spatial Planning, Slovenian Water Agency. URL: https://podatki.gov.si/dataset/vodna-knjiga

ZGS, 2023. Slovenia Forest Service. Forest management plans of forestry units. URL: https://prostor.zgs.gov.si/pregledovalnik/

Appendix:

Land use in the Sora catchment – exposed elements to drought&heat



Source: MKGP, 2024.

X-RISK-CC

RISK QUESTIONNAIRE

SORA CATCHMENT - FLOOD

(MULTI-) HAZARD ANALYSIS

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September 2024

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OUTLINE

The analysed project is addressing the understanding of the processes and factors contributing to current risk due to extreme weather events in your pilot region and how these are likely to change in the future. The following guiding questions are meant to provide an overview of these contributing factors. Answering these will help risk managers and decision-makers become aware of and study the drivers of current and future risks in their area. They will also serve as an input into the evaluation of key risks due to extreme meteorological events.

The specific part addressing the pilot region is addressing the Sora watershed.

(MULTI-) HAZARD ANALYSIS

1. Which are relevant weather extremes and how do you expect them to change in future?

1.1. Past/present weather extremes

The catchment of the Sora River was historically subject to severe flooding. Most sever historical floods, which are still relatively well recorded are the floods of 1901, 1923, 1926, 1964, 1965, 1979, 1982, 1984, 1990, 1992, 1995, 2007, 2009, 2012, 2014[1] and most recent floods of August 2023. The floods of 1923, 1926, 1990, 2007 and 2023 were of severe intensity, causing high damages, and in the most cases unfortunately also casualties.

Figure 1: Flooding of Žiri (27th September 1926)

Figure 2: Registered watermark of floods in 1924 – location: Puštal, Škofja Loka (photo Banovec)

[1] Ministrstvo za okolje in prostor (2019), Predhodna ocena poplavne ogroženosti

Unfortunately, the historical events on the Sora River were not well recorded, following the fact that most of the precipitation monitoring stations and river discharges monitoring stations were set in place only in the period between 1950 and 1960[2].

In Slovenia the extent of past flooding events is being registered since approximately 1980, with quite irregular approach towards the analysis and systematic registry of the past flood events. Nevertheless, some key flood events (of 2007) in the addressed watershed were registered, and are published on the public web site (Figure 3).

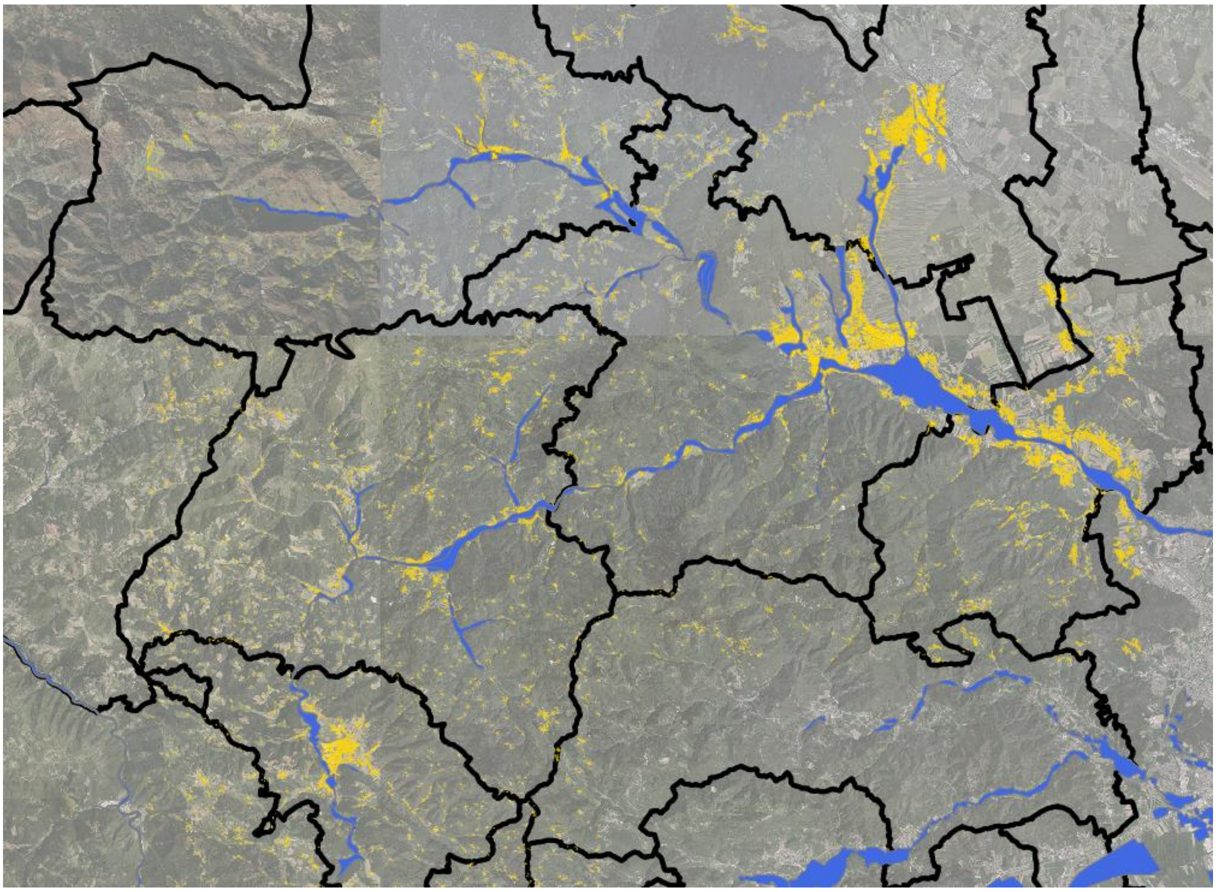

Figure 3: The extent of registered past flood events on the Sora catchment (Source: Atlas voda, evode)

More detailed analysis of specific events with detailed information on the hydrometeorological situation at specific event is published by ARSO since 2005[3]. The site and individual reports on the events are extremely important for the understanding of a specific event (post-event analysis), but also for the historical understanding of trends, based on the analysis of specific events.

Together with the observed flooding events, caused by heavy precipitation, other related phenomena were also observed, especially mass movements and landslides. Registry of landslides and landslide management in Slovenia not on the same level as flood management. Nevertheless, after the flood

[2] M. Trontelj (1997), Kronika izrednih vremenskih dogodkov: XX. stoletje. Ljubljana, Hidrometeorološki zavod Republike Slovenije, 1997.
[3] https://www.meteo.si/met/sl/climate/natural-hazards/archive/

event of August 2023, where more than approximately 5000 landslides were triggered, the process has started to address the landslides and their management in a better way.

1.2. Potential future weather extremes

Potential future weather extremes, related to intensive precipitation could be analysed on the basis of the:

- Shifts in the intensity of precipitation – changed IDF (Intensity, duration, frequency) curves, which are observing the past (observed) precipitations, and
- Trends induced by the climate changes

The shifts in the intensity of precipitation (IDF) were analysed based upon:

- Basic IDF study (ARSO 2012), which was analysing the precipitation of all available data until 2004,
- CROSS-RISK study (ARSO 2022), which analysed the precipitation of all available data until 2018, and
- Post event 2023 analysis for specific precipitation station (Airport Brnik) with the precipitation data until 2023, including the extreme event of August 2023 (X-RISK-CC analysis).

All analysis were using the same probability distribution function (Gumbel) and are considering the applied approach comparable. The latest study, performed in the X-RISK-CC project was using daily precipitations (accumulations from 6 UTC to 6 UTC) instead of 24h precipitations, resulting probably in slightly underestimated values. The Airport Brnik precipitation station is not directly on the Sora watershed, but it is relatively close (approx. 10 km) to it, and provides long time set of quality measurement information.

Table 1: Analysis of increased trend of IDF characteristics for the Brnik precipitation station 10-year return period.

10-year return period						
Duration	Data until 2004 analysis	2022 CROSS-RISK (until 2018)	Until 2024 (Avg incl.)	Increase (2004-2024)	RCP 4.5 - 1,2 °C increase (+8,6%), year 2100	
min	mm	mm	mm	%	% from (2004)	mm
5	11	14	15	36%	45%	16
10	17	19	20	18%	29%	22
15	22	23	24	9%	18%	26
20	25	26	27	8%	16%	29
30	29	31	33	14%	24%	36
45	33	37	39	18%	27%	42
60	36	42	44	22%	33%	48
90	40	49	52	30%	40%	56

10-year return period						
Duration	Data until 2004 analysis	2022 CROSS-RISK (until 2018)	Until 2024 (Avg incl.)	Increase (2004-2024)	RCP 4.5 - 1,2 °C increase (+8,6%), year 2100	
120	44	54	57	30%	41%	62
180	50	63	66	32%	44%	72
240	55	70	74	35%	45%	80
300	60	75	79	32%	43%	86
360	64	79	83	30%	41%	90
540	72	89	94	31%	42%	102
720	79	96	101	28%	39%	110
900	84	102	108	29%	39%	117
1080	88	107	113	28%	40%	123
1440	96	116	122	27%	38%	132

Table 2: Analysis of increased trend of IDF characteristics for the Brnik precipitation station (100-year return period).

100-year return period						
Duration	Data until 2004 analysis	2022 CROSSRISK (until 2018)	Until 2024 (Avg incl.)	Increase (2004-2024)	RCP 4.5 - 1,2 °C increase (+8,6%), year 2100	
min	mm	mm	mm	%	%	mm
5	16	19	21	31%	44%	23
10	25	28	30	20%	32%	33
15	32	35	38	19%	28%	41
20	37	41	44	19%	30%	48
30	43	49	53	23%	33%	57
45	48	58	63	31%	42%	68
60	51	65	70	37%	49%	76
90	57	77	83	46%	58%	90
120	64	86	93	45%	58%	101
180	73	98	106	45%	58%	115

100-year return period						
Duration	Data until 2004 analysis	2022 CROSSRISK (until 2018)	Until 2024 (Avg incl.)	Increase (2004-2024)	RCP 4.5 - 1,2 °C increase (+8,6%), year 2100	
240	80	107	116	45%	58%	126
300	87	114	123	41%	53%	133
360	93	119	129	39%	51%	140
540	104	131	142	37%	48%	154
720	112	139	151	35%	46%	164
900	118	146	158	34%	45%	171
1080	121	152	165	36%	48%	179
1440	134	163	177	32%	43%	192

The analysis of the trends shows already the significant increase in the intensity of the precipitation from the dataset of precipitation until 2004 to the dataset of precipitations until 2018 (+32% - 24h precipitation), following the national guidelines relative to the implementation of the EU climate proofing technical guidance document, the expected increase is 43%. These values are quite extreme. Technically we could estimate that a significant shift in return periods could be observed, where the 10-years return period intensity of precipitation will be on the comparable level to the intensity of precipitation for the return period of 100-years for 24h (data until 2004). Such increase in 100 years is extreme. We could assess that those existing hydraulic structures and the settlement pattern are not prepared for such a change.

In addition, the analysis of patterns and trends of past weather extremes which was carried out as a part of the X-RISK-CC project (WP1 results, Pilot analysis report) took into account the precipitation data from several meteorological stations, which are located also in hilly/mountainous terrain in the pilot area (The Brnik meteorological station mentioned above is located near the pilot area in the wide river plain). The analysis shows that since 1950, there has been an increasing trend of extreme 2- to 3-day precipitation intensity on an annual level (1-day precipitation does not show a trend), while summer shows a decrease. According to the future projections for the same stations, in case of 1- to 3-day extreme precipitation, the greatest changes (more than 20 %) in extremes are expected in spring. Changes up to 15 % are expected in other seasons. Similar findings apply to the frequency of 1- to 3-day extreme precipitation (days above the 97th percentile), as the number of days will increase slightly in all seasons (the most in spring and winter and the least in summer). A maximum 1-day precipitation in autumn as extreme as the 1-in-50-year event in 1991–2020 is projected to become up to 2.4 times as likely under global warming levels of 3 and 4 °C (a 50-year event in the reference period might become a 21-year event in a 3 °C to 4 °C warmer climate).

2. Which hazard processes can be triggered by current and future weather extremes (intensive precipitations)

Extreme precipitation can expose the addressed Sora River watershed to several hazard processes, mostly slope failures, landslides, river floods, flash floods. Recurring extreme precipitation events are confirming the expected hazards. The debris flows with the activation of alluvial fans are observed to the smaller scale.

The hazardous events are monitored by the gauging stations monitoring water levels and temperature. Discharge curves (Q-h) are available, but with limited data availability for the extreme events.

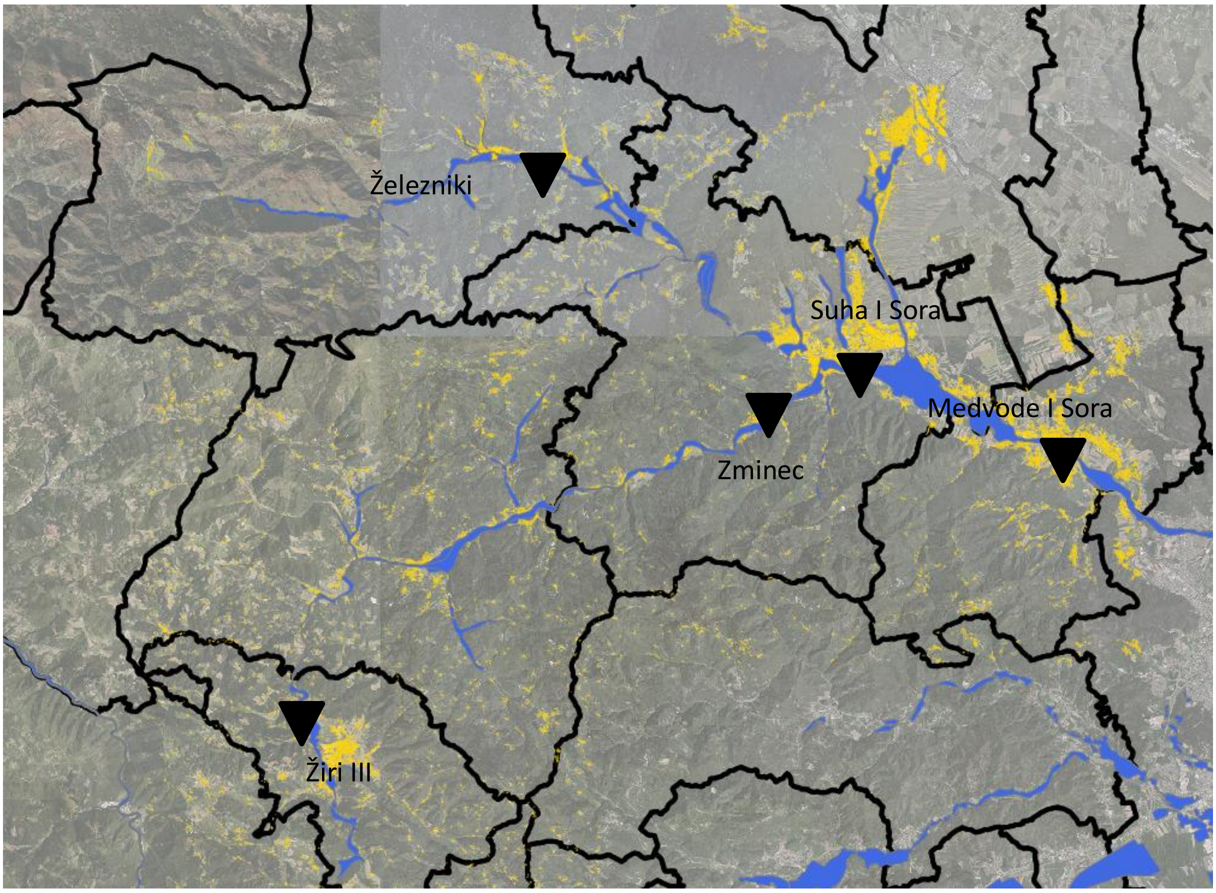

Figure 4: The extent of registered past flood events on the Sora catchment (Source: Atlas voda, evode)

Table 3: Active level/discharge gauging stations on the Sora River catchment

ID	Name	River	Area F (km^2)
4200	Suha I	Sora	566.34
4206	Medvode I	Sora	642.86
4222	Žiri III	Poljanska Sora	54.40
4230	Zminec	Poljanska Sora	305.51

ID	Name	River	Area F (km^2)
4270	Železniki	Selška Sora	104.10
4298	Vešter	Selška Sora	213.76

Table 4: Discharge (m3/s) on the hydrological stations in Sora River Catchment corresponding to the return periods, determined with the Pearson 3 distribution.

		Dataset*	Discharge (Pearson 3 distribution) m^3/s - by return period									
ID	Name	start (year)	2	5	10	20	30	50	100	300	500	1000
4200	Suha I	1945	305	407	467	520	549	584	629	696	725	764
4206	Medvode I	1988	353	472	542	603	636	676	727	803	837	881
4222	Žiri III	1949	66.7	98.4	119	139	150	164	182	210	222	239
4230	Zminec	1954	163	211	239	262	275	290	309	338	350	366
4270	Železniki	1991	66.6	122	177	240	279	331	403	521	576	649
4298	Vešter	1989	170	251	302	348	374	405	446	508	535	572

* - not all datasets are continuous

For the discharge measurement stations, which are measuring levels/discharges, the return period and expected future discharges, resulting in floods are even more uncertain than precipitation. Future, climate change induced discharges are therefore even more uncertain to predict. On the level of uncertainty, we could estimate that similar shift, related to climate change induced hazards, could be observed, which is partially on the optimistic side. The discharges usually respond to the changed precipitation more intensively, as the initial losses are already consumed by the initial precipitation (i.e. without the impact of the climate change), and additional CC related precipitation results in the more intensive runoff.

2.1. Past/present hazard processes due to weather extremes

Most relevant natural hazards are flood processes induced by heavy precipitation, such as river floods (after prolonged rainfall), flash floods (triggered by short, intense precipitation). Debris flows are occurring in smaller scale in the tributaries relative to the Sora River activating alluvial fans.

These processes are modelled in the basis of the EU (Floods directive 2007/60[4]) and national legislation - Regulation on conditions and restrictions (89/08)[5]. The Regulation (89/08) was adopted tor the

[4] Floods DIRECTIVE 2007/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2007 on the assessment and management of flood risks, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060

[5] Uredba o pogojih in omejitvah za izvajanje dejavnosti in posegov v prostor na območjih, ogroženih zaradi poplav in z njimi povezane erozije celinskih voda in morja, (Regulation on conditions and restrictions for the implementation of activities and interventions in space in areas threatened by floods and related erosion of inland waters and the sea) Off. Gazette 89/08.

purpose of administrative procedures related to: (a) permitting on the level of spatial planning and (b) on the level of construction permit limiting and providing specific conditions relative to the flood/erosion hazard and flood/erosion risk. On the basis of this Regulation flood hazard maps were developed and later published by the Water Agency (published on publicly available GIS: Atlas voda[6]).

Modelled flood hazard is providing an information on the flood hazard with the modelled return period of 10, 100, and 500 years, based on the precipitation dataset (until 2004 or later 2018), and dataset from the discharge gauging stations. The example of the flood hazard map for the municipality of Škofja Loka in provided on the following figure:

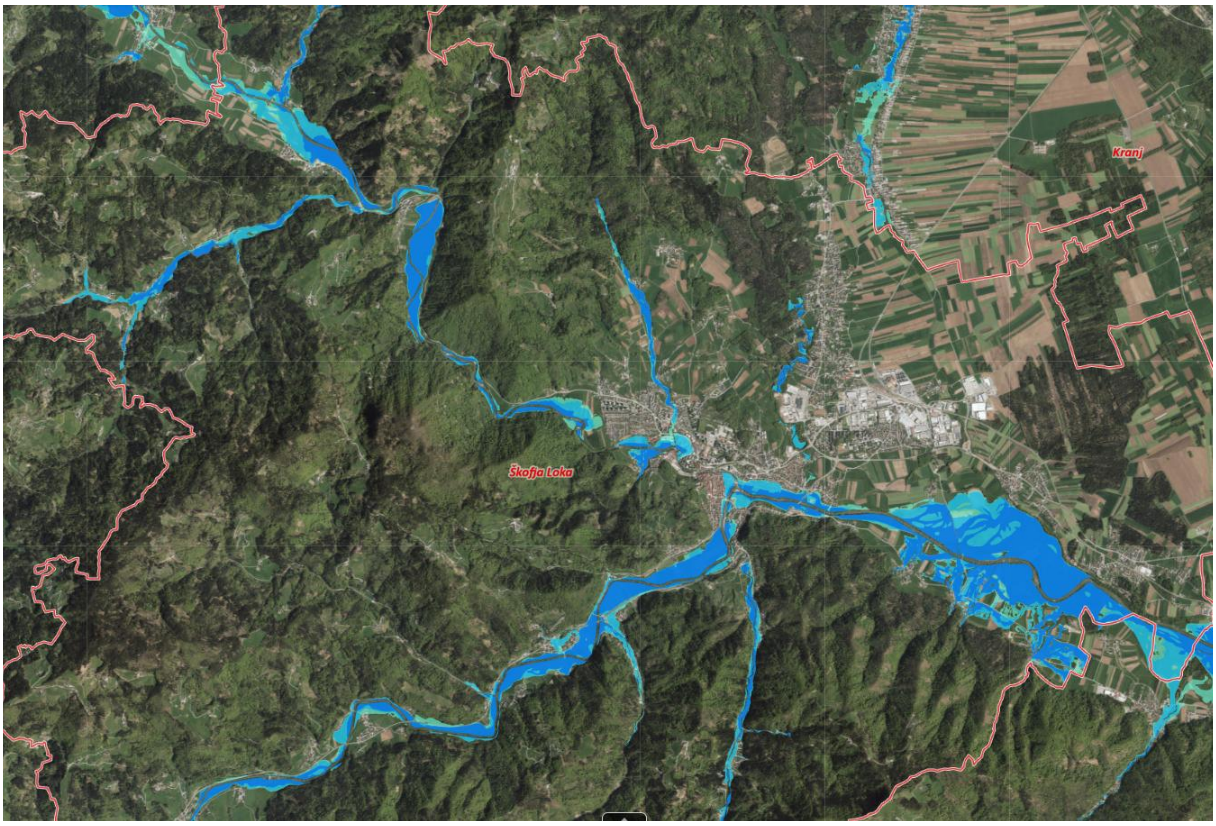

Figure 5: Modelling result – extent of floods with 10-, 100-, and 500- years return period, example for the Škofja Loka municipality. (Source: Atlas voda, evode)

6 https://geohub.gov.si/atlasvoda

Figure 6: Modelling result – extend of floods with 10-, 100-, and 500- years return period, example for the Škofja Loka (detail). (Source: Atlas voda, evode)

Following national regulations impact of climate change is not yet included in the modelling and regulative process in Slovenia.

2.2. Potential future hazard processes due to future weather extremes (floods and related phenomena)

Due to increase in expected precipitation intensity (IDF curves) all observed phenomena related to floods (all types), erosion processes, mass movements, debris flows will be intensified. The extreme events, like those observed in 1924, 1926, 2007 and 2023 will occur on even more frequent basis.

3. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

The expectance of the changed occurrence will result in the increase of the intensity/frequency of all the flood related phenomena as described in previous chapters.

3.1. Past/present frequencies and magnitudes

See table 1 and table 2.

3.2. Potential future frequencies and magnitudes

Beside the floods some other related impacts from CC and more intensive precipitation could be anticipated, they are closely related to the status of the forest on the Sora catchment:

- Windbreak – due to the higher wind velocities windbreaks could occur more often. Steep, hilly areas without or limited forest coverage are more exposed to erosion process and could provide lower potential for intercepted precipitation and retention capacity.
- Sleet - similar as windbreak, occurrence of extreme events of sleet (large ice formation
- Changes in forest species – due to the adaptation process where spruce trees shall be replaced with other, more CC resistant species, some areas could have different retention capacity for several years.

Expected higher frequencies and intensities in 1-day and 1-hourly precipitation (See table 1 and table 2) can affect the system in the following way:

- increased sediment supply by landslides (e.g., due to acceleration during heavy rainfalls) and increased hillslope-channel-coupling, debris-laden flows
- high saturation of the soil during 1-day (or longer) rainfall inhibits infiltration of water, leading to surface runoff and flooding
- more frequent flash floods triggered by short-duration rainstorms in the future, also visible in the trend observed at the gauging stations

4. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

Elements at flood risk are structured following different flood risk assessment sources theories like FDA (Flood Assessment)[7], and later Huizinga (2017[8]) method. Typical categories are:

- Population (housing);
- Public activities/buildings;
- Industrial activities;
- Agriculture;
- Infrastructure (transport, water, communication, energy).

For the purpose of flood damage assessment, providing framework for the Cost/Benefit analysis relative to EU guidelines[9,10] is used as a general framework. Assessment using the HUIZINGA (2017) vulnerability analysis and risk analysis was used also for the modelling of flood damages related to flood event of August 2023 in Slovenia and reporting of flood damage to the EC. Huizinga (2017) method is therefore used also for the purpose of the X-RISK project.

Flood risk modelling for the Sora catchment (X-RISK-CC project pilot site) is based on the following input data, which are provided in Slovenia following the EU INSPIRE directive[11] services:

- Maintained database of spatial information: Real Estate Register of the Republic of Slovenia (REN)
- The real estate register is connected with the inquiry to the maintained collection of spatial data: Cadastre of Buildings (KS), which provides the floor plan information of the building, which is the subject of a flood damage assessment (actual and CC impact).
- With the Cadastre of Buildings (KS), for the purposes of determining the extent of damage to buildings, we spatially connected it with the data of the flood extent modelled results for Qn10, Qn100, and Qn500[12] (existing), and with the roughly estimated values for the discharges in 2100 (RCP4.5 scenario – precipitations): the current Qn100 correspond to the flood with the 10-year return period in 2100, current Qn500 to 100-year return period discharge in 2100, and the current Qn500 increased for 20% to the 500-year return period discharge in 2100.

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[7] https://www.hec.usace.army.mil/software/hec-fda/
[8] https://publications.jrc.ec.europa.eu/repository/handle/JRC105688
[9] EUROPEAN COMMISSION Directorate-General for Regional and Urban policy (2015), Guide to Cost-Benefit Analysis of Investment Projects Economic appraisal tool for Cohesion Policy 2014-2020, https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf
[10] Guide to COST-BENEFIT ANALYSIS of investment projects Structural Funds, Cohesion Fund and Instrument for Pre-Accession 2008, https://ec.europa.eu/regional_policy/sources/guides/cost/guide2008_en.pdf
[11] Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)
[12] Source: database maintained on the basis of the Water Act, the Rulebook on the Methodology for Determining Areas Threatened by Floods and the Associated Erosion of Inland Waters and the Sea, and on the Method of Classifying Land into Classes risk (Official Gazette of the Republic of Slovenia, No. 60/07). The regulations determine the extent of flood lines in accordance with the EU Flood Directive (2007/60).

- Within the X-risk project we carried out a flood damage assessment for the affected buildings according to the Huizinga 2017 method, "Flood damage functions for EU member states", prepared by H.J. for the Joint Research Center of the European Commission. Huizinga of HKV Consulting (H. J. Huizinga, 2007; J. Huizinga, De Moel, & Szewczyk, 2017).

Beside the flood extent, specific uncertainties related to the risk modelling results are:

- Uncertainty due to the mechanism of intrusion into the building and the related determination of the angle of the ground floor of the building and the related onset of flood damage;
- Uncertainty due to insufficient information about the basement of the building and the associated onset of flood damage. (no basements applied for the X-RISK Sora model);
- Uncertainty due to insufficient information on the mechanism of flood occurrence - buildings that have suffered flood damage, but are not in the area of defined flood lines (Qn100, Qn500). In the case of these facilities outside the area of the flood lines, the mechanism of flood damage is as follows:
    - Damage caused by landslides, debris flows and rockfalls. All these phenomena are associated with pronounced erosion phenomena.
    - Damage caused by flooding of basements. The flooding of basements can be attributed to various factors (intrusion of underground water, intrusion through the sewage system, etc.).
    - Damage caused by flooding from shallow surface flows that occur in extreme rainfall events but are not identified in flood hazard maps.
    - Other.
- Inherent inaccuracy of the Huizinga method (damage curve used, damage potential on the object).
- The design of the modelling is related to the occurrence of flood damage and not to the collapse of the building. It is therefore necessary to carry out a separate damage assessment for buildings that are reported by municipalities as demolished buildings.
- Estimated flood damage defines flood damage to the facility and equipment, some activities carried out in facilities where the intended use is industrial/business facilities and agricultural facilities may have significant deviations from the modelled values due to the nature of the activity. Therefore, it is necessary to carry out a preliminary damage assessment for these facilities separately.
- Inaccuracies in coverage of flood damage due to indirect intrusion of water into the facility (via sewage, surface flows, underground water).

The Huizinga method is addressing only direct flood damages, as other flood damages are exposed to high uncertainties and sometimes also, in relation to that, speculations.

Direct flood damage covers all types of damage that relate to immediate physical contact of flood waters with people, property and the environment. This includes, for example:

- damage to buildings, property and infrastructure,
- loss of crops and livestock in agriculture,
- loss of human life and immediate impacts on human health and

- direct damage to economic companies is usually measured as damage to buildings, work equipment and direct loss of production.

Indirect flood damage is damage caused by disruption of physical and economic ties with economy and additional costs of emergency and other measures taken to prevent damage - floods and other losses. This includes, for example:

- loss of production of companies affected by the flood and the resulting production losses with an indirect effect on the costs associated with a reduction in the quality of relations with suppliers and customers. Indirect damage to commercial companies is often also measured as a medium- and long-term reduction in the volume of business
- costs of traffic disruptions and costs of intervention services.
- Indirect damages are not covered by the Huizinga method.

Damage that can be easily quantified in monetary terms, such as damage to property, loss of production, etc., is called tangible damage. For human casualties, health effects, damage to the environment and all kinds of goods and services that are not traded on the stock market, the damage is much more difficult to assess in money terms. Therefore, they are labelled as intangible damage" (Messner et al., 2007).

The applied method largely follows the HEC-FDA (USACE) standard approach. The authors originally developed a methodology for assessing the damage of European countries (H. J. Huizinga, 2007), but later the method was amended and extended to a wider area (J. Huizinga et al., 2017). An extended method was used to assess the benefits of the measures.

The aforementioned methodology defines a limited set of damage categories, which, on average, represent 80% of the total damage in all EU countries considered. The method covers damage assessment in (1) residential buildings, (2) commercial buildings, (3) industrial buildings, (4) roads, and (5) agriculture. The total damage can thus be calculated as a correspondingly increased partial damage.

The method of H.J. Huizinga for the selected categories below is produced by:

a) methodology for assessing the maximum damage of each category per m^2 of surface (building surface, road surface, agricultural surface).
b) the methodology for assessing the damage in the building according to the actual angle of the water in it. For this, he uses the concept of damage curves, which, depending on the height of the water in the building, appropriately reduce the maximum possible damage.

Table 5: Flood damage categories addressed by the Huizinga (2017) flood damage assessment method

	HUIZINGA
Calculation of direct flood damages	YES
Applied return periods	Q500, Q100, Q10 (higher resolution is possible)
Definition of damage categories	It enables the calculation of the most important damage categories. It estimates the total damage by increasing the estimate by 25%.

Residental Buildings (RB)	YES
Equipment of RB	YES
Industrial buildings (IB)	YES
Equipment of IB	YES
Agriculture buildings (AB)	YES
Equipment AB	YES
Major roads	YES
Local roads	YES
Water supply sstems	NO
Wastewater systems	NO
Ahydraulic structures	NO
Indirect damages (industry)	NO
Inventory (industry)	NO
Agriculture (land)	YES
Agriculutre (crops)	YES
Cultural heritage	NO
Water resources	NO
Aesthetic value of the environment	NO
Accidental pollution (chain events)	NO
Human health (casualties)	NO
Human health (injuries, mental health, etc.)	NO
Definition of maximum damage in a category	The values are based on expert assessment and the GDP of each country. The method defines the methodology for the calculation.
Definition of damage depending on depth	The method uses damage curves. The methodology for estimating the value of the damage curves for each country is given. For the purpose of X-RISK project depth of, 0,5 m was applied as simplification
Determination of damage depending on the speed of the water flow	NO

Definition of damages depending on the duration of the flood	NO

The maximum damage of each category was analysed for more than 290 countries in both studies by J. Huizinga. Based on past studies and analyses, they created a methodology for estimating the maximum damage for any country based on its GDP per capita (PPP). The methodology enables the calculation of damage to individual buildings - i.e. based on m2 of building area, as well as only based on land use obtained from Corine Land Cover data (CLC 2000) - i.e. built-up area. In the X-RISK study for the Sora catchment, we used the calculating the expected flood damage (now and with the expected climate change) based upon the individual buildings, which is consequently much more accurate than land-use based model.

The methodology for determining maximum damages uses various setting parameters, such as:

- Average depreciation rate of facilities (the value of new equipment is not taken into account, but the value of depreciated equipment). The default factor is 1.0, as we use the surrogate value method for flood damage assessment purposes.
- The ratio between damage to the building and equipment is 0.5 for residential buildings, 1 for commercial buildings and 1.5 for industrial buildings.
- The portion of the building area that is not damaged represents the difference between the gross and net area of the building. The default value is 0.71, which is also shown by the analysis of the REN real estate register.
- Possibility of reducing the damage value for areas built with cheaper materials. The default value is 1, which means that all considered areas are evaluated equally.
- Different parameters for calculating the maximum damage according to the type of land use according to CLC2000. According to the calculation method based exclusively on building area data, this data (Corine Land Cover) is not used.

Flood damage curve

The damage curve represents the value of the damage in the building (or other damage category) according to the height of the water in it. The methodology presents normalized damage curves, where each damage curve represents a damage reduction factor in relation to the height of the water. The study compared different European and global damage curves found in the literature.

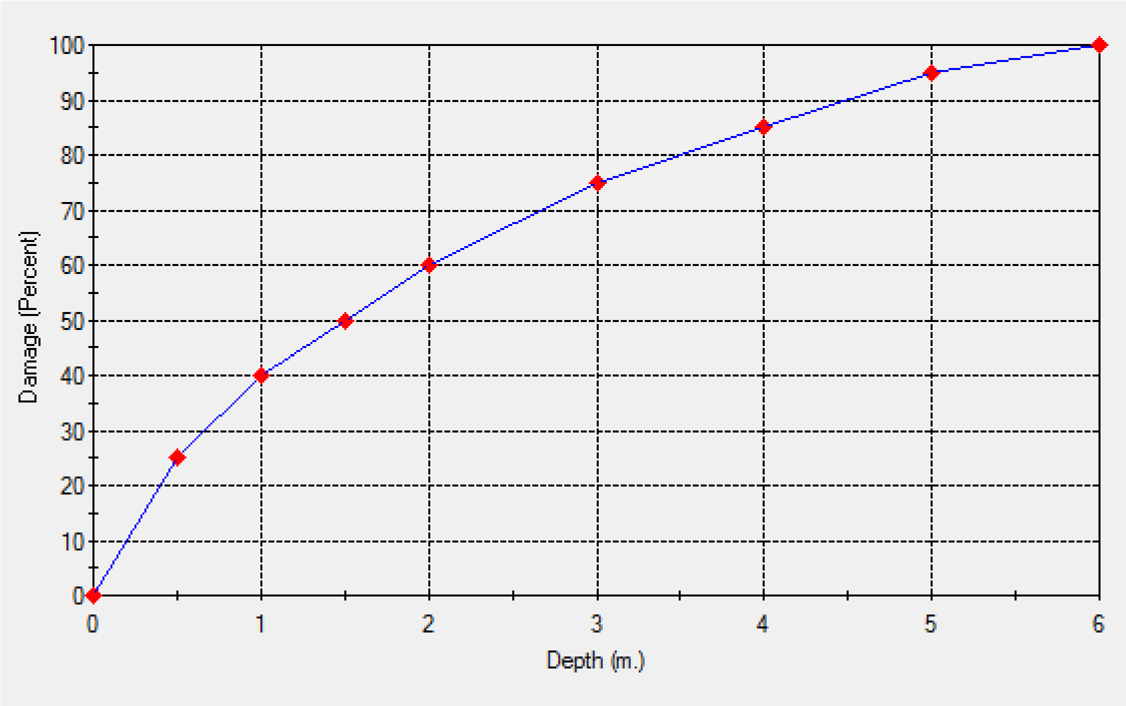

Figure 7: Average damage curve for each type of damage (J. Huizinga et al., 2017)

A comparison of the damage curves shows a certain difference between the countries, mainly due to the different construction methods and materials used for construction. Considering this, we can perceive a significant difference especially in the lower part of the curve between European countries and the USA, where due to the large scale of prefabricated construction, the damage begins to increase very quickly even at small depths. Masonry buildings are structurally less vulnerable to flooding.

Table 6: Comparison of different flood damage curves (Huizinga, 2017).

Damage class	Flood depth, [m]	Damage function						
		EUROPE	North AMERICA	Centr&South AMERICA	ASIA	AFRICA	OCEANIA	GLOBAL
Residential buildings	0	0,00	0,20	0,00	0,00	0,00	0,00	-
	0,5	0,25	0,44	0,49	0,33	0,22	0,48	-
	1	0,40	0,58	0,71	0,49	0,38	0,64	-
	1,5	0,50	0,68	0,84	0,62	0,53	0,71	-
	2	0,60	0,78	0,95	0,72	0,64	0,79	-
	3	0,75	0,85	0,98	0,87	0,82	0,93	-
	4	0,85	0,92	1,00	0,93	0,90	0,97	-
	5	0,95	0,96	1,00	0,98	0,96	0,98	-
	6	1,00	1,00	1,00	1,00	1,00	1,00	-
Commercial buildings	0	0,00	0,02	0,00	0,00	-	0,00	0,00
	0,5	0,25	0,24	0,61	0,38	-	0,24	0,34
	1	0,40	0,37	0,84	0,54	-	0,48	0,53
	1,5	0,50	0,47	0,92	0,66	-	0,67	0,64
	2	0,60	0,55	0,99	0,76	-	0,86	0,75
	3	0,75	0,69	1,00	0,88	-	1,00	0,86
	4	0,85	0,82	1,00	0,94	-	1,00	0,92
	5	0,95	0,91	1,00	0,98	-	1,00	0,97
	6	1,00	1,00	1,00	1,00	-	1,00	1,00

Research on the basis of which specific flood damage curves for Slovenia would be developed does not yet exist. Some individual tests were made for past flood events (Celje 1990, Celje 1998, Dobrepolje 2010), based on data from the AJDA system (National Regulation on Damage Assessment Methodology), but all analyzes came to the conclusion that the listed data are very inconsistent, so it is difficult to derive meaningful rules for creating a damage curve for Slovenia.

4.1. Existing flood risk and anticipated impact of climate change to flood risk (RCP 4.5 2100)

Table 7: Total flood damage (structure and contents) applied in the X-RISK model for the addressed Sora catchment

Flood damage category	Unit	Total damage (EUR), adaptation August 2024 (35,0 % inflation), X-RISK project model
Residental buildings	m^2	846,45 EUR
Commercial buildings	m^2	1192,05 EUR
Industrial buildings	m^2	984,15 EUR

Table 8: GDP/capita based adaptation of the flood damage (EUR/m²), Huizinga (2017)

	Building based assessment		
	Max Damage Structure	Max Damage Content	Total
Country	(€/m^2, 2010)	(€/m^2, 2010)	(€/m^2, 2010)
Argentina	317	159	476
Australia	567	284	851
Austria	544	272	816
Bosnia and Herzegovina	219	110	329
Canada	549	274	823
Croatia	338	169	507
Cuba	243	121	364
Cyprus	447	223	670
Czech Republic	391	196	587
Denmark	591	296	887
Estonia	349	174	523
Germany	522	261	783
Greece	441	220	661
Hungary	333	166	499

Country	Building based assessment		
	Max Damage Structure	Max Damage Content	Total
	(€/m^2, 2010)	(€/m^2, 2010)	(€/m^2, 2010)
Iceland	522	261	783
Italy	493	246	739
Kosovo	196	98	294
Latvia	317	159	476
Liechtenstein	0	0	0
Lithuania	321	161	482
Luxembourg	739	369	1108
Monaco	844	422	1266
Montenegro	257	129	386
New Zealand	476	238	714
Poland	328	164	492
Portugal	412	206	618
Romania	278	139	417
Russian Federation	309	155	464
Serbia	237	119	356
Slovak Republic	365	183	548
Slovenia	418	209	627
Sweden	569	284	853
Switzerland	652	326	978
Turkey	303	151	454
Ukraine	189	94	283
United Arab Emirates	482	241	723
United Kingdom	505	253	758
United States	553	276	829

4.2. Flood damage evaluation on the Sora catchment (pilot case X-RISK-CC project)

For the purpose of evaluation of vulnerability and risk (expressed in monetary terms) scenario evaluating the existing flood damages and projected flood damages addressing the RCP4.5 temperature scenario (temperature increase from 2024 values for 1,2 ˚C). The scenario is anticipating the described significant shift that 2004 IDF values for the return period of 100 years will result in 10-year return period in 2100 due to the climate change. Similar shift in relation to 500-year return period, occurring with the probability of 100 years.

Table 9: Expected annual flood damages for the municipalities on the Sora catchment

Stage	**Municipality**	**Expected annual flood damage**
With CC RCP4.5 2100	Gorenja vas-Poljane	66.543,53 €
With CC RCP4.5 2100	Kranj	1.021.781,14 €
With CC RCP4.5 2100	Medvode	343.057,62 €
With CC RCP4.5 2100	Škofja Loka	3.265.768,70 €
With CC RCP4.5 2100	Železniki	4.398.606,25 €
With CC RCP4.5 2100	Žiri	4.026.767,25 €
With CC RCP4.5 2100	SUM	13.122.524,49 €
Existing (2004 precipitation data)	Gorenja vas-Poljane*	40.023,83 €
Existing (2004 precipitation data)	Kranj	584.914,66 €
Existing (2004 precipitation data)	Medvode	199.531,61 €
Existing (2004 precipitation data)	Škofja Loka	1.995.689,97 €
Existing (2004 precipitation data)	Železniki	2.764.076,11 €
Existing (2004 precipitation data)	Žiri	1.961.742,94 €
Existing (2004 precipitation data)	SUM	7.545.979,13 €

*Modelling results for the municipality of Gorenja vas-Poljane are not comparable with others due to the limited availability of flood hazard maps.

Table 10: Modelled increase of flood damages following the expected IDF change (2004-2100 CC RCP4.5 scenario)

	Increase 2004 - 2100 - modelled flood damage
Gorenja vas-Poljane*	66%
Kranj	75%
Medvode	72%
Škofja Loka	64%
Železniki	59%
Žiri	105%
Total average	74%

*Modelling results for the municipality of Gorenja vas-Poljane are not comparable with others due to the limited availability of flood hazard maps.

Table 11: Vulnerability data used for the flood damage modelling

Municipality	**Scenario**	**Return period**	**No. Of Buildings**	**Population in buildings (2020)**
Gorenja vas-Poljane	CC RCP4.5 2100	Q10	9	3
Gorenja vas-Poljane	CC RCP4.5 2100	Q100	19	20
Gorenja vas-Poljane	CC RCP4.5 2100	Q500	19	20
Gorenja vas-Poljane	2004 no CC RCP4.5 2100	Q10	3	3
Gorenja vas-Poljane	2004 no CC RCP4.5 2100	Q100	9	3
Gorenja vas-Poljane	2004 no CC RCP4.5 2100	Q500	19	20
Kranj	CC RCP4.5 2100	Q10	254	541
Kranj	CC RCP4.5 2100	Q100	337	733
Kranj	CC RCP4.5 2100	Q500	337	733
Kranj	2004 no CC RCP4.5 2100	Q10	76	169
Kranj	2004 no CC RCP4.5 2100	Q100	254	541
Kranj	2004 no CC RCP4.5 2100	Q500	337	733
Medvode	CC RCP4.5 2100	Q10	71	83
Medvode	CC RCP4.5 2100	Q100	100	147
Medvode	CC RCP4.5 2100	Q500	100	147

Municipality	Scenario	Return period	No. Of Buildings	Population in buildings (2020)
Medvode	2004 no CC RCP4.5 2100	Q10	20	15
Medvode	2004 no CC RCP4.5 2100	Q100	71	83
Medvode	2004 no CC RCP4.5 2100	Q500	100	147
Škofja Loka	CC RCP4.5 2100	Q10	756	1262
Škofja Loka	CC RCP4.5 2100	Q100	913	1715
Škofja Loka	CC RCP4.5 2100	Q500	913	1715
Škofja Loka	2004 no CC RCP4.5 2100	Q10	262	419
Škofja Loka	2004 no CC RCP4.5 2100	Q100	756	1262
Škofja Loka	2004 no CC RCP4.5 2100	Q500	913	1715
Železniki	CC RCP4.5 2100	Q10	518	1246
Železniki	CC RCP4.5 2100	Q100	724	1876
Železniki	CC RCP4.5 2100	Q500	724	1876
Železniki	2004 no CC RCP4.5 2100	Q10	155	328
Železniki	2004 no CC RCP4.5 2100	Q100	518	1246
Železniki	2004 no CC RCP4.5 2100	Q500	724	1876
Žiri	CC RCP4.5 2100	Q10	723	1625
Žiri	CC RCP4.5 2100	Q100	1063	2385
Žiri	CC RCP4.5 2100	Q500	1063	2385
Žiri	2004 no CC RCP4.5 2100	Q10	63	92
Žiri	2004 no CC RCP4.5 2100	Q100	723	1625
Žiri	2004 no CC RCP4.5 2100	Q500	1063	2385

On following figures, the modelling data: buildings (vulnerability) and flood risk for each addressed municipality on the Sora River catchment are presented. They provide an insight into the flood damage modelling approach.

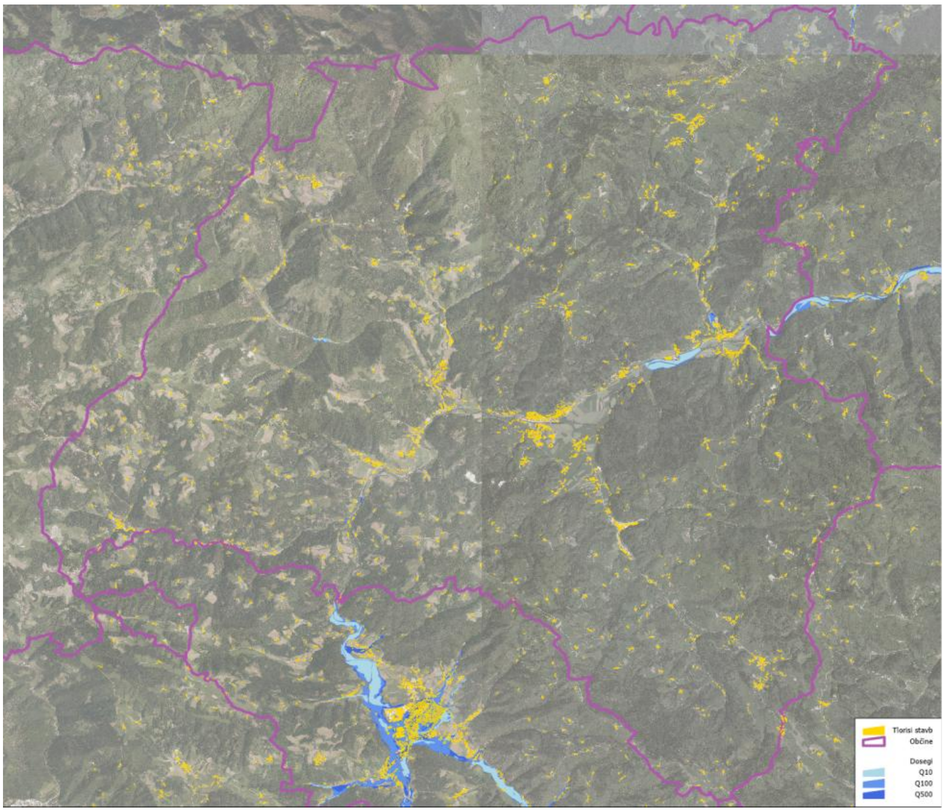

Figure 8: Gorenja vas – Poljane municipality – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model (flood hazard maps are not available).

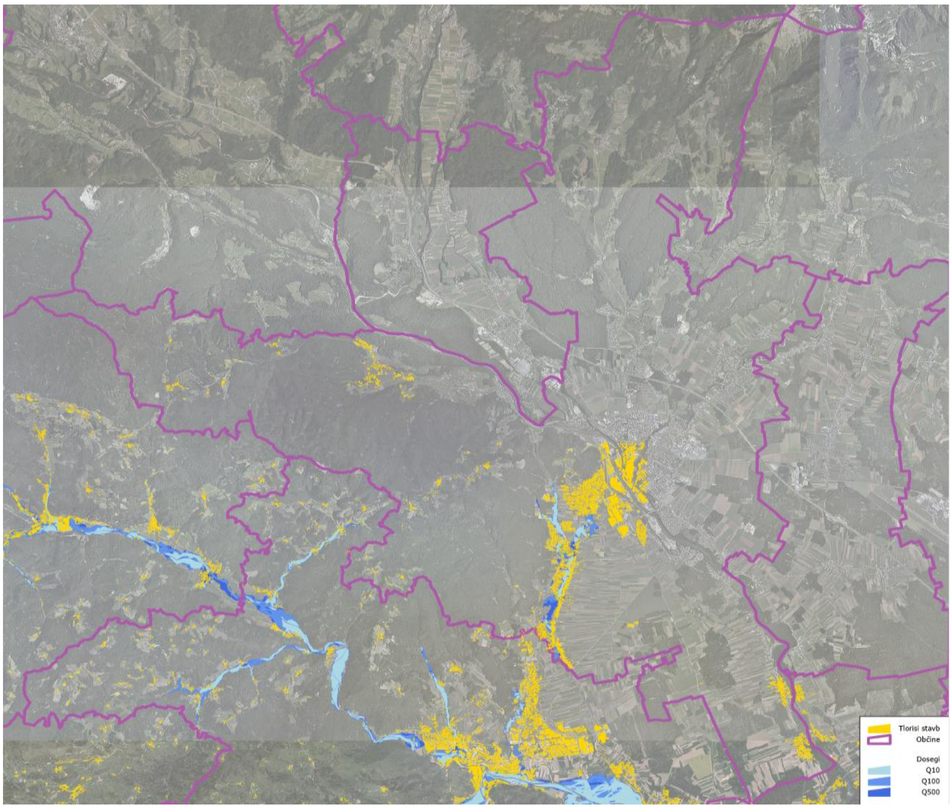

Figure 9: Kranj municipality (part of it on Sora catchment) – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model.

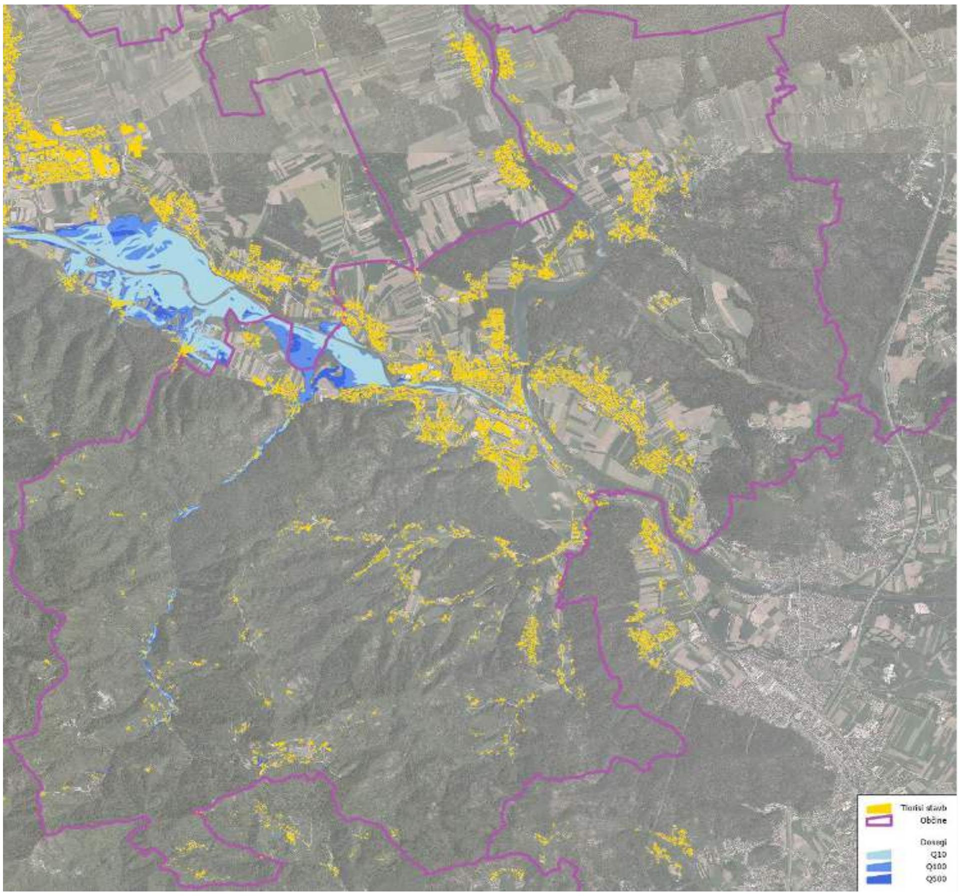

Figure 10: Medvode municipality (part of it on Sora catchment) – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model.

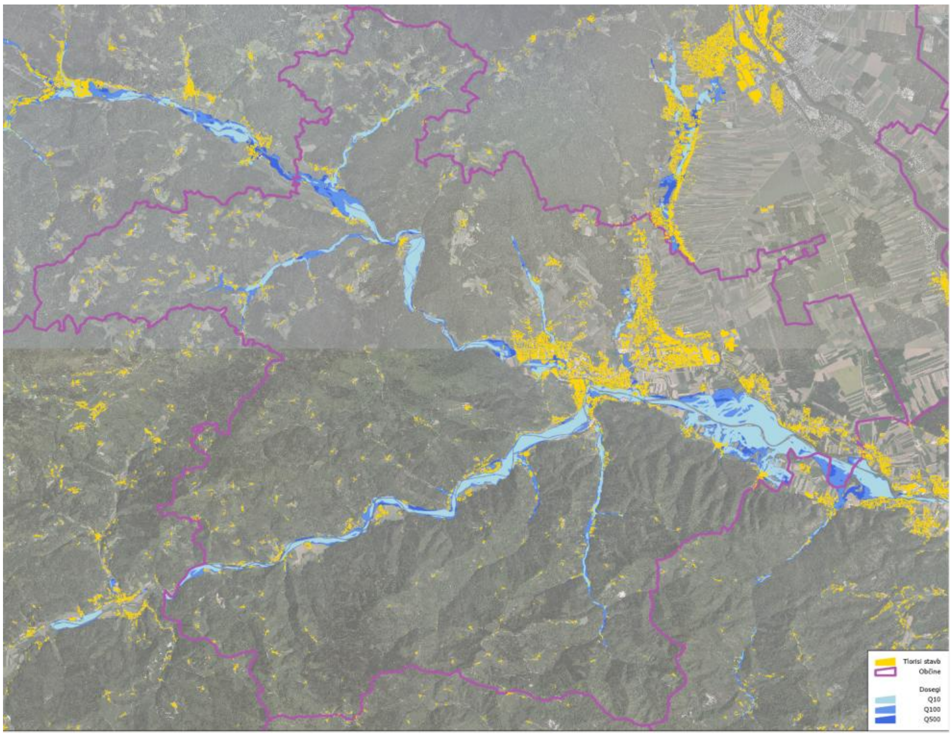

Figure 11: Škofja Loka municipality – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model.

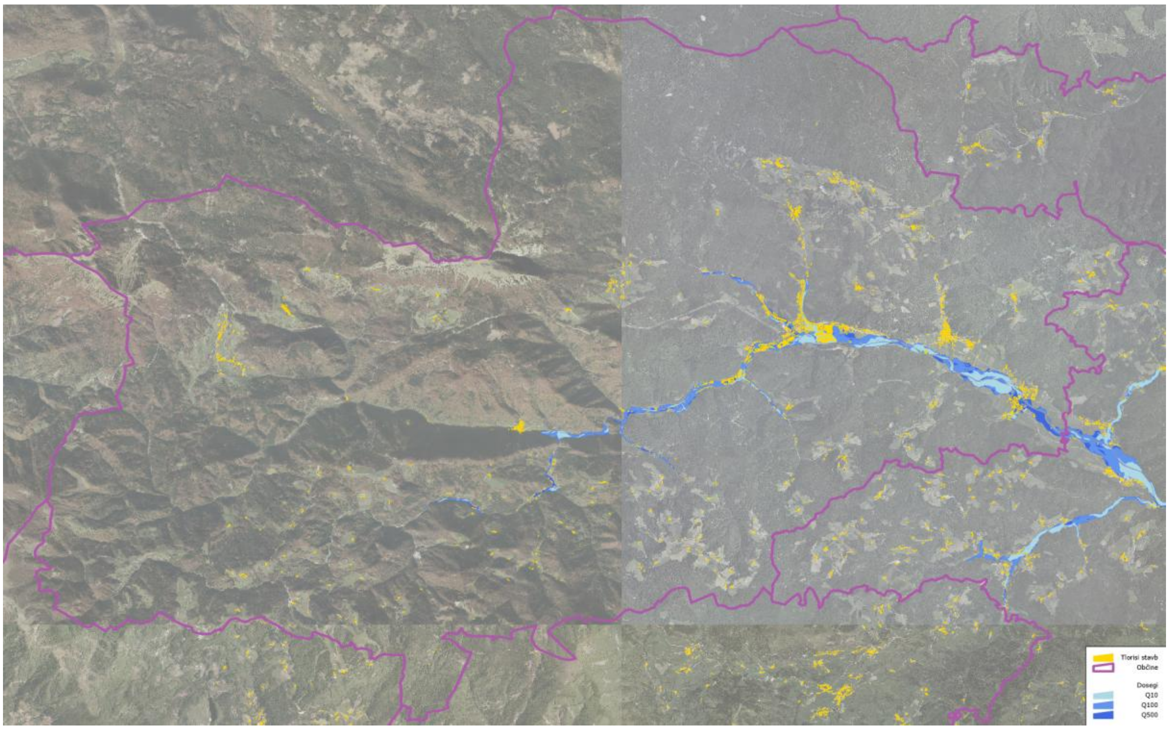

Figure 12: Železniki municipality – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model.

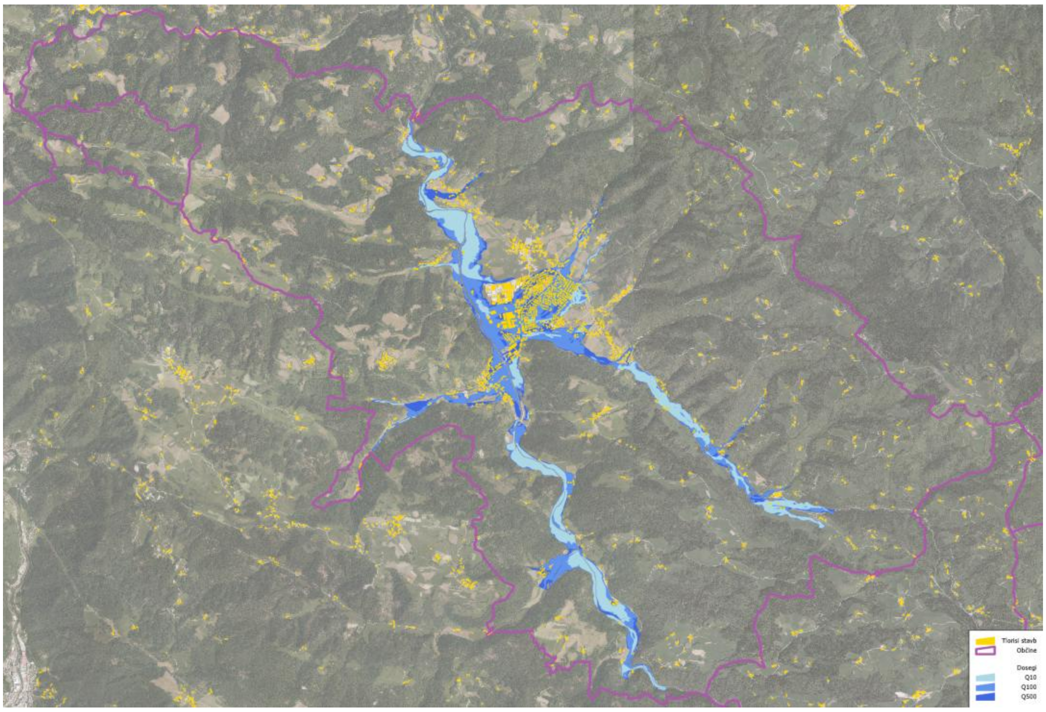

Figure 13: Žiri municipality – data from the building cadastre (vulnerability) and flood hazard maps used for the flood damage model.

4.3. The most important exposed elements at risk and expected changes in the future

The risk as a probability compositum of hazards and vulnerability is modelled and evaluated in the chapter 4. In this chapter we are addressing elements, which are related to the increase damage potential (vulnerability). Beside the increased hazard (due to the climate change), it is the vulnerability which is an important part of the equation, which is defining existing and future risks.

Vulnerability could be addressed with the efficiency/effectiveness of the following measures:

- Adequate spatial planning and permitting procedures preventing users from entering the flood hazard zones (existing, future);
- Adequate legislation framework – existing legislation framework is not yet addressing the climate change scenarios,
- Enforcement of the adopted legislation – currently non-legal interventions are in Slovenia sanctioned only to extremely limited extent. There are no public data available on the efficiency/effectiveness of the inspections. Available media information from the Ministry of natural resources and spatial planning is providing a message, that the number of inspectors don't meet the number of open procedures requesting their actions.

4.3.1. Past/present exposure and impacts

Present and future exposure is modelled and explained in the chapter 4. Table 10 in providing information on existing exposure (buildings, people) and anticipated exposure following the RCP4.5 2100 scenario (simplified).

Indirect effects associated with a hazard event can exacerbate conditions during the event response and recovery phases and have to potential to significantly increase overall monetary losses. The main sectors that might be indirectly affected are:

- Tourism in the area is an activity of growing importance, nevertheless the municipalities on the X-RISK addressed Sora rive catchment are currently not in the central spotlight of tourist activities in Slovenia. Floods could affect the existing tourism especially by affecting transport routs limiting accessibility to touristic locations[13].
- Traffic: the area is of major importance for the national R4 corridor which is currently being analyzed for the improvement of road infrastructure. No train infrastructure on the Sora catchment.

4.3.2. Potential future exposure and impacts

The population in the area is relatively stable with slight increase. The increase could be recognized in the largest municipality (Škofja Loka) which is also most urbanized and sub-regional centre of the area with several educational facilities and services.

[13] https://www.visitskofjaloka.si/si/

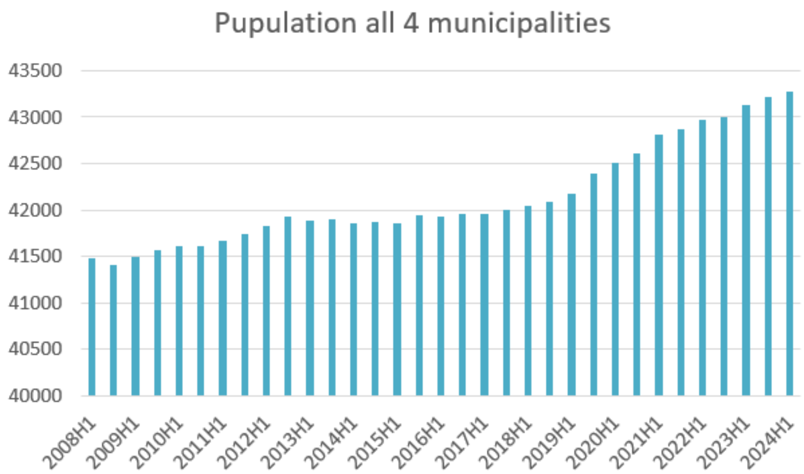

Figure 14: Population in the municipalities Škofja Loka, Žiri, Železniki and Gorenja vas - Poljane (Source: SURS – Statistical office).

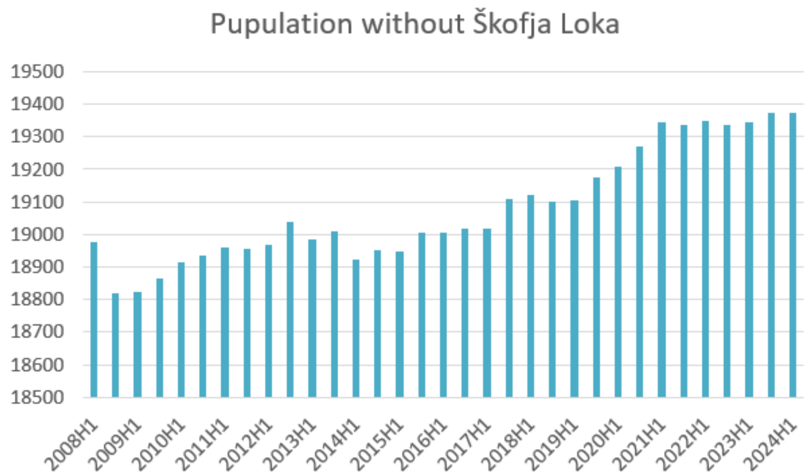

Figure 15: Population in the municipalities Škofja Žiri, Železniki and Gorenja vas - Poljane (Source: SURS – Statistical office).

It is expected that the increase of the population will not affect long term vulnerability of the area significantly.

5. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

Some changes, which are not addressed in the chapters above might affect the flood risk:

- Trends related to the snow precipitation and snow coverage – precipitations in the form of snow and snow coverage are a very important retention mechanism. With the highest mountains on the watershed Ratitovec (1667 m.a.s.l.) and Porezen (1630 m.a.s.l.) and several ski resorts (Soriška planina, Črni vrh) snow was an important retention mechanism. The absence of snowfall and snow coverage will significantly affect the runoff in the catchment.
- Technical floods – technical floods are used as term for floods which are related to the maintenance and functioning of existing flood control structures. Similar to many European countries many of these were constructed in the period 1950 – 1970, which means, that they are at the end of their envisaged design life span. These structures were also build on the hypothesis of the return periods and intensity of events from that period.
- Urban drainage and urban flooding – of the addressed municipality perhaps only Škofja Loka has an urban centre, which is large enough to develop specific urban runoff control mechanisms. Urban drainage and urban flooding should be part of the adaptation process, also in the light of the climate change.

6. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

Risk management measures related to the implementation of the EU Floods Directive (2007/60) are set in place. Water agency and the Ministry of Natural Resouces and Spatial Planning have, following the directive, developed National Flood Risk Reduction Plan (current planning period is 2023-2027). There are several areas of important flood impact (Območja pomembnega vpliva poplav) on the Sora catchment:

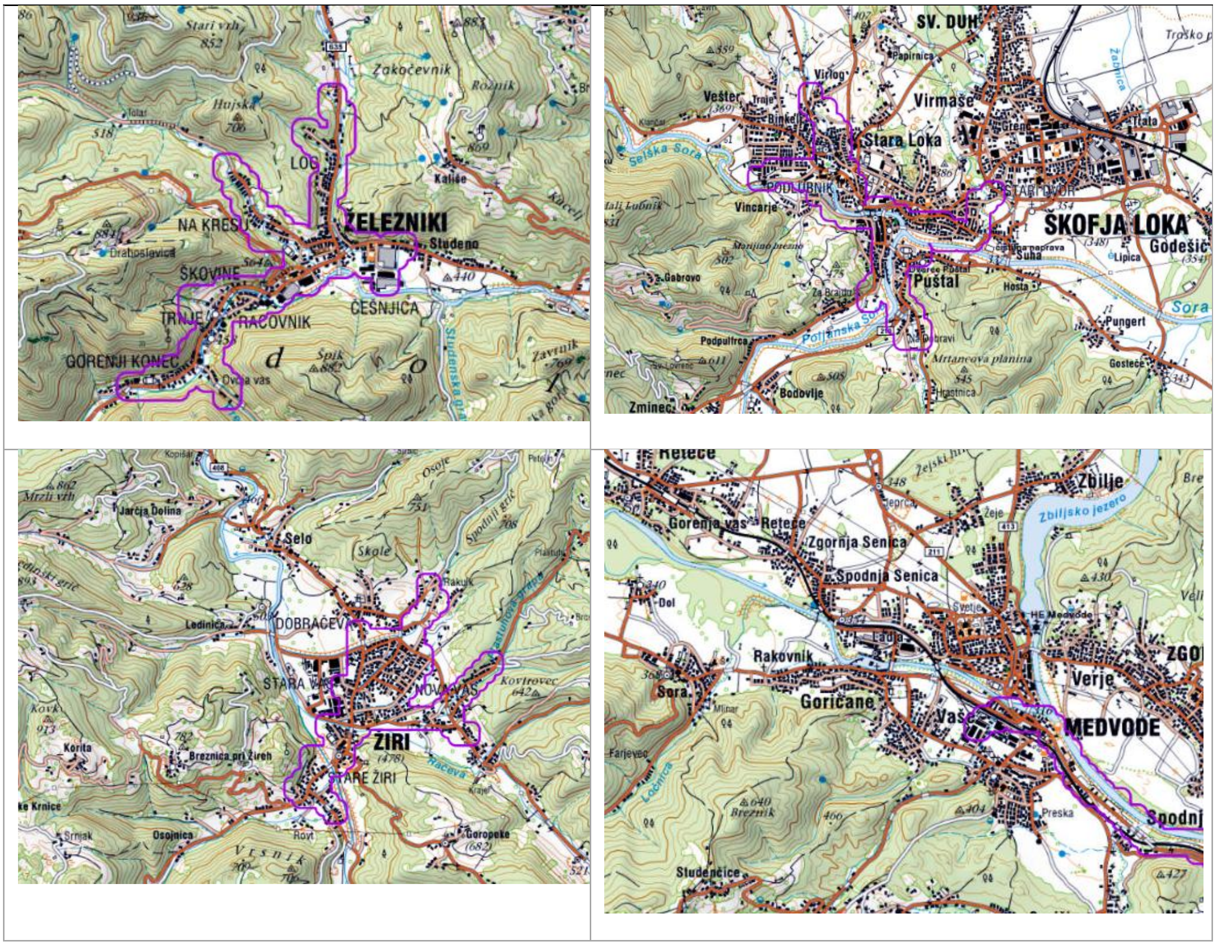

Figure 16: Defined areas of important flood impact (OPVP) as defined by the National Flood Risk Reduction Plan (2023-2027) – OPVP SI1_23 (Škofja Loka), SI1_20 (Železniki), SI1_22 (Medvode-Tacen)

National Flood Risk Reduction Plan (2023-2027) is identifying the priority areas in which the measures are ongoing for the reduction of flood risk. Among the listed priority areas, for the area of Železniki, which was most affected by the floods of 2007 several measures were already constructed following the spatial planning document adopted on the national level[14].

[14] Uredba o državnem prostorskem načrtu za preložitev regionalne ceste R2-403/1075 Podrošt–Češnjica skozi Železnike ter ureditev vodne infrastrukture za zagotavljanje poplavne varnosti Železnikov (Ur. list RS, št. 37/2013 z dne 29.4.2013

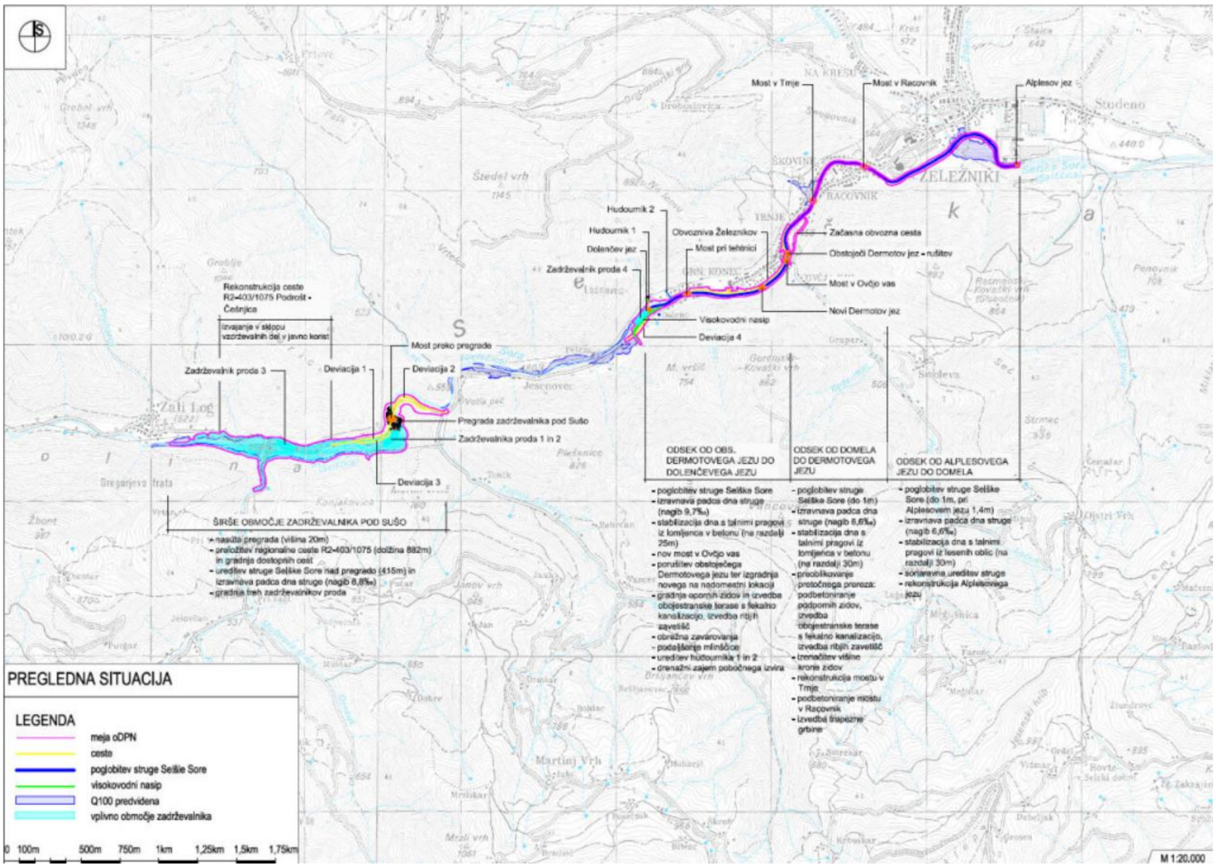

Figure 17: Flood risk reduction measures in Železniki municipality (State Spatial Plan) – implementation of measures is closing to the end

In 2013, the Government of the Republic of Slovenia issued the Decree on the State Spatial Plan for the relocation of the regional road R2-403/1075 Podrošt-Češnjica through Železnike and the arrangement of water infrastructure to ensure flood safety of Železnike (Official Gazette of the Republic of Slovenia, No. 37/2013 of 29.4. 2013; hereinafter: Regulation). The goals of the state spatial plan are to protect the settlement of Železniki from 100-year flood high waters by implementing appropriate anti-flooding arrangements and the arrangement of the regional road that runs through the old core of the settlement of Železniki (the bypass road of Železniki). The investor of the water arrangements defined in the Regulation is the Ministry of Environment and Spatial Planning of the Republic of Slovenia (MOP), from which the newly established Water Directorate of the Republic of Slovenia (DRSV) took over essential activities in 2016, while the investor of the bypass road is the Ministry of Infrastructure, Directorate of the Republic of Slovenia for Infrastructure (DRSI). The investment is co-financed by the Republic of Slovenia and the European Union from the Cohesion Fund.

In accordance with the Regulation, which provides for the implementation of functionally completed units, water arrangements are divided into two phases. The first phase of the water regulations includes the regulations in the area of influence of Železniki (from the Dolenčevo dam to Alples), where measures are planned in four sections to increase the flow rate and equalize the dynamic characteristics of the river bed. A bypass regional road will also be built along Sora on this section. The second phase of the water arrangements includes the water management arrangements in the area of the "Pod Sušo" reservoir with the arrangement of a high barrier, with measures to contain sediments (gravel and sand) in the retention area and other accompanying arrangements.

From the entry into force of the regulation, MOP has been carrying out activities to obtain a building permit for the implementation of the first phase of water arrangements. In 2016, the essential activities for obtaining a building permit for the implementation of the first phase of water arrangements were taken over by the newly established DRSV, which will also be responsible for the second phase of water arrangements according to the State Spatial Plan (DPN). In parallel with the activities of MOP and DRSV, DRSI also carried out activities to obtain a construction permit for the postponement of the regional road. After the completion of both phases, Železniki will be protected against the "century floods" of the Selška Sora.

In April 2017, all three investors concluded a tripartite agreement, with the aim of the joint performance of all three entities in obtaining the right to build, in obtaining environmental approval and in obtaining a single building permit.

7. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

Probability of simultaneous occurrence of different extreme precipitation events is generally already addressed in the applied modelling approach requested by the Slovenian Technical Guidance for the preparation of flood hazard maps[15]. The Technical Guidance document is addressing the issue of envelope of extreme flood events modelled, as well as consideration of simultaneous occurrence of precipitations of different duration on confluence of rivers.

However there are several issues which are very difficult to address:

- Simultaneous occurrence of floods of different typologies: urban flooding, technical flooding, groundwater flooding;
- Integration of erosion events – erosion of different typologies – river bank erosion, surface erosion;
- Operational status/maintenance of hydraulic structures.
- Landslides and debris flows.

These phenomena are usually closely related to the intensive precipitation events, where precipitation is the trigger of these events, or in some cases, like erosion, floods (high velocity flows) trigger these events. These events were observed on the Sora catchment during past extreme flood events and influence the exposure of vulnerable categories like settlement, industry, agriculture, infrastructure.

8. Current impacts of compound/cascading hazard events

Current impacts of compound/cascading hazard events are not evaluated.

[15] Technical Guidance on the methodology for determining areas at risk from floods and the related erosion of inland waters and the sea, and on the method of classifying land into risk classes Official Gazette of the Republic of Slovenia, no. 60/07

9. Recommendations

As described in the previous chapters flood management on the Sora river catchment has a long tradition, with abundance of data and information of flood hazard, flood vulnerability, with ongoing implementation of the flood risk reduction measures. Nevertheless, we could describe in a figurative way the current position in regard to the observed and anticipated climate change as being on the edge of a dangerous abyss - considering a rich history of extreme events, these events are expected to become quite regular and we should get ready for it. As a starting point for the recommendations we can use the anticipated categories of measures, as they are defined by the Slovenian Flood Risk Reduction Plan (2022-2027)[16]:

U1 Determination and consideration of flood zones

U2 Identification, establishment and preservation of spillways of high water

U3 Adaptation of land use in river basins

U4 Implementation of hydrological and meteorological monitoring

U5 Establishing and keeping records in the field of flood risk

U6 Education and awareness of flood risk

U7 Planning and construction of construction anti-flood measures

U8 Implementation of individual (self-protection) anti-flood measures

U9 Regular checking of the effectiveness of existing (construction) anti-flood arrangements

U10 Regular maintenance of watercourses, water facilities and water and coastal land

U11 Implementation of river control

U12 Anti-flood management of water facilities

U13 Provision of financial resources for the implementation of the economic public service of water management

U14 Preparation of flood protection and rescue plans

U15 Flood forecasting

U16 Flood warning

U17 Flood intervention

U18 Damage assessment and rehabilitation after floods

[16] Načrt zmanjševanja poplavne ogroženosti 2023–2027 ((NZPO SI II), https://www.gov.si/assets/ministrstva/MOP/Javne-objave/Javne-obravnave/NZPO_II/NZPO_II.pdf

U19 Documentation and analysis of flood events

U20 Systemic, normative, financial and other measures

Same measures (U1 - U20) were also in the past planning period - Slovenian Flood Risk Reduction Plan (2017-2021)[17], but were implemented only to very limited extend. For example the measure U19 Documentation and analysis of flood events was not implemented yet after the floods of August 2023. The actual level of implementation of other measures should be thoroughly analysed and resulting corrective measures towards the improved implementation of the measures applied.

Some additional measures, beside those defined by the Flood Risk Reduction Plan, could be added:

- Re-allocation of buildings/persons, for which flood risk reduction measures are difficult to apply or are extremely expensive;
- Measures addressing chain hazardous events, like: landslides, erosion, debris flows;
- A broader understanding of floods, including urban drainage, technical floods, groundwater floods;
- Improved governance of the sector on all levels, including public participation as part of the Nature Based Solutions standard (IUCN[18]), addressing bottlenecks also concerning the capacity and human resources limitations in the governance process.
- Currently the flood risk reduction (planning, implementation, maintenance) is limited to the governance structures on the national level. Following the Water act[19] regions and municipalities have only extremely limited position in the flood risk reduction and CC adaptation process (urban drainage, processes related to spatial planning on local level). Improved vertical integration is suggested.

The last Slovenian Flood Risk Reduction Plan (2022-2027) is in the appendix F already addressing the issue of climate change on flood risk and flood management, but only in a very general way summarizing the results of the ARSO report[20]. More elaborated plan of measures related to floods and climate change (impact assessment, risk assessment, strategy, plan of activities) should be elaborated on the national level with operational guidance and action plans on regional and municipality level.

[17]Načrt zmanjševanja poplavne ogroženosti 2017–2021 (NZPO SI I), 35500-5/2017/8 Date 27. 7. 2017, https://www.gov.si/assets/ministrstva/MOP/Dokumenti/Voda/NZPO/606504549e/nzpo_2017_2021.pdf

[18] IUCN Global Standard for Nature-based Solutions (2020) (https://iucn.org/our-work/nature-based-solutions

[19] Zakon o vodah (ZV-1), https://pisrs.si/pregledPredpisa?id=ZAKO1244

[20] ARSO (2018) OCENA podnebnih sprememb v Sloveniji do konca 21. stoletja : sintezno poročilo / [avtorji besedila Renato Bertalanič ... [et al.] ; urednica Mojca Dolinar]. - Ljubljana : Ministrstvo za okolje in prostor, Agencija Republike Slovenije za okolje, 2018.

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2. Garmisch-Partenkirchen, Germany

RISK QUESTIONNAIRE

Garmisch- Partenkirchen (DE)

January 2025

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

a) Past/present weather extremes

In the Garmisch-Partenkirchen pilot area, the main weather extremes considered are heavy precipitation events, especially short-duration rainfall occurring during the summer period. Such meteorological events are found to trigger subsequent hazard, like gravitational mass movements, or hyperconcentrated flows.

To investigate potential changes under different climate scenarios, station data and climate model projections were used to assess current and future levels of daily and sub-daily precipitation extremes. In particular, three station sites in the pilot area were analysed: Garmisch-Partenkirchen, Mittenwald Buckelwiese and Zugspitze.

The intensity of 1-day precipitation maxima on an annual basis was found to increase only at Zugspitze (2’956 m a.s.l.) over the period 1950-2022 by + 2.5 % / decade. 1-day precipitation maxima in summer show an increasing tendency at all stations but with no statistical significance. On a sub-daily scale, based on the observations at Garmisch-Partenkirchen, the annual number of events with hourly precipitation above the 99th percentile increased over the period 2000-2023 by + 4.3 events / decade and + 1.8 events / decade by considering only summer events. Approximately half of the annual trend can be attributed to increasing occurrence of intense hourly precipitation events in summer.

Analysis of climate trends (1951-2015) in the Bavarian Alps reported by the Bavarian Environment Agency show an increase in mean annual temperature by +1.5°C and approximately + 7 days of dry conditions without rain from April until June.

b) Potential future weather extremes

The frequency and intensity of extreme 1-day precipitation is expected to increase in the future at all station sites. The annual number of days with daily precipitation above the 97th percentile increases with the level of global warming, reaching between 12 to 25 more extreme precipitation days, as median of the model ensemble, under GWL4 with respect to 1991-2020, depending on the location. The largest frequency increases are projected at Zugspitze.

As regards the intensity of 1-day precipitation extremes, increases with respect to 1991-2020 are projected for all sites on both annual and summer scales, especially under the worst-case scenarios GWL3 and GWL4. Under GWL4, 1-day precipitation summer maxima are projected to increase in intensity of 7 % and 8 % in Garmisch and Mittenwald, respectively, and of about 5 % at Zugspitze station, as median changes reported by the model ensemble. Similarly, projected changes in return levels of annual 1-day precipitation extremes are positive for all sites and return periods, especially under higher global warming levels. The return levels of 100-year recurring event are projected to increase between 33 % and 41 % in Garmisch (by considering the median values over all model simulations, the current 164 mm will be between 207 mm and 213 mm in the future) and between 15 % and 37 % in Mittenwald (by considering the median values over all model simulations, the current 188 mm will be between 237 mm and 272 mm) under GWL3 and GWL4.

Furthermore, the Clausius-Clapeyron relationship was applied to scale precipitation patterns to account for global warming. The scaling factor based on Alpine Space wide precipitation data is 7.6% ± 1.1% per °C of warming (scaling between temperature and logarithm of precipitation). Warming in this case is defined as Alpine Space warming, which is roughly twice the amount of global warming, based on historical records for near-surface temperature. Using 1991 to 2020 as reference period, it yields increases, for the current 99^{th} percentile (based on hourly precipitation totals from station data on wet days), from 8.2 [mm/hour] to (11.0 ± 0.5) [mm/hour] for the Global Warming Level (GWL) 1.5°C. For GWL 2°C, (12.83 ± 0.86) [mm/hour], GWL 3°C (17.44 ± 1.99) [mm/hour], GWL 4°C (23.71 ± 3.81) [mm/hour] and for GWL 5°C (32.32 ± 6.7) [mm/hour]. Other [mm/hour] values can be scaled using the same scaling factor for each GWL.

Climate projections for the Bavarian Alps (by the Bavarian Environmental Agency) indicate rising mean annual temperatures of 1.1°C (max.1.6°C) and 4.1°C (max. 5.1°C) for scenarios with and without climate protection, respectively (climate protection = RCP2.6, no climate protection = RCP8.5). In addition, drier conditions in summer months are expected due to a rise in temperatures and a deficit in summer precipitation of up to -24%.

References:

Bayerisches Landesamt für Umwelt (2021): Bayerns Klima im Wandel – Klimaregion Alpen

II. Which hazard processes can be triggered by current and future weather extremes?

The region of Garmisch-Partenkirchen is exposed to multiple alpine hazards such as rock slope failures, landslides, river floods, debris flows, hyperconcentrated flows, and flash floods (Figure 1). Recurrent extreme precipitation events in the last decades caused multiple natural hazard events, e.g., in 1999, 2005, 2013, 2018, 2020, and 2021, affecting the touristic Partnachklamm & Höllentalklamm with respectively 200,000 and 70,000 visitors per year as well as the town of Garmisch-Partenkirchen with approx. 30,000 inhabitants.

The upstream areas, including the Hammersbach catchment (10 km^2) and Partnach catchment (130 km^2, with Ferchenbach and Kankerbach subbasins), are located in one of the wettest regions of Bavaria with total annual precipitation values of 1,350 mm in Garmisch-Partenkirchen and more than 2,000 mm at the Zugspitze summit (Götz & Schrott, 2010). The Garmisch-Partenkirchen weather station records the highest annual precipitation in the summer months due to orographic lifting at the main chain of the Alps combined with the occurrence of frequent thunderstorms. The clear link of hazardous torrential processes to intense summer precipitation makes the region especially susceptible to changing rainfall intensities in the foreseeable future in a changing climate.

Figure 1 serves as an overview of the hazard processes that have happened in the past (see event table), or which can potentially occur in the watersheds of the pilot GAP under current conditions. We will focus our answers to section II a) and II b) in more detail to torrential processes.

Pilot GAP: Hazard process chains

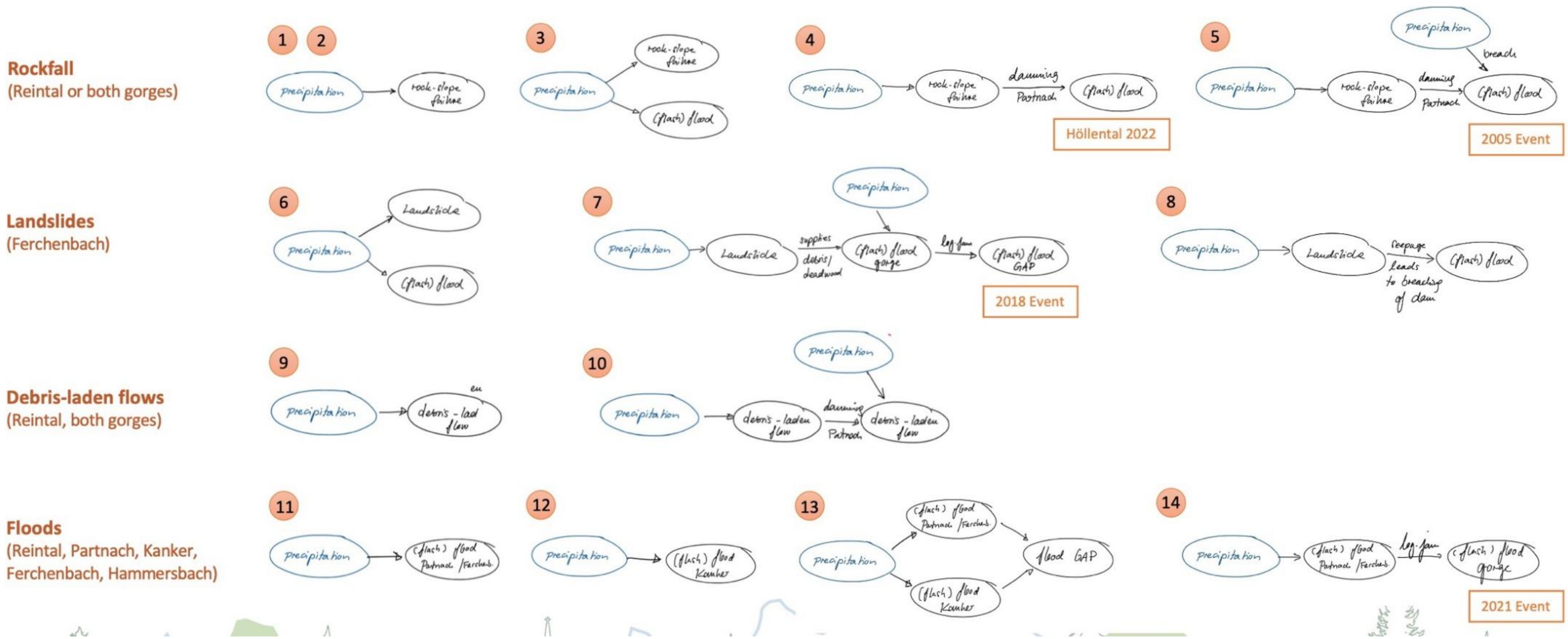


Figure 1: Sketch of hazard process chains that can occur in the catchments around Garmisch-Partenkirchen

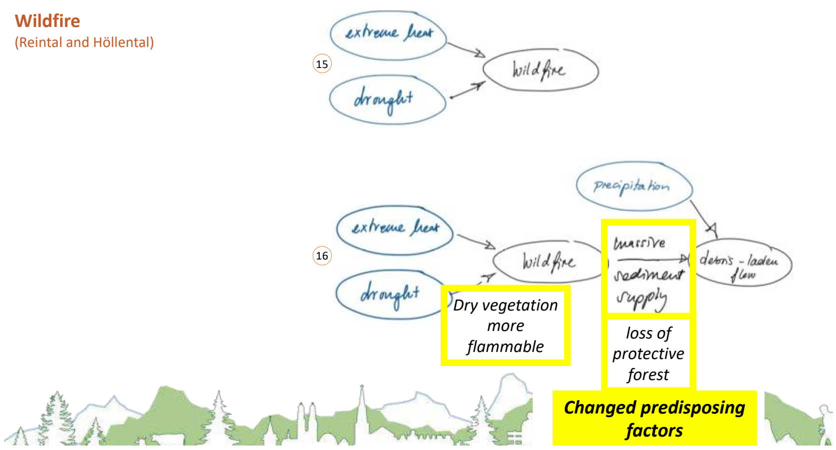
a) Past/present hazard processes due to weather extremes

Most relevant natural hazards are torrential processes controlled by heavy precipitation, such as river floods (after prolonged rainfall) or flash floods (triggered by short, intense precipitation). Debris flows are occurring frequently in the tributaries further upstream in the Reintal valley (closest debris flow fans at Schindeltalschrofen) and have not affected the Partnachklamm yet. Nevertheless, sediment availability in the Reintal is very high with abundant calcareous debris (Hauptdolomit and Wetterstein formation) on talus slopes fed by rockfalls or larger scale rock-slope failures and historic bergsturz events. In the neighbouring Höllentalklamm however, on 16.08.2021, a more sediment-enriched, hyperconcentrated flow occurred, revealing the potential for such types of flow in the pilot area.

The Partnachklamm is frequently affected by flooding events with relatively low sediment concentration (stream flows). However, driftwood mobilised in the lower slopes of the sub-catchment Ferchenbach are a major issue and have led to logjams in the narrow Partnachklamm and in some cases outburst after dam breakage (e.g., flash flood with logjam in 2018, about 1000 m^3 of driftwood). Soft marly rocks (Raibl formation and Partnach formation) dominate the slopes of the Ferchenbach catchment, leading to numerous large landslides with displacement rates up to 1m/year, which supply wood as well as debris to the channel.

b) Potential future hazard processes due to future weather extremes

Due to expected increasing summer temperatures and drought conditions in summer (see Q1), **wildfires** could become more likely to occur in the Alpine catchments of the Hammersbach, Partnach and Ferchenbach. After a wildfire has devastated a watershed, **debris flows** are especially likely, but it also increases the susceptibility to also landslides and flooding due to the loss of protective forest. It is also important to note that “many watersheds susceptible to post-fire debris flows may not be, or rarely are, subject to debris flows in the absence of wildfires” (Jakob & Nolde, 2024).



Another key source of debris are large landslides along the Ferchenbach: four currently active, large landslides have been identified with a volume of approximately 270,000 m^3 and displacement rates of up to 1 m/year, affecting the river over a total length of 400 m (Master thesis Pfluger, 2021). After heavy precipitation in early summer 2024, 8 large landslides along the Ferchenbach have been reactivated. The largest of these has a volume of approximately 50,000 m^3 and showed maximum displacement rates of 8mm/week in the summer.

During heavy precipitation events (in combination with high antecedent soil moisture), these landslides can accelerate, contributing massive amounts of debris to the channel. This in turn increases the potential of **debris-laden flows**, given that the water level and discharges would also be high due to the extreme precipitation event. It is important to note that debris flows originating in the Ferchenbach valley can potentially reach the Partnachklamm. In general, we expect debris-laden flows to occur more frequently in the future: publications of fieldwork conducted in the Reintal and at Plansee (ca. 23 km off the pilot GAP) both show an increase in debris flow frequency and magnitude:

- Reintal (Sass & Krautblatter, 2007): 5 times increase in debris flow volume from 19th (about $100 m^3/a$) to 20th century (about $560 m^3/a$)
- Plansee (Kiefer et al., 2021): ∼1920 to 2018 CE exhibits a drastic increase in debris flow frequency, followed by the overall highest debris flow frequency of the whole record, which is about 7 times higher than during ∼1520 to ∼1920 CE.
- Plansee (Dietrich & Krautblatter, 2017): Debris flow volume increased by a factor of 10 from 1947-1952 to 1987-2000; post-1980 rates exceed pre-1980 rates by a factor of >3

Furthermore, the increasing intensity and frequency of extreme 1-day precipitation could also increase the likelihood of **flooding** events in the future, affecting the Kankerbach, Partnach and Hammersbach. A potential scenario of combined hazards describes concurrent flood waves coming from the Partnach and the Kankerbach, leading to discharge overload of the conduits that manage water distribution between Kankerbach and Partnach in the S-E residential area of GAP.

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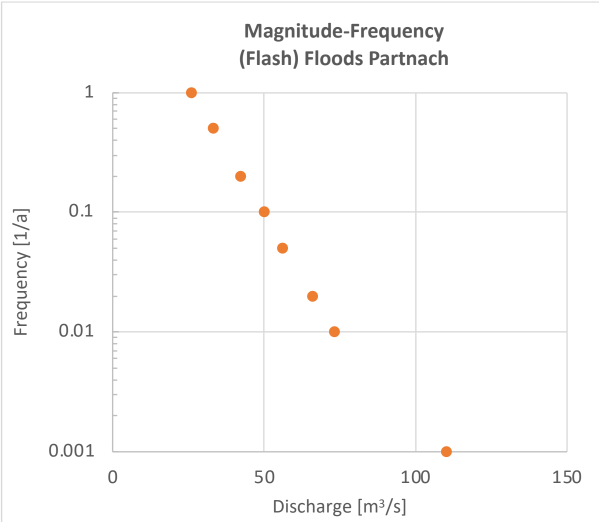
Sass, O., Krautblatter, M., Morche, D., (2007) Rapid lake infill following major rockfall (bergsturz) events revealed by ground-penetrating radar (GPR) measurements, Reintal, German Alps: Holocene v. 17, p. 965-976.

III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

a) Past/present frequencies and magnitudes

Magnitude and frequency of flood events in the Partnach river have been estimated by the Water Agency Weilheim based on maximum annual discharges measured since 1920 at the gauging station Partenkirchen/Partnach. The discharge of the last major flood event on 23.08.2005 corresponds to a 100-year flooding event (HQ100).



	MHQ	HQ1	HQ2	HQ5	HQ10	HQ20	HQ50	HQ100	HQ1000
Discharge [m3/s]	32	26	33	42	50	56	66	73	110

Figure 2: Magnitude-frequency of foods and flash floods, derived from discharge measurements between 1920-2012 at the station Partenkirchen/Partnach. Analysis by the Water Agency Weilheim.

An analysis of discharges (accessible via Gewässerkundlicher Dienst) above the mean flood discharge MHQ (32 m^3/s) for the period from 1920-2020 shows a clear trend of flood events happening more frequently since the 1970s.

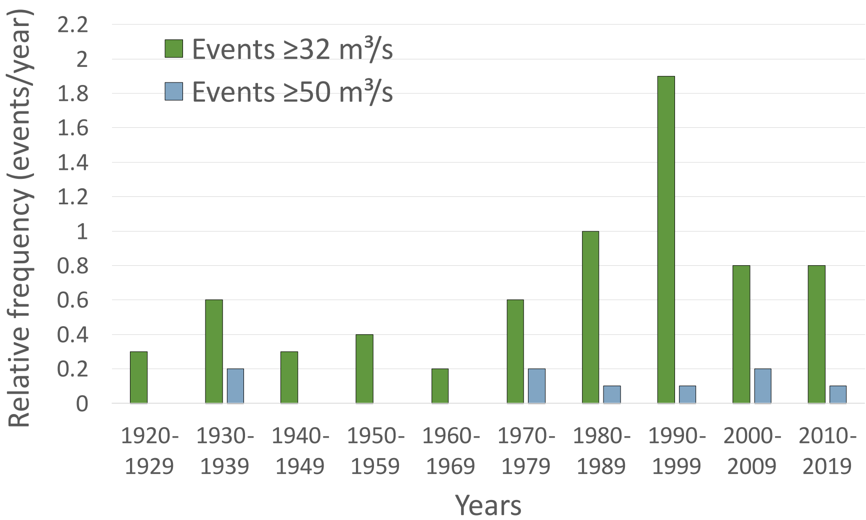


Figure 3: Frequency of floods above the mean flood discharge (MHQ) per decade since gauging started in 1920. Data obtained from gauging station Partenkirchen/Partnach operated by Water Authority Weilheim.

For other types of torrential hazards like hyperconcentrated flows and debris flows, only few documented records of past events exist. The hyperconcentrated flow on 13.06.2020 at the Höllentalklamm reached a volume of about 60,000 m^3 (Stammberger et al, 2024). A very large debris flow (extreme event) in the upper reaches of the Partnach watershed has been observed on 23.08.2005, reaching a volume of about 50,000-100,000 m^3 (Morche et al., 2007), depositing 75% of the debris within proximal reaches (without affecting the lower reaches of the Partnach or the Partnachklamm). This debris flow was caused by an unusual event, the rupture of Vordere Blaue Gumpe lake in the upper course of the Partnach. At the location "Schindeltalschrofen", about 1.5-2 km upstream of the entrance of the Partnachklamm, as well as on talus slopes in the upper Reintal, debris flows are occurring more frequently. Geomorphological analysis around the Schindeltalschrofen in 2021, including mapping of river terraces and creation of a DoD between 2019-2021, revealed average annual sediment supply to the Partnach from the catchments of the Schindeltalschrofen of about 1000 m^3/a.

b) Potential future frequencies and magnitudes

Some aspects have already been touched in Question II b).

Expected **drought conditions** in summer can change the predisposition in the following way:

- increased ignition probability (lower moisture content, thus higher flammability of fuels) due to changes in weather factors including high temperatures/heatwaves, prolonged drought periods, and strong winds → **wild fire**
- drier soils and vegetation due to earlier melting of snowpacks in spring, meaning that forests are drier for longer periods of time (more flammable) → **wild fire**

After a wildfire has ravaged a watershed, it has different implications:

- loss of (protective) forest and vegetation due to preceding wildfire and increased hillslope-channel coupling → **debris-laden flows, also reaching Partnachklamm**
- enhanced debris flow activity for at least 2 years: "The magnitude of debris flows is largely a function of the intensity of short-duration rainfall (minutes to hours), basin relief and the percentage of the watershed burned. […] Common to most post-fire debris flows is that they can be triggered by rainstorms with 0.5-year annual probability or even greater frequencies. Given that the worst effects of post-fire debris flows last for at least 2 years (see Gartner et al., this volume), it is likely that this rainfall threshold will be exceeded over that time period, resulting in a high likelihood of debris flow." (Jakob & Nolde, 2024).
- Sass et al. (2012) have investigated two slopes north of Innsbruck (Arnspitze and Bettlwurf), that have been affected by a wildfire in 1946: they found that measured **erosion rates were** roughly **ten times higher** than the undisturbed sediment yields.
- We estimate that debris-laden flows with volumes of approximately 10,000 m^3 can potentially occur in the Partnach, under the assumption that normal sedimentation rates of approx. 1000 m^3/a at Schindeltalschrofen can increase by a factor of ten after a wildfire

Runout distances and inundated area of potential debris-laden flows reaching and passing the Partnachklamm are still to be estimated in modelling studies.

Expected higher frequencies and intensities in 1-day and 1-hourly precipitation can affect the system in the following way:

- increased sediment supply by **landslides** (e.g., due to acceleration during heavy rainfalls) and increased hillslope-channel-coupling → **debris-laden flows, also reaching Partnachklamm**

- higher probability of debris-flows at location Schindeltalschrofen → increased sediment supply to Partnach river → **debris laden flows, also reaching Partnachklamm**
- high saturation of the soil during 1-day (or longer) rainfall inhibits infiltration of water, leading to surface runoff → **flooding**
- **more frequent flash floods** triggered by short-duration rainstorms in the future, also visible in the trend observed at the gauging station Partenkirchen/Partnach closely downstream of the Partnachklamm

References:

Gewässerkundlicher Dienst: https://www.gkd.bayern.de/de/fluesse/wasserstand/isar/partenkirchen-16425003

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Morche, D., Schmidt, K.-H., Heckmann, T. and Haas, F. (2007), Hydrology and geomorphic effects of a high-magnitude flood in an Alpine river: Geogr. Ann., v. 89 A, p. 5–19.

Sass, O., Haas, F., Schimmer, C., Heel, M., Bremer, M., Stöger, F. and Wetzel, K.-F. (2012), Impact of forest fires on geomorphic processes in the Tyrolean Limestone Alps: Geografiska Annaler: Series A, Physical Geography, v. 94, p. 117–133.

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ANALYSIS OF KEY RISK PATHWAYS

IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

a) Past/present exposure and impacts

In the past, extreme 1-day or multi-day precipitation has resulted in gravitational or hydrological hazards affecting the Partnach Gorge and/or the city of Garmisch-Partenkirchen. We do not explicitly investigate the impacts of hazards upstream of the Partnach Gorge, as there is little exposure located in that part of the catchment. In that area, exposure comprises paths used for hiking and general access to the Ferchenbach catchent and southern parts of the Reintal Valley. The trail following the Partnach is frequented on the ascend to Zugspitze.

The **Partnach Gorge** has been affected by multiple hazard events since the 1990s. These include (flash) floods in 1999, 2005, 2010, 2013, 2015. 2017, 2018, 2020 and 2021, and rockfall events of various sizes e.g. 1991 and 2003, 2017 and 2023.

- **Exposure of people:** In 2022 around 430.000 people visited the Partnach Gorge, the majority of which, ca. 340.000, visited the Gorge in the summer season (i.e. May to October)(Hoffmann and Frimberger, 2023). Entry to the Gorge is regulated via an automatic turnstile system which is open between 8 am and 8 pm during the summer months. As a result, we estimate an average of 1850 people visiting the Gorge per summer day. The Partnach Gorge extends over a length of 699 m and increases in 80 m in altitude from the north entrance to the southern exit. For most of the distance, the path, which runs along the eastern side of the Partnach, is located several meters above the normal water level. At its lowest point, close to the Madonna Statue at 0+480 m, the distance between the path and mean water level decreases to less than 2 m. Stating from that point in southward direction, a few dozen meters (assumption for calculation: 30 m) of the hiking path are at immediate risk of being flooded during high discharge. Assuming uniform temporal and spatial distribution of visitors during opening hours of the gorge up to 7 people per hour could potentially be exposed to flooding in this section. A slow rise in discharge is most likely registered by the gorge management and appropriate measures are taken to close access and evacuate (using both exits) any visitors remaining inside the gorge. We therefore focus mainly on flood events that occur with a sudden increase in water level inside the gorge. These can be caused either by very intense and sudden rainfall or by the forming of logjams (as in the event of 2018) or other sources of damming (debris or rockfall) which lead to a sudden rise in backwater levels. During the flood events in 2018, a group of students was surprised by sudden rise in water levels but managed to evacuate the gorge in the south. We estimate that for water levels rising above the height of the path within 15 minutes it can be difficult for the gorge management to react in time, and an average of 2 people could be exposed to the flood. In 2015, time to peak discharge (at the gauging station downstream) was approx.15 min with no casualties reported in the event.

- **Exposure of Gorge infrastructure:** The main value of the Gorge itself lies in its' function as a natural monument. The Gorge infrastructure consists of the entrance building and the turnstile system, the hiking path including railings and fall protection nets. Electric systems around the gorge include an emergency call system and power supply for the gates and electronic equipment (e.g. cameras). Upstream and downstream of the Gorge the embankments of the Partnach are constructed and

- **Indirect effects:** in its function as a tourist destination the gorge amplifies the attractiveness of the entire area for visitors and directly impacts visitor numbers to surrounding infrastructure, such hiking paths, inns and chalets. Closures of the gorge to visitors, especially for multiple days, involve the balancing of conflicting interests of safety/acceptable risk and economic revenue (both of gorge but also of nearby inns) (Hoffmann and Frimberger, 2023).

  Tourism numbers from the past nine years reflect an upward trend (excluding the years 2020 and 2021 where tourism globally was significantly hampered by the covid-19 pandemic) (see Figure 4). In the year 2018, the Partnach Gorge was closed for almost 6 weeks after a flood event that destroyed the slopes downstream of the Gorge. This constitutes the longest time that the gorge needed to stay closed to visitors since comprehensive works after the 1991 rockfall event. The flood event occurred in June 2018. Despite a long closure during the most frequented time of the gorge, overall tourism numbers in Garmisch-Partenkirchen are not significantly affected by this event.

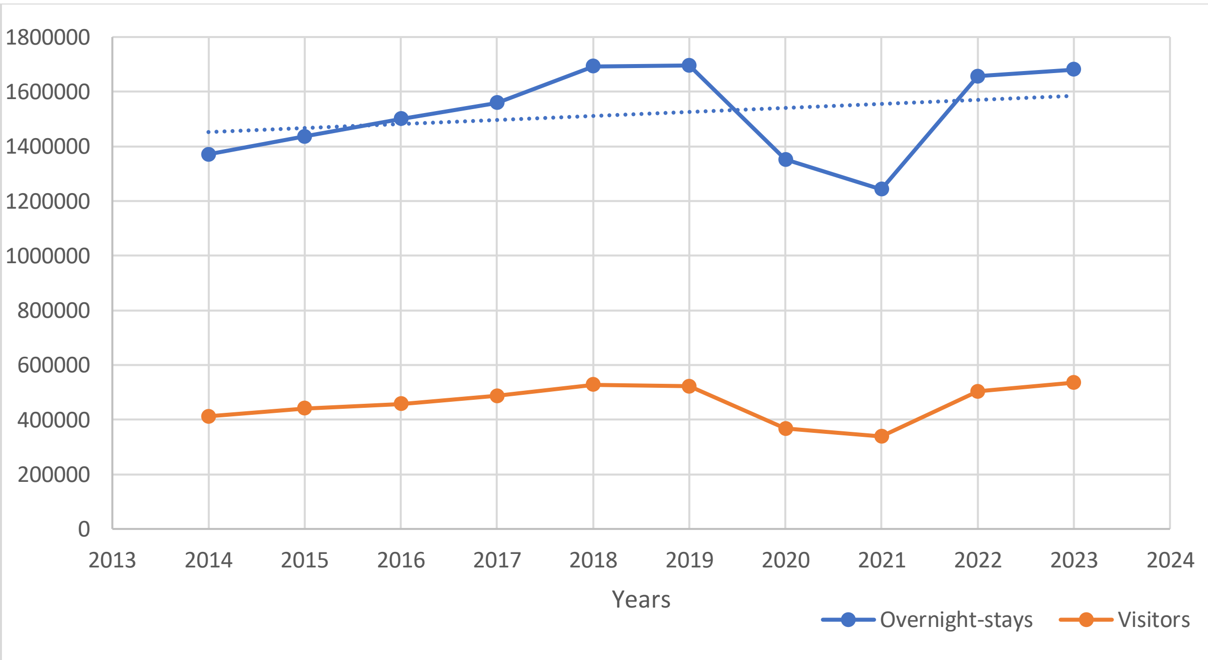

Figure 4: Tourism records from the years 2014 to 2023 showing the number of overnight stays and absolute number of visitors that stayed in Garmisch-Partenkirchen per year (Haushaltsjahr 2024)

The **city of Garmisch-Partenkirchen** is at risk of flooding from multiple streams, namely Partnach, Kanker and Fauken. Flooding along the Loisach river, which is fed by the beforementioned streams, has in the past been the cause of significant damages in the region. However, the Loisach river is not the focus of this study, and its impacts are merely described if they are significant in combination with other investigated hazard processes. Following the disastrous floods in 1999, extensive plans and measures to improve flood protection were drawn up and implemented, which can now protect the city from a 100-year flood event at Partnach or Kanker (see also answer to Question VI).

The assessment of exposure is based on the BEAM dataset (Geomer, 2022a) and the official flood hazard maps for frequent, 100 year and extreme floods at Partnach or Kanker. We also estimate the effects of a compound flood event (see answer to question VII). In this case the diversion of discharge from the Kanker into the Partnach, which ensures the protection from the 100-year event at the Kanker, might no longer be possible. We focus on tangible damages that might occur due to the **direct effects** of flooding in the area.

The BEAM dataset comprises the following land-use classes:

- **Buildings:** including residential buildings and the household contents. Up to 110 ha of urban and discontinuous urban areas would flood in case of an extreme flood event at Partnach or Kanker. The affected areas comprise a mixture of single-family homes and multi-apartment buildings with most residential buildings having two or more stories. We have no information about the prevalence of basements in the project area.
- **Agriculture:** net fixed assets (incl. agricultural land, buildings, machinery and equipment) as well as agricultural stock and livestock. Agriculture in the area includes roughly 1000 businesses (in the Zugspitz region), the vast majority of which cultivate grassland and livestock (99% of the districts agricultural area). There are few areas around Farchant, Uffing and Spatzenhausen that cultivate maize crops, but for the area of interest in this analysis we can assume that mainly grassland and livestock are affected.
- **Industry:** net fixed assets (incl. property, machinery and equipment) as well as industry stock.
- **Services:** net fixed assets (incl. property, machinery and equipment) as well as service stock. Services includes everything from commercial services (e.g. stores, hotels, restaurants) to public services (e.g. administrative and education facilities) and health services (e.g. hospitals and health practices). Such assets can be located within urban areas and discontinuous urban areas.
- **Vehicles:** including cars and motorcycles located on road infrastructure, urban areas and industrial areas.
- **Population:** The city had a population of ca. 28.400 people (primary residence) in 2023. In addition, around 1.300 people have secondary residence in the city. The actual number of people present in the city is likely much larger. In 2023, the city registered more than 400.000 visitors, the majority of which come to stay in the summer season.

The asset values provided in the BEAM dataset are based on net values. It does not reflect replacement costs or insured values and does not include the value of the properties themselves. Regionalized asset values are reported in €/m² (2018 prices) for the various land use classes. We convert these base values into current values in accordance with the net value development. The updating is based on the price development between the years 2018 and 2023 of a mixed index which consists of the construction price index (80%) and the consumer price index (20%). In this timeframe, the indices increased 44.20 %, and 19.39 % in Bavaria respectively. Asset values are updated by 39.24 % to 2023 prices. The mixed index accounts for the fact that in recent flood events in Germany approx. four fifths of the damages to buildings (which make up most of the direct exposure) can be attributed to physical damages to the buildings structure and approx. one fifth to damages to building contents (same approach is applied in cost-benefit study of the Bavarian Danube Flood Polder Program).

Among the different land uses included in the BEAM data, building assets are exclusively located in areas of urban land uses. Both industrial assets and service assets are mainly in in areas of industrial land use and to a smaller degree located in areas of urban land use. Vehicles assets can be found both on areas of urban and industrial land uses as well as designated infrastructure area (e.g. roads). The vulnerability differs between the different components of exposure classes, e.g. between private buildings and household contents. The vulnerability is discussed in the answer to Question V.

The Figure 5 shows the share of the different exposure categories on the overall asset values located in the hazard zones of the 100-year and extreme flood event at the Partnach and the Kanker. The frequent flood event is not illustrated here, as it does not result in notable flooding outside the river channel. Compared to the HQ_{100} events, the $HQ_{extreme}$ along both rivers affects more assets in the industry and service categories. Industrial areas, that mostly contribute to the value (in €/m²) of the industry and service category are located further away from the rivers and are therefore increasingly affected with increasing flood magnitudes.

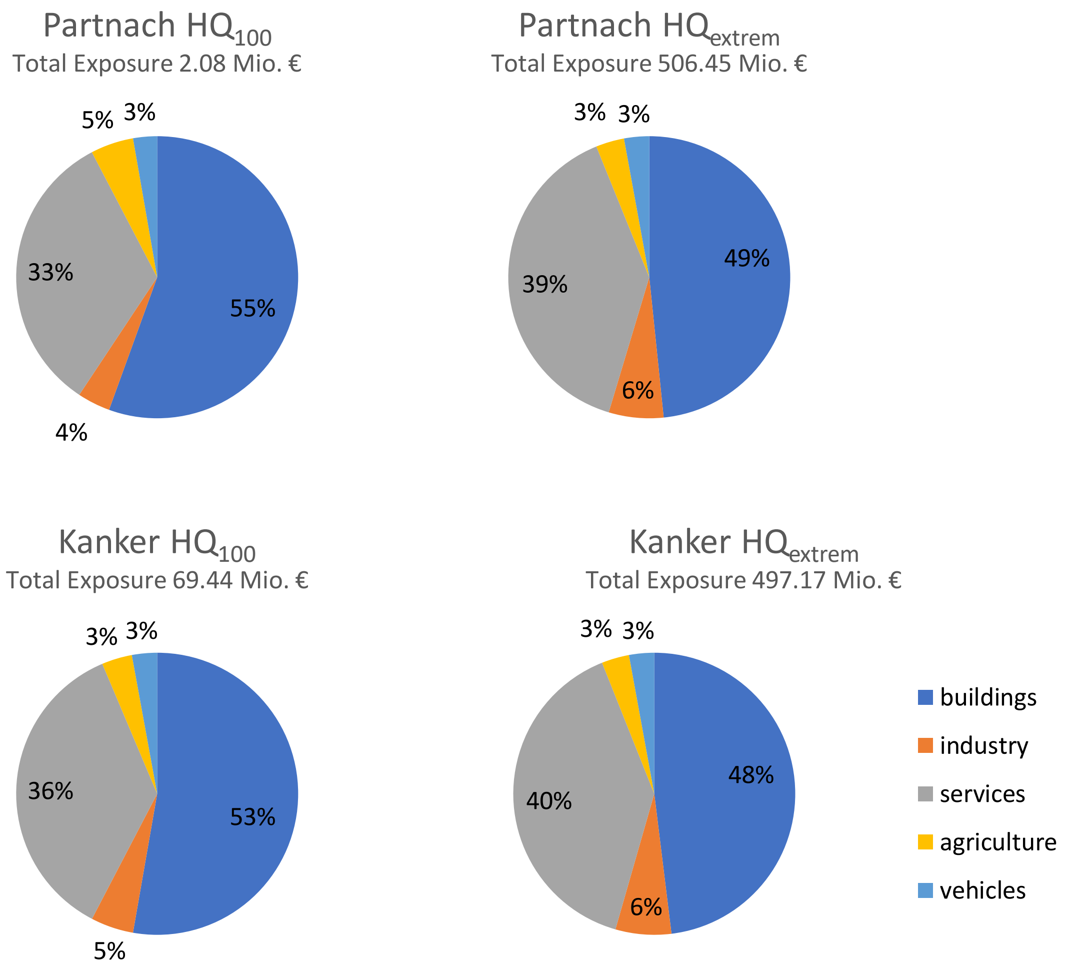

Figure 5: Share of different exposure categories of the overall asset value exposed to the 100-year or extreme flood along Partnach (above) and Kanker (below). The total exposed asset value (2023 prices) differs between the flood events.

Indirect effects associated with a hazard event can exacerbate conditions during the event response and recovery phases and have to potential to significantly increase overall monetary losses. The main sectors that might be indirectly affected are

- **Mobility**: Garmisch Partenkirchen is of major importance for transalpine traffic along the North-South connection B2 towards Innsbruck and B23 towards Fernpass, especially during the summer months. In the past, road access to Garmisch-Partenkirchen has been disconnected after multi-day precipitation events that lead to largescale flooding (also due to dike failures) north of the city along the Loisach river (e.g. in 2019). Floods along the Loisach frequently affect the train dikes near Oberau which can lead to interruptions of the trainlines between Murnau and Garmich-Partenkirchen (this last occurred during the June 2024 flood in Bavaria (Merkur, 2024a)).

Figure 6: Flooding of train tracks between Murnau and Garmisch-Partenkirchen in May 2019 (Merkur, 2019).

- **Tourism:** local events that affect mainly the Partnach Gorge can decrease tourism numbers and touristic spending in the area around the gorge. Larger scale events that affect the city of Garmisch-Partenkirchen might directly affect the availability of hotels, restaurants and other touristic infrastructure. Additionally, large scale events might affect accessibility to the area.

b) Potential future exposure and impacts

Future exposure in the area is the result of multiple developments. Some if these developments can lead to an increase in future risk while others might decrease risk.

- **Population development:** Between 2014 and 2023 the City of Garmisch-Partenkirchen observed an absolute increase in population from approx. 28.200 to 29.700 inhabitants. However, the population did not increase steadily. In some years, a decrease can be observed, which is explained by increased migration losses (Markt Garmisch-Partenkirchen, 2024). Overall, we observe a positive trend of 5 % in this timespan. Based on a continuation of this trend, in the year 2050 the city of Garmisch-Partenkirchen can grow to approximately 33.100 inhabitants. In contrast, the regional population projection, published in 2022 by the Bavarian State Office for Statistics, projects a population increase for the district of Garmisch-Partenkirchen of 2.5 % until 2042 (Bayerisches Landesamt für Statistik, 2024). The share of above 65-year-olds is likely to observe the largest increase. The elderly are generally considered more vulnerable than the average person to the adverse effects of flooding.

- **Settlement development:** The future exposure of assets and population depends largely on the development of settlements. Any increase in population or assets will contribute only the expected damages if this development intersects with areas at risk of natural hazards. We have no detailed information on future building zones and development potential of the city of Garmisch-Partenkirchen. In general, it is not allowed to designate new building zones in floodplains in accordance with § 78 of the Federal Water Act (WHG).

- **Tourism development:** While overall tourism might increase in Garmisch-Partenkirchen, the number of visitors to the Partnach Gorge is unlikely to increase significantly, as it is already operating close to capacity. There is an ongoing debate about the maximum number of visitors that can be handled and what measures can be taken to limit visitor numbers (Hoffmann and Frimberger, 2023, and Merkur, 2023).

- **Traffic development:** Innercity average traffic volumes along the B 2 (towards Mittenwald) and B 23 (towards Fernpass) can reach up to 25.000 Kfz/24h and 16.000 Kfz/24h respectively. In the future, traffic is likely to decrease due to bypass tunnels Kramertunnel (in construction) and Wanktunnel (in planning).

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

a) Current vulnerability factors

As a major touristic attraction, the **Partnach Gorge** is accessible for visitors who have no experience with mountain hazards and are therefore less likely to be aware of the risks related to extreme precipitation.

- **People:** The close monitoring of the risk situation within the Klamm by the gorge manager and multiple mitigation and risk management measures counteract the increased vulnerability. In the case of reasonable threat of extreme weather possibly impacting the safety of visitors inside the gorge, access to the gorge will be closed. There have been no casualties reported due to flooding inside the gorge in the past. While the current strategies have proven successful in past events, it is possible to imagine scenarios where the rise in water levels occurs very quickly (logjams, damming through debris or rockfall) or is not registered by the gorge management (measurement errors at gauge, human error). Different studies investigate the stability of humans subjected to flows which name water depth and flow velocity as critical flow parameters (Roesch, 2024). During the flood events in 2018, a group of students was surprised by sudden rise in water levels but managed to evacuate the gorge in the south. We expect that due to the high velocity of the Partnach inside the gorge, even small water depths affecting the path could prove to be fatal. A person carried away by the flood inside the gorge is unlikely to survive due to high velocities and steep embankment.

  Gorge infrastructure: Experience from past events shows that repair works mainly consist of reconstruction of paths and the removal of driftwood. The recovery time and costs recorded by the Gorge manager for past events vary largely (Roesch, 2024). Upstream and downstream of the Gorge historic flood events have regularly caused damage along embankments and affecting the paths. The erosive damages have been especially large for events with high driftwood load and sediment transport. To repair minor damages along railings inside the Gorge could be achieved swiftly within few days whereas the reconstruction of the slopes and paths outside the Gorge (e.g. in the 2018 event) takes considerably longer. Incomplete cost breakdowns show that events with larger discharges generally incur higher costs. Large driftwood accumulation, which is expensive and cumbersome to remove, and extensive damages to slopes are major contributors to high repair costs in the past. Additionally, any closure of the gorge, because of safety-relevant flow conditions or for the purpose of maintenance or repair works, reflects in the number of tickets sold and therefore incurs revenue losses.

To estimate the expected damages from hydrological hazards in the **city of Garmisch-Partenkirchen**, we employ the vulnerability functions (see Figure 7) that were developed and calibrated for the BEAM dataset (Geomer, 2022b).

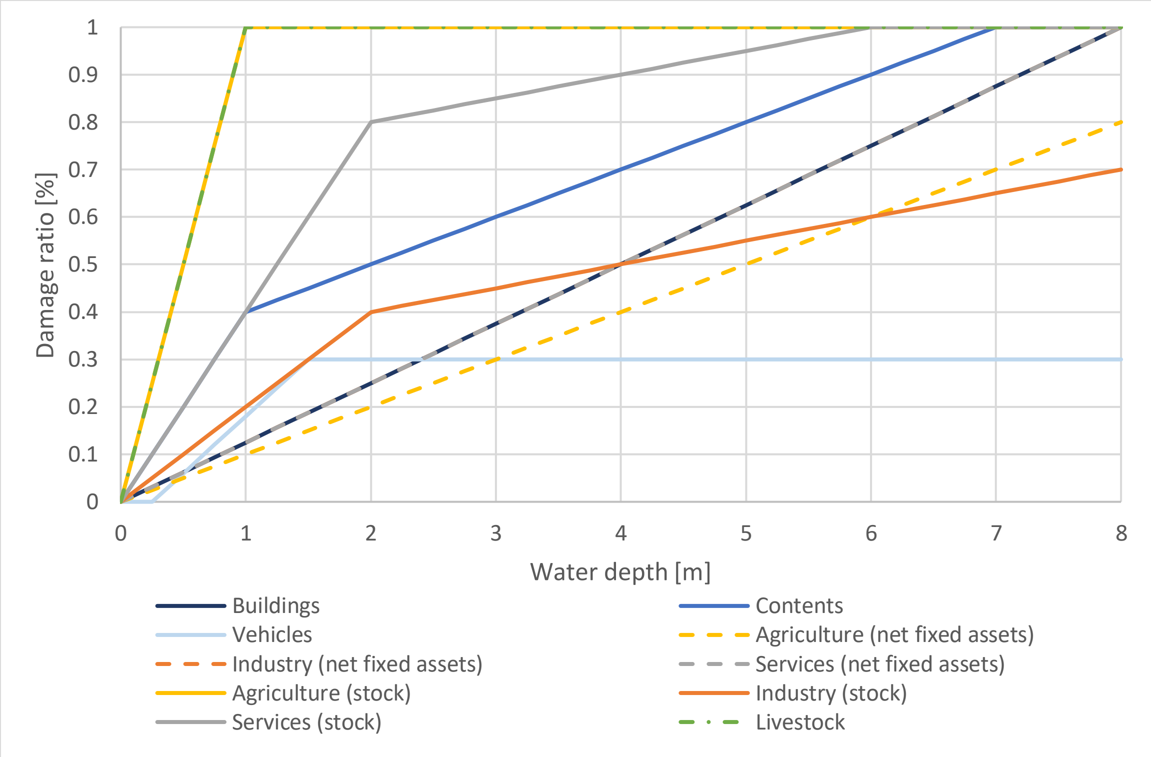

Figure 7: Vulnerability functions, developed and validated in combination with the BEAM dataset (Geomer, 2022b).

Different factors influence the vulnerability of different exposure categories to flooding. The foundation for the vulnerability functions is described for each exposure category, as discussed in Geomer (2022b). We give some additional information on relevant indicators of vulnerability.

- **Buildings:** Average vulnerability function of buildings with mainly one or two levels. A range of indicators are relevant to differentiate the actual vulnerability of individual structures. Relevant indicators can be, for example, building materials (e.g. concrete, masonry, wood), condition, openings (stream side, slope side or no openings), building age, number of floors, and existence of a basement.
- **Building contents:** Contents are more vulnerable than the buildings themselves. Already small water depths can result in the complete destruction of household contents, such as furniture, carpets, electronic equipment etc. Relevant indicators can be, for example, prior flood experience, time between warning and onset of inundation, and household adaptation measures.
- **Industrial facilities:** Flooding of the ground level is likely to induce severe damages to buildings, machinery and equipment. The same vulnerability function as private buildings is assumed. A mean vulnerability is used for stocks in the industrial sector, as they can differ significantly depending on the storage solution. sensitivity to water; in addition, some are stored in storage in elevated warehouses,
- **Service facilities:** Same vulnerability function as industrial net fixed assets, as commercial facilities are not too different from manufacturing facilities. Commercial stock is dominated by the retail sector. Storage mostly takes place close to ground level, which is reflected in a higher vulnerability compared to industry stock.
- **Agricultural:** Average vulnerability function of agriculture net fixed assets. Due to a larger storey height in buildings, the impact is assumed to be slightly lower than for private buildings. Agricultural stock (such as agricultural chemicals and seeds) is extremely vulnerable to water. They are typically stored close to the ground and will therefore be affected at low water levels.

The livestock vulnerability is an average of the vulnerability of different animal species, all of which will be affected by water depths above 1 m. An evacuation or cage-rearing above 1 m hight is not considered.

- **Vehicles:** combines multiple vehicle types and is limited to 30 % damage. This assumes that 70 % of the vehicles in the affected areas can be evacuated before exposure.

Vulnerability is defined here solely in terms of the inundation depth. Other intensity measures of the hazard can be explanatory parameters for damages such as flow velocity, sediment and wood transport, water rise and withdrawal rate (Endendijk et al., 2023). Factors such as prior flood experience and sufficient time between receiving a warning and onset of inundation can decrease the vulnerability of people and household contents (Endendijk et al., 2023).

Expected damages in monetary terms as well as expected population affected is calculated by intersecting the hazard map of the frequent, 100-year and extreme flood events (Bayerisches Landesamt für Umwelt, 2023) along Partnach and Kanker with the exposure data of the BEAM data and employing the vulnerability functions discussed above. Figure 8 exemplifies the spatial distribution of consequences of an $HQ_{extreme}$ at the Partnach.

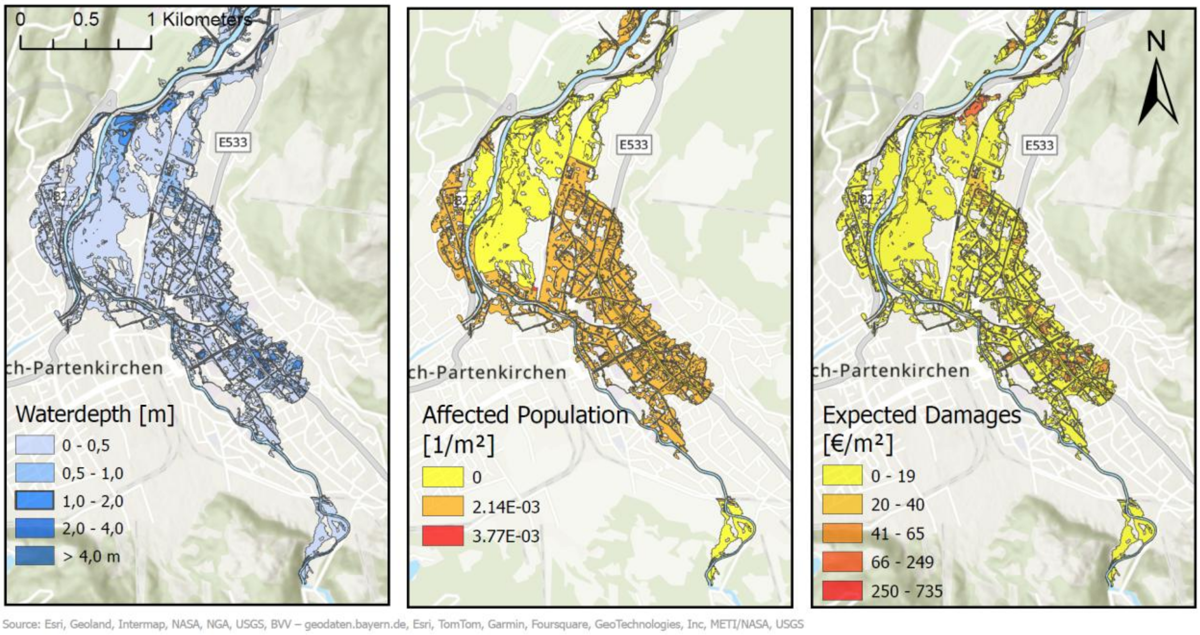

Figure 8: Consequences of the $HQ_{extreme}$ flood event at the Partnach in Garmisch Partenkirchen in 2018 prices and population (Frimberger et al., 2023).

The results of the calculation of expected direct damages for the frequent, 100-year and extreme flood events along Partnach and Kanker are summarised in Table 1. The contribution of different exposure categories to the overall expected damages are illustrated in Figure 9. For both rivers, the share of building damages on the overall damages decreases for the $HQ_{extreme}$ compared to the HQ_{100} event.

Table 1: Summary of expected consequences in direct damages [Mio.€] and affected population [-] of flood scenarios along Partnach or Kanker.

	Direct Damages [in Mio. €]		Affected Population [-]	
	Partnach	Kanker	Partnach	Kanker
$HQ_{frequent}$	0	0	0	0
HQ_{100}	0.13	3.41	23	731
$HQ_{extreme}$	35.41	41.14	4887	4766

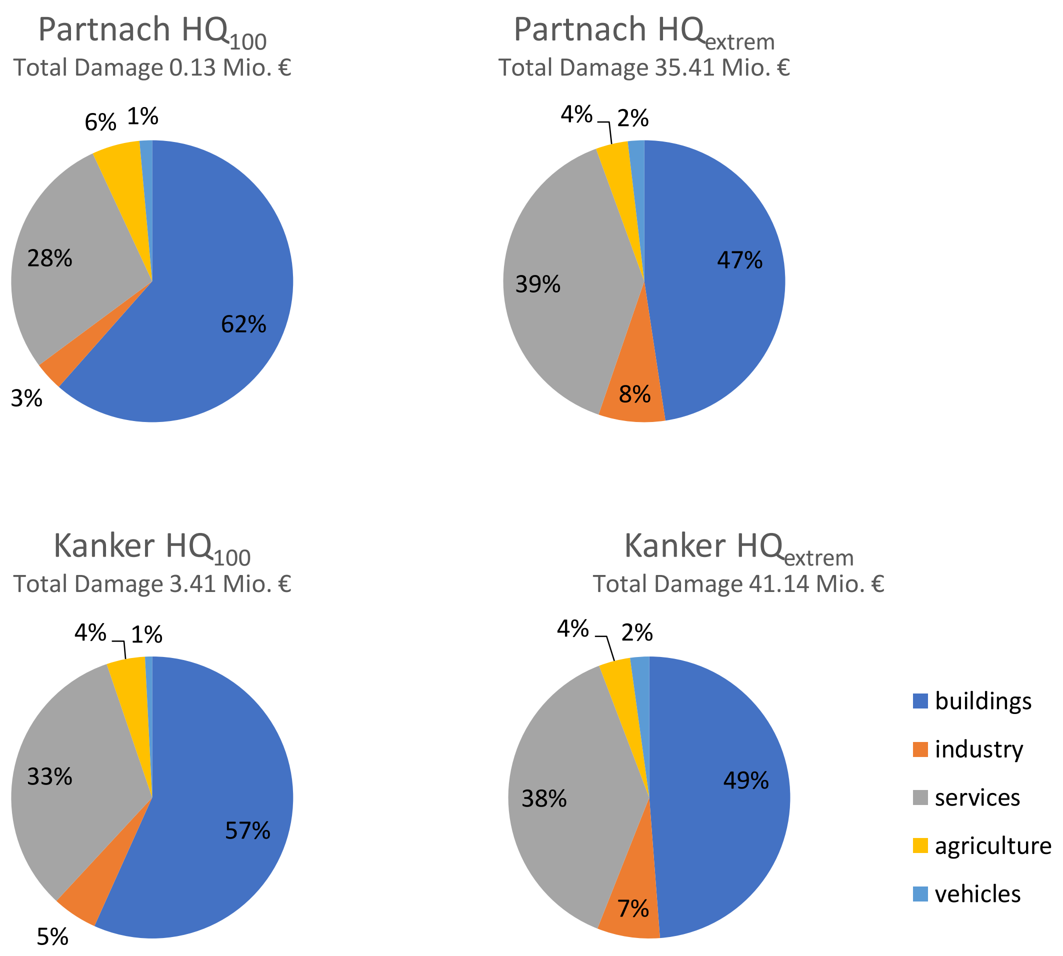

Figure 9: Contribution of different exposure categories on the expected direct damages in the 100-year or extreme flood along Partnach (above) and Kanker (below). The total expected direct damage (2023 prices) differs between the flood events.

The **expected impact on people** is evaluated in terms of the population that might be impacted by an event based on the population density in the BEAM dataset. The population increase of approx. 2.2 % between 2018 and 2023 is applied to the number of affected people evaluated based on the population density applied in the BEAM data.

- **Physical vulnerability:** Physical vulnerability of people is highest with regard to high water depths and high flow velocities. At low water depth (<1m) velocities of larger than 1 m/s can prove critical [Jonkman and Penning Rowsell]. Flood events at mountain torrents can easily exceed 3 m/s. People are es especially vulnerable during flood event if they do not evacuate to higher floors (or even access basements).
- **Factors for social vulnerability:** Demography, wealth, livelihood (e.g. occupation type, (un)employment, location of workplace), knowledge and skills (e.g. local knowledge, language proficiency, access to information, previous flood experience), health, housing (e.g. household composition, insurance cover), social capital (e.g. participation in decision-making, networks, trust) and access (e.g. to critical infrastructures, rural-urban divide and vehicle ownership) (Englund et al 2023).

b) Potential future vulnerability factors

We expect the **Partnach Gorge** to become safer overall, due to the continuous effort to improve the management of current hazards (such as rockfall and flood) and proactively facing emerging challenges (such as landslide risk at Ferchenbach). New structural and technological solutions (such as the rake at Ferchenbach, a gauging station upstream of the Partnach Gorge), will mitigate some hazards and increase preparedness in future events. At the same time, we do not expect visitor number to increase significantly.

Physical vulnerabilities of buildings and infrastructure in **Garmisch-Partenkirchen** are not likely to change significantly in the near to medium future. Better warning systems and better preparedness are likely to be a major contributor reducing risk in the future.

The developments that we expect to dominate increasing risk in Garmisch-Partenkirchen are changes in exposure of people and buildings (because of increasing population, tourism and building assets), and changes in hazard frequencies and magnitudes as well as the development of new hazards.

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

a) Current risk management measures

The **Partnach Gorge** and its immediate surroundings in the south (500m of water course upstream of the Partnach/Ferchenbach confluence) fall within the jurisdiction of the Gorge Management (and therefore the city or Garmisch-Partenkirchen). They are extensively monitored and managed already.

- **Hydrological hazards**: Water levels are closely monitored by the gorge management. Because no measurements of discharge, water levels or velocities were available in the past, the monitoring is mainly based on the exceedance of a water level threshold at the Partenkirchen Gauging station further downstream (threatening situation can arise inside the Gorge before water levels at the gauge reach the first official warning level), and information about expected precipitation by the DWD. In addition, cameras located at the two Gorge exits allow for a visual monitoring of the water levels.
  The 1991 rockfall at the southern end of the gorge, flow characteristics were substantially altered. In that area, the hiking path now passes through a tunnel that was constructed in the aftermath of the event. Another section of the path that would now be flooded due to the new flow direction is permanently protected against flooding with a concrete railing (1.2 m height).
- **Gravitational hazards:** Both upstream and downstream of the gorge slopes are protected against gravitational hazards. After the devastating flood in 2018 extensive repair works were required at the northern exit. The reconstruction of the path and construction of a new Gorge entrance building was combined with new embankment and slope protection in that area. The paths upstream of the gorge are secured with avalanche and debris barriers as well as nets along existing debris flow channels.
- **Forest Management**: Deadwood is removed from forests in the catchment to minimize driftwood accumulation. The last removal of deadwood, after the 2018 event, could effectively reduce driftwood accumulation in the 2020 and 2021 events. Driftwood accumulations inside the gorge are frequently cut down and removed or blasted to avoid the forming of dangerous logjams.
- **Visitor management:** The turnstile entry system makes it possible to close access to the Gorge in case of a threatening situation, leaving the Gorge is always possible. After the flooding in 2021, an emergency call system was installed inside the gorge. It is now possible to contact emergency services call points along the hiking path, who can advise on how to evacuate or handle emergency situations.

The **city of Garmisch-Partenkirchen** mainly needs to be protected from hydrological hazards. Comprehensive flood protection measures were developed and implemented after the flood in 1999. These included enhancing flood defenses for the Kanker and Partnach rivers. As of summer 2024, all structural measures are completed (Merkur, 2024b). Its main components are described in the following.

- **Along the Kanker:** The construction of a 220 000 m^3 flood retention basin, to store excess water during flood events. After an event, the water can be released either back into the Kanker channel or into the Partnach River via a newly built diversion structure. Raised embankments along the Kanker prevent inundation, where the river flows in an open channel. To prevent backwater flooding along the Fauken, a partition wall has been installed at the underground confluence of Fauken and the Kanker channel. Further downstream, the open channel between Rathausplatz and the Partnach has been widened and deepened to accommodate increased floodwater from both the Kanker and Fauken streams.

- **Along the Partnach:** To safely discharge water diverted from the Kanker retention basin, the embankment of the Partnach upstream of the Kanker confluence was raised. The channel can now accommodate a discharge of 97 m^3/s. Downstream of the Kanker confluence, the Partnach was adapted to accommodate a discharge of up to 131 m^3/s. Additionally, the confluence of the Partnach with the Loisach was redesigned to prevent backwater flooding.

b) (Potential) future risk management measures

A number of new risk management measures centred around the Partnach Gorge are currently in discussion or under development:

- **Ferchenbach rake**: a new rake will be installed at Ferchenbach, directly upstream of the Partnach confluence (Hübl et al, 2019). The rake will reduce risk as it will reduce wood accumulation inside the gorge and avoid the forming of dangerous logjams that can lead to sudden increases of water levels inside the gorge, which directly endanger visitors of the Partnach Gorge. Additionally, the bursting of a logjams releases a sudden flood wave, which gives little time for preparation and evacuation downstream. In the 2018 flood, one person died when they were caught by sudden flooding just a short distance downstream of the Partnach Gorge.
- **Gauging station:** A new gauging station at the southern entrance of the Partnach Gorge was put into operation in summer 2024. Its use is manifold. It will increase warning time, as any significant changes in discharge at the Partnach will be recorded approx. half and hour earlier than at the downstream gauge. This time will be especially valuable in the case of a compound flood event of Partnach and Kanker, since a share of the volume stored in the Kanker basin can be diverted to the Partnach. The diversion should only be operated in such way that the combined discharge of the two streams does not exceed the capacity of the Partnach channel. The existing Partnach gauge lies close to the confluence of the diversion channel into the Partnach and can provide evidence of an impeding flood from the Partnach approximately 10 minutes prior, which is not enough time to shut down the diversion of discharge from the Kanker basin. Additionally, the new gauge will (in combination with the downstream gauge) help gain valuable insights into the translation of floods trough the Partnach Gorge. There is currently no way to reliably estimate flow velocities or the forming of logjams inside the gorge, as there are no instruments for measuring or recording these parameters installed inside the gorge.
- **Visitor limit:** discussion about limiting the number of visitors allowed into the Partnach Gorge are ongoing. Any measures of this type will avoid increasing the exposure of people to potential future hazards and therefore help contain risk in the long-term.
- **Landslide warning:** Active slopes along the southern Ferchenbach pose a contiuous threat. The consequences range from providing debris and wood to the Ferchenbach and destruction of the road running in parallel to the stream (for smaller events in the past) to the potential complete damming of the Ferchenbach and consequent outburst-flood (for a future large landslide). An early warning system that would indicate large slope movements could allow for timely closure of the gorge and evacuation of visitors.

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

The main hazard cascade affecting the Partnach Gorge in the past is the flushing of logs and driftwood into the Partnach. The wood originates the forested slopes, mainly along the Ferchenbach, and is transported into the torrents either by erosion or slides, along tributary torrents, or as a result of snow or storm loads (Hübl et al, 2019). Increased discharge as a result of heavy precipitation is sufficient to mobilise driftwood accumulations and transport them towards the Partnach Gorge. In the event of 2018 a large rootstock was the cause of a logjam (Hübl et al, 2019), which was registered at the gauging station downstream (as seen in Figure X). The gorge itself is not accessed (even by gorge management) during critically dangerous discharges. The response time at the gauging station is therefore the only indicator if how quickly dangerous water levels are developing in the case of logjams in the gorge.

b) Potential future impacts of compound/cascading hazard events

In the case of a flood event at the Kanker, the retention basin can store up to 220 000 m^3. A maximum discharge of 13.5 m^3/s can safely be released from the basin into the Kanker. Additionally, a maximum discharge of 30 m^3/s can be diverted from the Kanker basin to the Partnach. The diversion is possible as long as the combined discharge in the Partnach doesn't exceed 97 m^3/s at the gauging station *Silberackersteg*. Peak discharges of the Kanker and the Partnach have, in historic records, not occurred simultaneously. This can be explained with different catchment sizes and discharge characteristics. If a compound flood event along the two torrents were to occur in the future, it would likely exceed the discharge capacity of the existing flood protection systems and could pose significant challenges in the response and recovery phases.

We illustrate the potential risk arising from single or compound floods event by combining the official flood hazard maps along the Partnach and Kanker rivers. Table 2 shows the scenarios used for calculating the risk in terms of expected damages and expected affected population.

While the gauging station at the Partnach can provide more than a century of discharge records, the lack of a long discharge record at the Kanker makes it impossible to perform a reliable analysis of the joint probabilities of exceedance of the discharges at Kanker and Partnach that correspond with the scenarios. An estimate of the joint probability of exceedance is given in the Table 2. It is based on the assumption that, due to the spatial proximity of Kanker and Ferchenbach (which is part of the Partnach catchment) it is likely that a large flood event along the Kanker will be accompanied by a flood along the Partnach. A large flood event along the Partnach could also stem from high precipitation in the more distant Reintal which is less likely to simultaneously affect the Kanker catchment. The effect of this assumption on the resulting risk estimate is explained by also providing risk estimates for the assumption of total independence and total dependence between the discharges along the two rivers.

Table 2: Overview of compound flood scenarios, their joint exceedance probabilities and expected consequences. Expected consequences are estimated based on the BEAM data.

#	Partnach	Kanker	Flood Control Strategy (diversion from Kanker to Partnach)	Estimate of Joint Exceedance Probability of Q_P and Q_K	Affected Population [#]	Expected Damage [Mio. €]
1	< HQ_{10}	< HQ_{10}	Not relevant	1/1.2	0	→ 0
2	HQ_{10}	< HQ_{10}	Not relevant	1/10	0	→ 0
3	< HQ_{10}	HQ_{10}	Max. 30 m³/s diversion	1/10	0	→ 0
4	HQ_{10}	HQ_{10}	Max. 30 m³/s diversion	1/25	0	→ 0
5	HQ_{100}	< HQ_{10}	Not relevant	1/100	11	→ 0.14
6	< HQ_{10}	HQ_{100}	Max. 30 m³/s diversion	1/100	366	→ 3.41
7	HQ_{10}	HQ_{100}	Max. 30 m³/s diversion	1/200	366	→ 3.41
8	HQ_{100}	HQ_{10}	No diversion possible	1/500	11	→ 0.14
9	HQ_{100}	HQ_{100}	No diversion possible	1/800	377	→ 3.55
10	HQ_{1000}	< HQ_{10}	Not relevant	1/2500	2449	↗ 35.41
11	< HQ_{10}	HQ_{1000}	Max. 30 m³/s diversion	1/2500	2388	↗ 41.15
12	HQ_{10}	HQ_{1000}	Max. 30 m³/s diversion	1/2500	2388	↗ 41.15
13	HQ_{1000}	HQ_{10}	No diversion possible	1/2000	2449	↗ 35.41
14	HQ_{100}	HQ_{1000}	No diversion possible	1/3000	2399	↑ 38.82
15	HQ_{1000}	HQ_{100}	No diversion possible	1/4000	2449	↑ 41.15
16	HQ_{1000}	HQ_{1000}	No diversion possible	1/10000	3084	↑ 76.55

→ low deviation expected ↗ medium deviation expected ↑ large deviation expected

For scenarios 9 to 16, the exected damages [Mio. €] is given as the sum of the expected damages in individual floods along Kanker or Partnach. In reality, the consequences of a compound event will likely deviate from the sum of damages caused by individual flood events. Table 2 gives an indication of the degree of deviation we expect for the different scenarios. The affected population is set equal to the population inhabiting the hazard area of the combined hazard area.

Due to the protection standard in Garmisch-Partenkirchen, scenario 9 results in no overlap of hazard areas and the expected damages not expected to deviate much from the sum of the individual flood damage estimates. The underlying discharges are of such magnitude that existing risk management measures should be sufficient to contain flooding and respond adequately.

For scenario 14 the overlap of the hazard areas is still negligible. In the case of scenarios 15 and 16, the overlapping hazard areas likely overestimate the direct damages in the hazard area. Locally, the flood depth will not be equal to the sum of the flood depths of the individual floods. Instead, the area affected by flooding is likely to increase downstream of the confluence (and possibly upstream, due to backwater flooding). Additionally, the vulnerability functions show that an increase of the flood depth will not result in the same increase in resulting damages. In some cases, the damage ratio is bounded to a maximum.

Generally, extreme precipitation resulting in 100 or 1000-year discharges is likely to cause additional damages outside the indicated hazard area (e.g. due to pluvial flooding). Large discharges can lead to exceedance of protection levels and possibly the failure of protection structures downstream which may result in large indirect consequences. In past events this has been the case with flooding along the Loisach river, that is also likely to observe increased discharge because of large and long duration precipitation events, that impacted response and recovery within the city of Garmisch-Partenkirchen.

Based on the 16 scenarios, four probability distributions of damages along the Kanker conditional on observing certain levels of discharge at the Partnach are constructed. The risk is calculated from the unconditional probability distributions using a trapezoidal rule. The annual risk is estimated at 0.7 Mio € expected losses and 47 expected number of inhabitants affected. In the case of assumed independence or full dependence between discharges at Kanker and Partnach, the annual expected losses are 0.4 Mio € and 28 the expected number of inhabitants affected, or 1.8 Mio € and 114 inhabitants respectively.

In addition to the compound flood event, other emerging cascading events include sediment- or debris-laden flows affecting the Partnach Gorge and the city of Garmisch-Partenkirchen. Debris-laden flows have previously been observed in the Reintal but did not reach the Partnach Gorge. Multiple developments (as described in the answer to Question III) can contribute to a likely increase of the probability of sediment- and debris-laden flows.

Compared to flash floods, that have been observed in the past, we expect the impacts of sediment- and debris laden flows with similar magnitude of discharge to be different. Inside the **Partnach Gorge** the sediment particles or debris can develop an immense force that has the potential to permanently alter the shape of the slopes. A similar effect, with lateral erosion of up to 1 m, was observed in the Höllentalklamm in 2020 (Stammberger et al, 2024). Damages of this type would significantly damage the paths and infrastructure inside the gorge. To remove the debris, reconstruct the paths and remove damages will likely take several months.

If a sediment-laden flow occurs as the result of a massive landslide at the Ferchenbach, the sudden breach presents a particular challenge for evacuation of the Partnach Gorge. Depending on the intensity of initiating rainfall event, the newly formed dam could breach within minutes. The released sediment-laden wave would dissipate and decrease in depth before reaching the gorge. A numeric model is required to better investigate the exact behaviour of the flow and therefore the risk posed inside and downstream of the Partnach Gorge. We expect that the depth of a flow with this origin could be much greater than the recent floods and therefore endanger visitors over the entire length of the gorge and leave no time for evacuation.

Downstream of the gorge, the high velocity of the flow can continue to cause massive erosion and permanent damage to the channel construction in the **city of Garmisch-Partenkirchen.** The widespread destruction of the newly completed flood protection measures along the Partnach can be considered as a worst-case scenario. Eroded banks and large depositions of debris entail that the required protection level could not be guaranteed until the cleanup and reconstruction has been completed. Until then the city remains particularly vulnerable to subsequent hazard events. In addition, sediment-laden flows act with a larger force upon the structures located in the hazard area than flood events of the same extend. As a result, larger direct damages and higher reconstruction costs are expected.

In the future, debris availability could also originate elsewhere in the Partnach catchment as the result of loss of protective forest after drought or wildfire. To keep up with the status quo of sediment- and debris-laden flow risk in the gorge, we expect extensive investments will be necessary to manage any future increases in debris-availability upstream of the Partnach Gorge.

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3. Stubaital, Austria

RISK QUESTIONNAIRE

Stubaital (AT)

13.12.2024

Introduction

The following deliverable comprises the answers to the X-RISK-CC risk questionnaire, which was conceptualised by the TUM for the project consortium. The Austrian Research Centre for Forests (BFW) was contracted by the Austrian Forest-Technical Service for Torrent and Avalanche Control (WLV) to answer this questionnaire for the WLV pilot site in X-RISK-CC, the Stubaital, or more specifically, for the process types debris flow and hyper-concentrated flow in the following five catchments within the Stubaital: Mutterbergbach, Grawanockbach, Oberbergbach, Margaretenbach, Mühltalbach. To this end, the BFW developed a pragmatic and (semi-)quantitative risk analysis methodology to assess the potential monetary impact of these processes under current and future climatic regimes. The analysis is based on the wealth of data and documented events available in the catchments, as well as results from previous (research) projects. Further key datasets include an expert assessment by the WLV regarding the extent of hazard zones under changing climatic conditions, and an area-wide dataset to estimate real and potential damages caused by natural hazards – the Basic European Assets Map (BEAM). This allowed the BFW to not only make comparative statements regarding the natural hazard risk (e.g., "*the risk to roads is much higher than the risk to buildings*"), but in conjunction and close cooperation with the WLV-experts, offer concrete statements on the development and trend of the expected extent and frequency of debris flows in the studied catchments and thus site-specific calculations on their potential monetary impact in the pilot area.

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

a. Past/present weather extremes

In the Alps, about two thirds of debris flow events are triggered by intense, short duration precipitation events (Prenner et al. 2019). Similarly, in the Stubaital, the weather extremes considered most relevant for debris flow occurrence are heavy precipitation events, especially short-duration rainfall occurring during the summer period. Such meteorological events were found to trigger several gravitational mass movements in the area, especially debris flow processes.

By analysing the annual and summer 1-day precipitation maxima over the last 40 years (1980-2022), based on available station observations in the area and close surroundings, an overall increase of precipitation intensity was found, even though the trend is not statistically significant. The trends in the annual frequency of 1-day precipitation extremes are positive at almost all sites up to + 14 % per decade with respect to the long-term averages. The highest increases are reported in the eastern portion of the pilot area, where trends are statistically significant.

b. Potential future weather extremes

In the future, the frequency of heavy precipitation is projected to increase throughout the pilot area, with the magnitude of change depending on the level of global warming reached by the end of the century. The increases with respect to the current period (1991-2020) range between + 3 % and + 23 % in the Stubaital. The projected changes in return levels of 1-day precipitation extremes corresponding to 10, 20, 50 and 100-year recurring intervals were also analysed for future 50-year periods corresponding to different global warming levels and compared to the current values (1971-2020). The intensity of 1-day precipitation extremes is projected to increase for all return periods and under all global warming levels in the Stubaital. As spatial average over each subregion, the projected increases of precipitation intensity for 20-year recurring event are in the range of + 5 % and + 15 % for Stubaital, depending on the warming level (Eurac Research et al. 2024).

Sub-daily precipitation data was analysed by applying the Clausius-Clapeyron relationship to precipitation data from stations on wet days. Results indicate that the 99th percentile of hourly precipitation totals increase by 7.3% ± 1.1% per °C of warming. Historical data show that the Alpine space warms at roughly double the rate compared to the global mean near-surface temperature (UBA 2023). Using Alpine space warming levels as twice the amount of global warming levels, and 1991 to 2020 as reference period, it yields increases, for the current 99th percentile, from 8.6 mm/hour to 9.8 mm/hour (± 0.18) for the Global Warming Level (GWL) 1.5°C. For GWL 2°C, 10.43 mm/hour (± 0.28), GWL 3°C 11.68 mm/hour (± 0.46), GWL 4°C 12.94 mm/hour (± 0.65) and for GWL 5°C 14.19 mm/hour (± 0.84).

II. Which hazard processes can be triggered by current and future weather extremes?

a. Past/present weather extremes

Due to the involvement of the WLV, who is responsible for planning, implementing and maintaining mitigation structures, as well as documenting events, the most risk-relevant process-types in the pilot area Stubaital were already known: These are debris flows and hyper-concentrated flows. Figure 1 gives an overview of the 55 events documented in the five torrent catchment areas, selected as study sites of the WLV in the project X-RISK-CC (Mutterbergbach, Grawanockbach, Oberbergbach, Margaretenbach, Mühltalbach), all of which are located in the Stubaital. The analysis of the documented events underlines the relevance of these processes. Landslides and rockfalls are only sporadically documented. Hazard-relevant fluviatile events occurred only in one of the five catchments, the Oberbergbach.

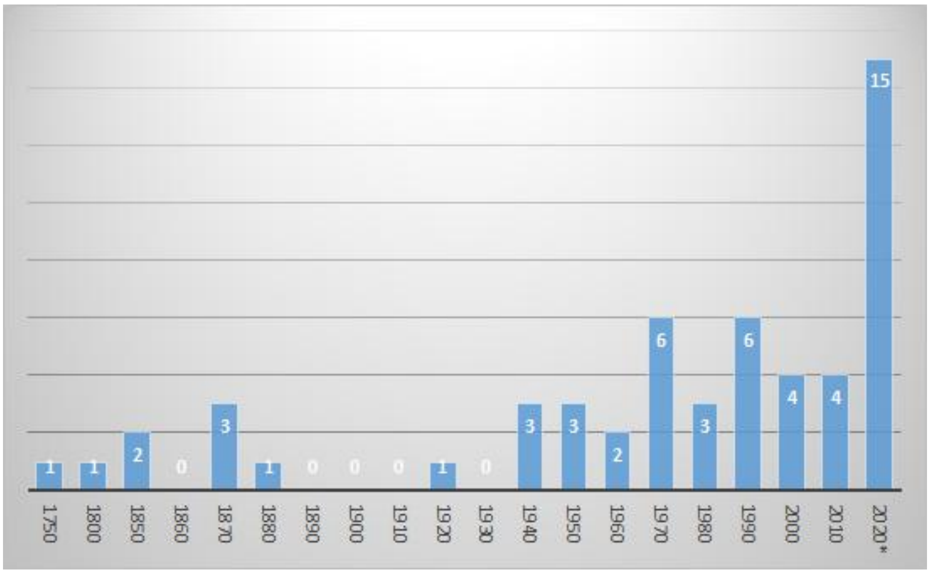


Figure 1: Number of documented events in the five catchments, 2020 covers only the timespan 2020 to 2023.

Figure 2 shows the number of triggers, Figure 3 the triggers split by catchment. Short duration precipitation events with high intensities are most relevant, however also long-duration precipitation events caused debris flows, especially in the Margaretenbach and the Oberbergbach (Figure 3). In older documentation, the type of precipitation event is often not specified; in this case they are classified as 'heavy precipitation'; if there is no clear information on the trigger, they are shown as 'undefined'.

Figure 2: Triggering causes of torrential events (sums of the five catchments), based on the event documentation.

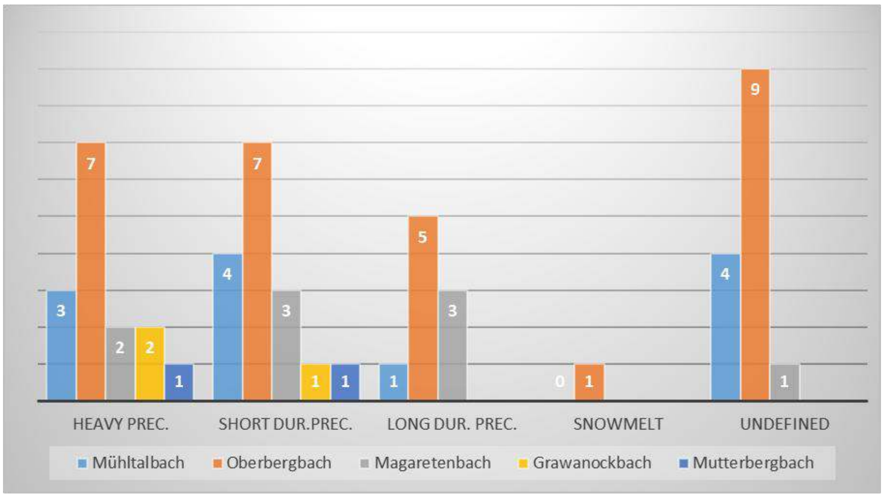


Figure 3: Triggering causes of torrential events in the five catchments, based on the event-documentation.

In the reference period 1991 to 2020 the medium temperature was already 0,54° higher than in the prior reference period (1961 to 1990), which means that precipitation intensities should have already risen.

b. Potential future weather extremes

For the Stubaital, CC-models show an increase in intensities for short duration precipitation of about + 20 % until the middle of the 21st century. Thus, the design precipitation determined by the model (60 min 100-year return event) rises from about 64 mm/h to 77 mm/h in 2050 (eHyd gridpoint 5057), based only on considering the rise of precipitation intensities due to the increase of temperature (Eurac Research et al. 2024). The reduction in the movement speed of thunderstorms is expected to promote the occurrence of quasi-stationary events, but hardly any reliable information is available. Not taking this into account, means that longer lasting convective events might be underestimated. The eHyd provides information on water balance parameters for Austria, based on measurement data and modelling, particularly regarding precipitation intensities and design events.

Besides, temperature will continue to rise in the entire Alpine region for all IPCC emission scenarios. Strongest warming is projected for the summer season (Figure 4); medium to high elevations might show an amplified warming (Kotlarski et al. 2023). This fact implies a rising snow line of several 100 m, less solid precipitation and less snow cover during events, which could potentially buffer parts of the precipitation, discussed in chapter VII b of this report.

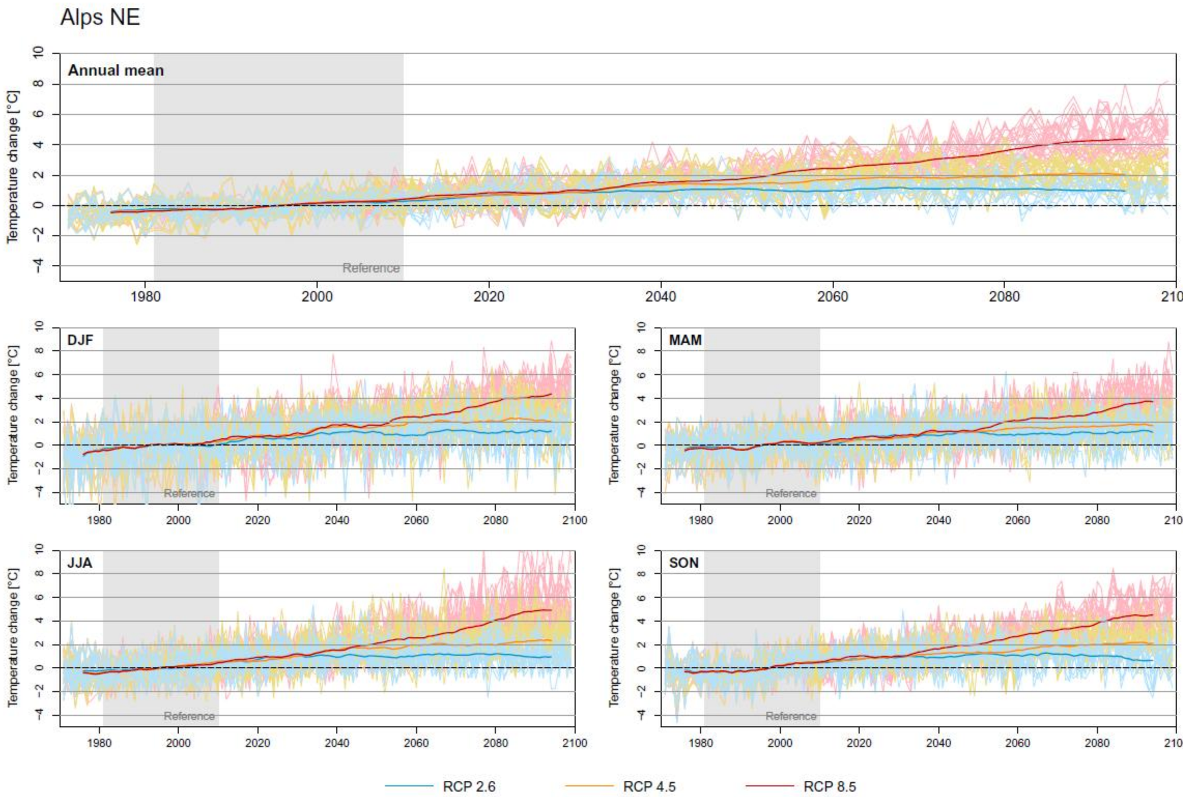


Figure 4: Modelled rise of temperature in the northeastern Alps compared to the reference period (1981-2010, grey) and for selected IPCC scenarios (Koltarski et al. 2023).

III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

a. Past/present frequencies and magnitudes

Statistically based functions describing the relationship of probability event-occurrence, as known from river engineering, require long continuous measurements, constant conditions and the event-independence from one event to the other. **All these requirements are hardly met in the case of debris flows at least in the pilot area Stubaital.** Debris flows are complex processes. Their occurrence and magnitude do not show a clear relationship to the precipitation intensity due to varying sediment availability, blockage (and breaking) processes or sediment deposition, channel-outbreaks and erosion processes within one event (several waves). Hence, debris flow events may vary significantly in the same catchment given comparable precipitation events. Moreover, there are two relevant event parameters to be considered according to magnitude and frequence: the maximum discharge (m^3/s) and the total event-volume. Usually only the latter is documented.

Due to the varying topography and mitigation measures, we found that there is no common, valid, reliable relationship between the increase of the event discharge and volumes, and the areas affected. Therefore, and since the objective of this deliverable is the assessment of endangered areas (in dependence of the probability), we developed a hazard zone map-based approach for the Stubaital.

Hazard zone maps (GZP) are provided by the WLV in Austria and describe the extent and roughly the effects of events with a return period of 150 years (Federal Minister for Agriculture, Regions and Tourism, 2021). For the five catchments, new hazard zone maps considering the assumed changes for 2050 (Figure 5) were created. The assessment is based on expert knowledge, considering the issues mentioned for the identification of the key hazards. The difference of exposed elements (ΔA_{exp}) is determined by equation 1

$$\Delta A_{exp} = A_{cc} - A_{haz} \quad 1)$$

where A_{haz} are affected areas according to the current hazard zone maps (without consideration of climate change) and A_{cc} represent the assumed areas effected in 2050.

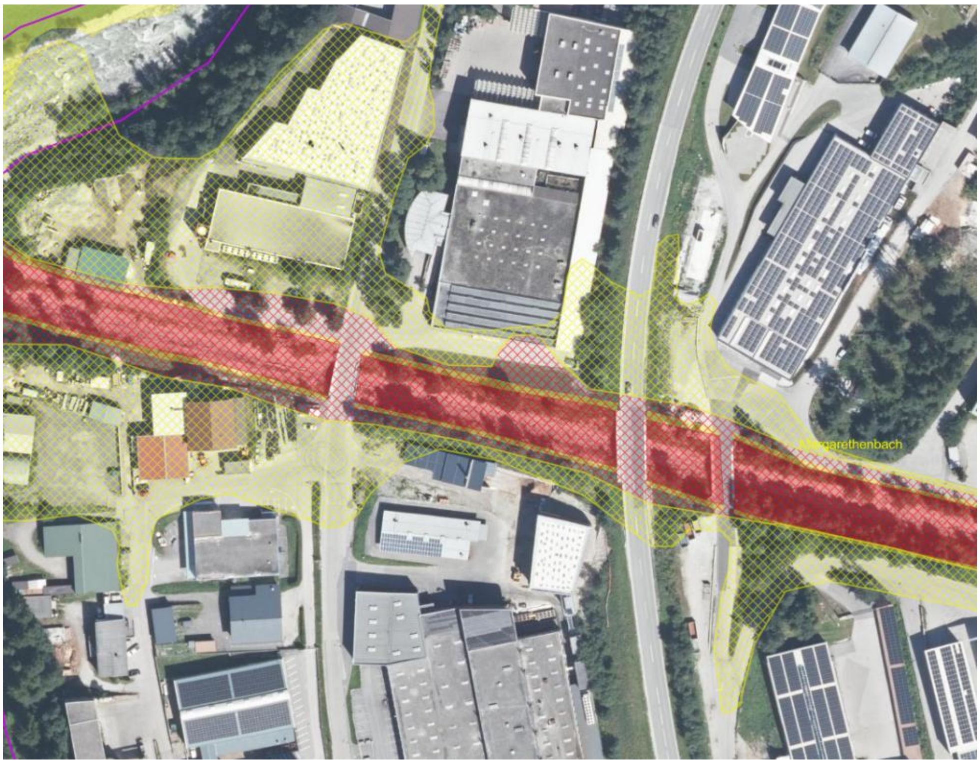


Figure 5: Current hazard zones for the Margaretenbach (solid colours) and zones, considering climate change effects (hashed colours), both determined by the experts of the WLV.

Method for estimating the frequency of debris flow events

To determine the frequency of debris flow events, we suggest the following simple decision scheme (Table 1):

Table 1: Decision scheme to determine the frequency of debris flow events.

Process change possible (from fluvial to debris flows)	Effect	
Yes	Reassessment is necessary	
	Limited material supply	**Effect**
No	Yes	decreasing frequency of debris flows, increase fluvial
	No	increasing frequency of debris flows

First, the probability of changes regarding the type and course of the events due to CC-impact need to be assessed. If "Yes", a reassessment of the entire hazard process and subsequently a new hazard zone mapping is necessary. If the question about the possibility of changing the process is answered with "No", we suggest the estimation on the base of runoff or precipitation data as shown in Figure 6: Based on the eHyd data, we determined the intensity of a current 150-year event (eHyd, 73 mm/60 min). In the next step we gained a curve with the eHyd values increased by 20%, which is assumed to represent precipitation events around 2050. At this point, the 73 mm/60 min will have an annuality of approximately a 50-y in the catchments. This means, that events will affect the red and yellow zones three times more often than they currently do, if there is unlimited sediment supply.

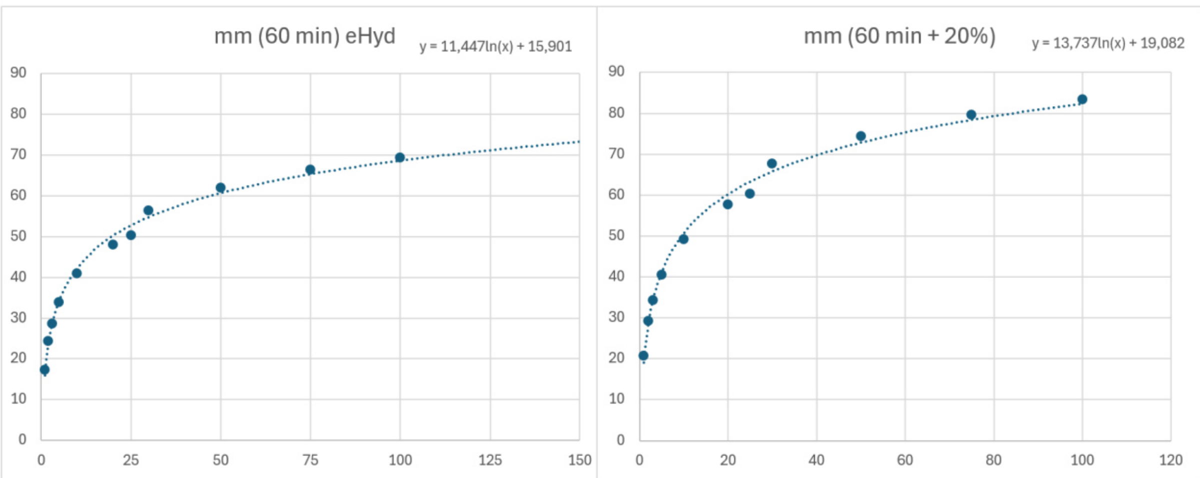


Figure 6: 60 min precipitation annuality (x-axes) against precipitation [mm] (y-axes), according to current eHyd-dimensioning values for the pilot area (left); extrapolated and increased by 20% (right).

Method for estimating the magnitude of debris flow events

The determination of the magnitude of events and potentially affected areas is more complex than determining the frequency. We suggest a decision scheme as shown in Table 2. Cross sections and mitigation measures are assumed to be unchanged and well maintained.

Table 2: Decision scheme for the magnitude of debris flow events.

process change	limited material supply	situation: cross sections, retention	effect - process	effect on hazard areas
	Y	sufficiant CC	discharge increase with runoff/prec.	no significant effect
	N	not sufficiant CC, stable in CC	discharge increase stronger than runoff/prec.	significant effect-rezoning
		instable in CC	catastrophic scenarios	extreme effects

Process-change and material-supply are already determined for the frequency of events. After that, other frame conditions need to be discussed:

1. Relation of cross sections to the assumed increase of discharge and effects of endangered areas: Figure 7 for example shows the situation at the catchment Mutterbergbach. First, increasing volumes and discharge will lead to marginal effects since the estuary of the Mutterbergbach is a ravine. Downstream the effects on hazard zones due to the increasing discharge will be not significant either, since the valley bottom is wide, and the banks are steep and high. The hazard zones were enlarged because of the effects on the receiving water (river Ruetz). In Austria, there is a clear boundary of competences between the WLV on the one hand and the Federal Hydraulic Engineering Administration on the other. As the hazard zone map of the WLV is only drawn up within its own area of responsibility, the zones defined in the process seem to be “cut off” further downstream, where their area of responsibility ends.

2. If there are significant changes in the assigned affected areas, like in the Margaretenbach, CC-hazard zones need to be determined (see Figure 5).

3. Behaviour of existing mitigation measures (retention basins etc.), considering the assumed increase of discharge. Are they designed to keep their protective effects, also under future conditions? If “Yes”, only a rise of frequency is assumed. If they are stable but dimensioned too small for the assumed CC-scenario, they cannot buffer additional discharge and volumes, thus hazard zones must be adapted. If they are possibly not stable, volumes and discharge can multiply. In this case either mitigation measures and/or hazard zone maps need to be adapted.

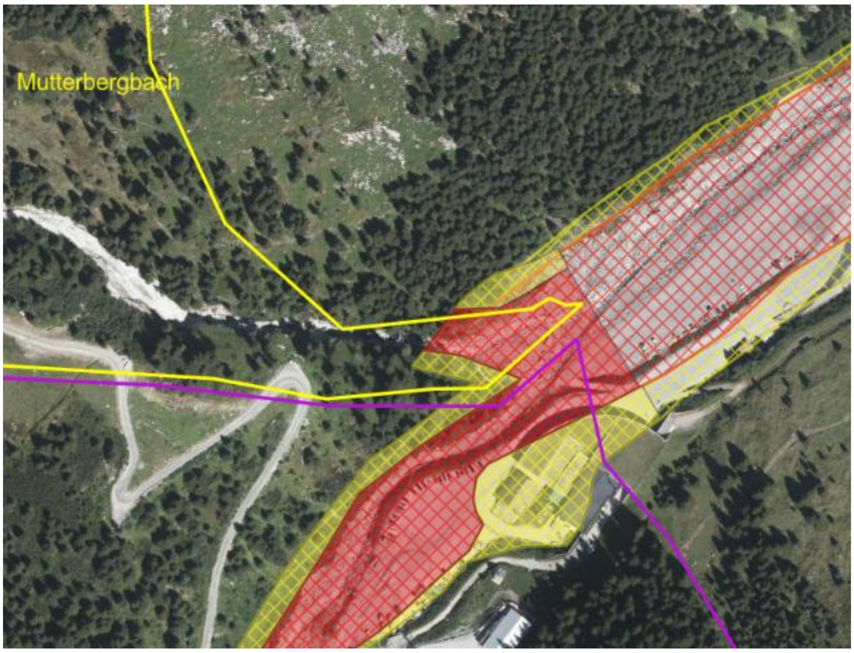


Figure 7: Mutterbergbach estuary, existing hazard zone map (solid) and with X-risk scenario of increased discharge (hashed).

Assessment of the Stubaital

Generally, the potential of torrential catchments to produce events (debris flows, hyper-concentrated flows) can be assessed by a susceptibility analysis (Figure 8). The susceptibility depends on the basic disposition, which is largely constant over the time (e.g., relief, geology, vegetation cover), and variable parameters (e.g., soil moisture, vegetation behaviour, pasturing). Trigger of torrential events is usually heavy rainfall (system load, intensity/occurrence, probability). It is assumed that the basic disposition influences the magnitude of events whereas the variable susceptibility controls the frequency of the process-occurrence (Stoffel et al. 2024).

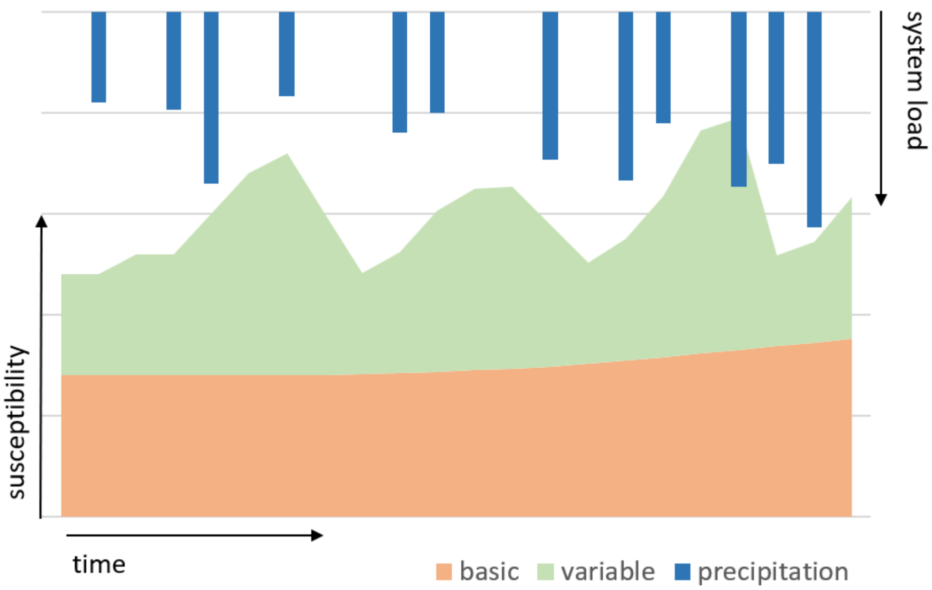


Figure 8: Concept of basic and variable event-susceptibility and system load, modified after Zimmermann et al. 1997.

Table 3 shows the number of events with a certain process-type in the catchments and in total, based on the event documentation. It is stated that the documentation is not homogenous. Since the 1970s all events, which led to measures of the WLV had to be documented using a specific documentation form. This might lead to an apparent increase of event frequency. The increase of infrastructure has the same effect, as only events, which led to measures were documented in the Digital Torrent and Avalanche Register (WLK). The enhancement of mitigation measures had the opposite effect. Events at Grawanockbach and Mutterbergbach are not documented before the 1970s, because there was no infrastructure. In the comparatively large catchment of Oberbergbach, events are registered as debris flows as soon as this process-type was documented in a subcatchment, while in the main channel fluviatile or hyper-concentrated flow occurred. In the test areas, primary debris flows, and hyper-concentrated flows occur, which may have strong impact on the course of the flood events (effect-chain) in the receiving water of the river Ruetz.

Table 3: Documented events in the five catchments until 2023 by process-type.

	process-type				
	debris flow	hyperc. flow	fluvial/flood	undefined	total
Mühltalbach	6	5		1	12
Oberbergbach	11	7	7	4	29
Margaretenbach	5	2	2		9
Grawanockbach	3				3
Mutterbergbach		1		1	2
total	25	15	9	6	55

b. Potential future frequencies and magnitudes

The impact of climate change on the sediment availability and transfer process is governed by the changes in precipitation, surface run-off and air temperature. However, these effects are difficult to quantify for torrential catchments (Hirschberg et al. 2021). Generally, it is obvious that an intensification and an increase of precipitation extremes can lead to a higher probability of hazardous processes in torrential catchments, underlined by several papers (Stoffel et al. 2024, Kiefer et al. 2021). Kaitna (2023) found, in dependence of the triggering type, an increasing number of days with critical conditions, especially in the springtime. Hirschberger et al. 2021 however, found a decrease of sediment production due to rising temperatures and thus less frost weathering, which results in a decrease of debris flow occurrence. Stoffel et al. (2024) underline the importance of indirect effects on debris flows, such as glacial retreat, permafrost degradation, upward shift of the snow line, deforestation due to storms, beetles or wildfire (i.e. cascading and compounding events).

In the higher altitudes catchments (Mutterbergbach, Grawanockbach, Oberbergbach), permafrost degradation and glacier retreat increase the basic susceptibility to debris flows, due to increased sediment availability. In the catchments with significant forest cover (Mühltalbach, Oberbergbach & Margaretenbach), the basic susceptibility may slightly decrease due to the rising tree line, however beetle calamities or windthrows can reverse this effect. At the catchment level, the increase of the precipitation intensities (system load) in general will lead to a higher event-frequency – the rise of magnitude depends on the catchment characteristics, its assessment follows the introduced decision scheme in Table 2.

Figure 9, based on the documented events, shows the distribution of process-types by decades and an increasing number of events. Since the 1970s the influence of documentation coverage should be low. The high number of events in the last decade (which includes only 4 years!) indicate a clear current raising trend of the event frequency at the studied catchments.

A trend from debris flows to hyper-concentrated flows and fluviatile events can be assumed, probably due to enhanced technical debris sediment management measures of the WLV. However, it must be noted, that the classification into hyper-concentrated flows was first introduced in the early 1970s.

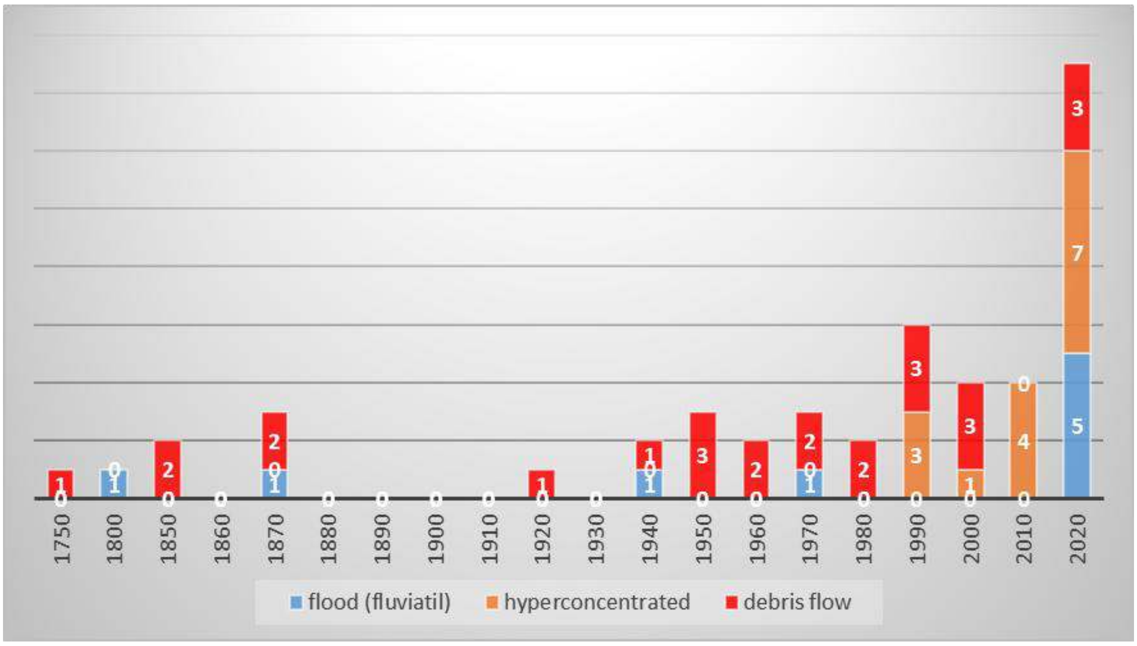


Figure 9: Distribution of assignable process types and number of events in the catchments (sums) per decade.

Annuality and trends for the magnitude of single events are hardly deducible on this basis, since the event-magnitudes are incompletely documented, inhomogeneous and the number of events per catchment is low. Nevertheless, analyses showed, according to the increasing frequency of events (Figure 7), rising sums of mobilised material within the last years. The sum of mobilised material (Figure 10) and the quotient of mobilised material and number of events (Figure 11) indicate an increase in magnitude in the average of the catchments as well. However, to derive a trend for the magnitude on the event documentation is insecure.

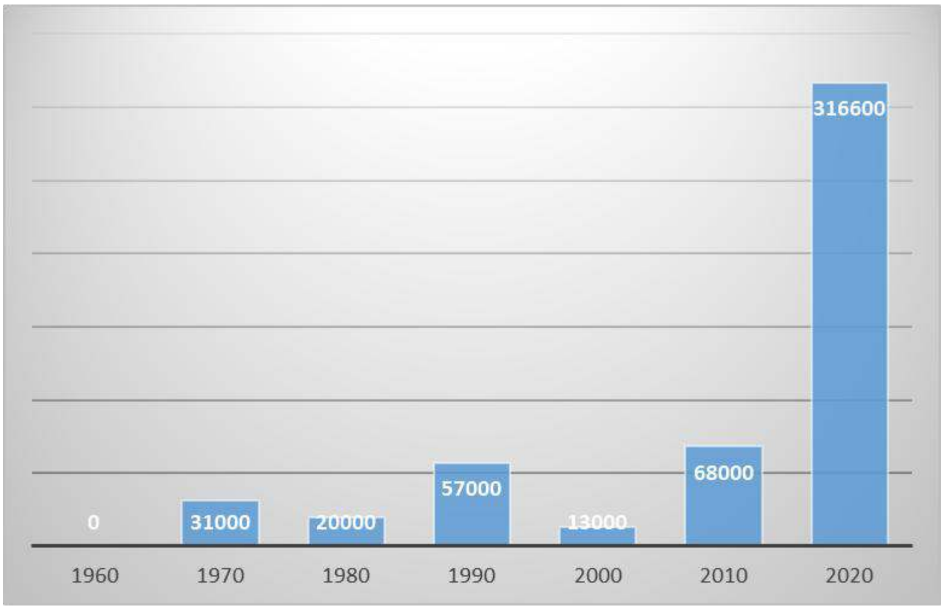


Figure 10: Mobilised material (m³) in the catchments (sums) per decade (since 1961).

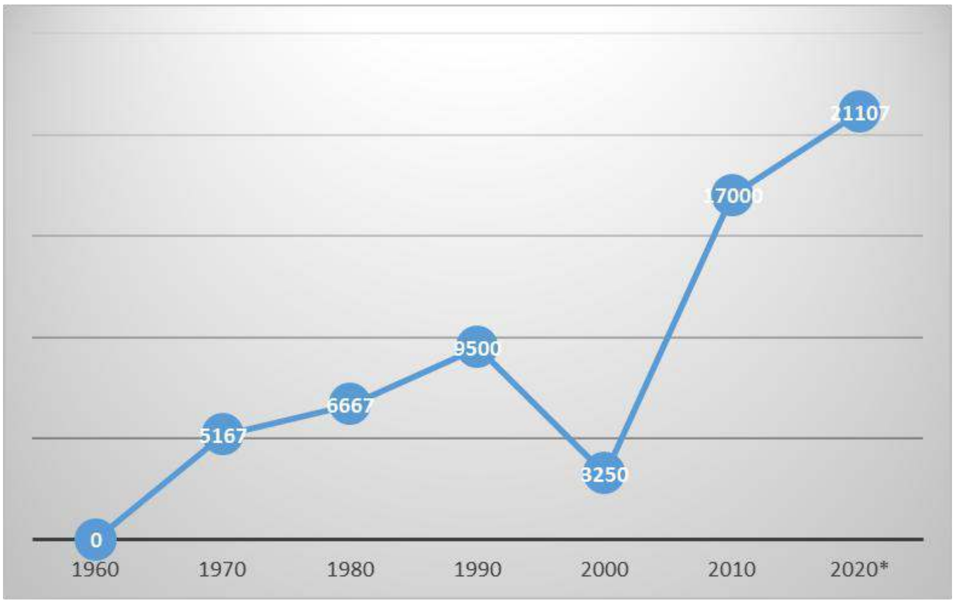


Figure 11: Quotient of mobilised material in the catchments (sums) and number of all observed events (see Figure 1, decades since 1961).

To summarise, torrential catchments react differently to changing climatic conditions due to different catchment-specific characteristics (Stoffel et al. 2024), namely the availability, production and location of sediment, the altitude and forest coverage. Investigations dealing with the impact of climate change on the debris flow magnitude yield, in dependence of the catchment-conditions, varying results. It was stated that the magnitude of debris flow events can decrease with increasing frequency and limited sediment supply. In catchments with rapidly retreating glaciers and permafrost, the magnitude of the events will most likely increase, glacial collapses and breaches of pro-glacial lakes can lead to thus far unknown consequences (Stoffel et al. 2024, Seelig et al. 2023). Thus, the single catchments are assessed based on expert knowledge considering:

- the increase of (especially) short duration precipitation intensities
- sediment supply due to weathering, permafrost degradation and glacial retreat
- rising temperatures and thus glacial retreat, permafrost degradation, changed snowline and snow cover
- afforestation due to rising tree lines and deforestation due to storms, beetles or wildfire
- changing process-characteristics
- cascading effects

For the catchments, CC-models show an increase of intensities for short duration precipitation of about + 20% until the middle of this century. Thus, the design precipitation (one hour 100-year return period will rise from about 64 mm/h to 77 mm/h in 2050). At the same time temperature will increase between 1.5 to 3°C in dependence of the chosen IPCC scenario, which means a rising snow line of several 100 m, less solid precipitation and less snow cover during events, which can retard parts of the precipitation.

c. Catchments - key hazards

Mühltalbach (municipality Mieders)

In the Mühltalbach, debris flow was and is the key hazard. Increasing precipitation already caused a system change in the upper catchment, since a debris flow channel formed in the last years, probably due to more intense precipitation. Figure 12 shows the mid-section of the channel in 1970 (left) and in 2023 (right), highlighting this change. Thus, substantially more material can potentially reach the valley bottom and the channel. As a result, the event of 2022 already clearly exceeded the design event and a further increasement of the sediment volumes is to be expected. Comparatively to that process-change the loss of forest cover is assumed to have only moderate effects.

Margaretenbach (municipality Fulpmes)

The Margaretenbach is extensively built-up with mitigation measures (Figure 13, right) - the key hazard is debris flow. However, debris can block the channel, endangers the federal state road and will (probably increasingly) cause substantial flooding. In 2022 (BML 2023), after 40 years without any major events, the channel bank above these constructions was heavily eroded and a large quantity of loose debris is still available there (Figure 13, left). Thus, a further increase of the sediment volume due to higher transport capacities is expected, if no further mitigation measures are put in place in the upper section of the channel. The loss of forest cover is assumed to have comparatively moderate effects, due to the geological situation (limestone), whereas more woody debris may affect the mitigation measures negatively.

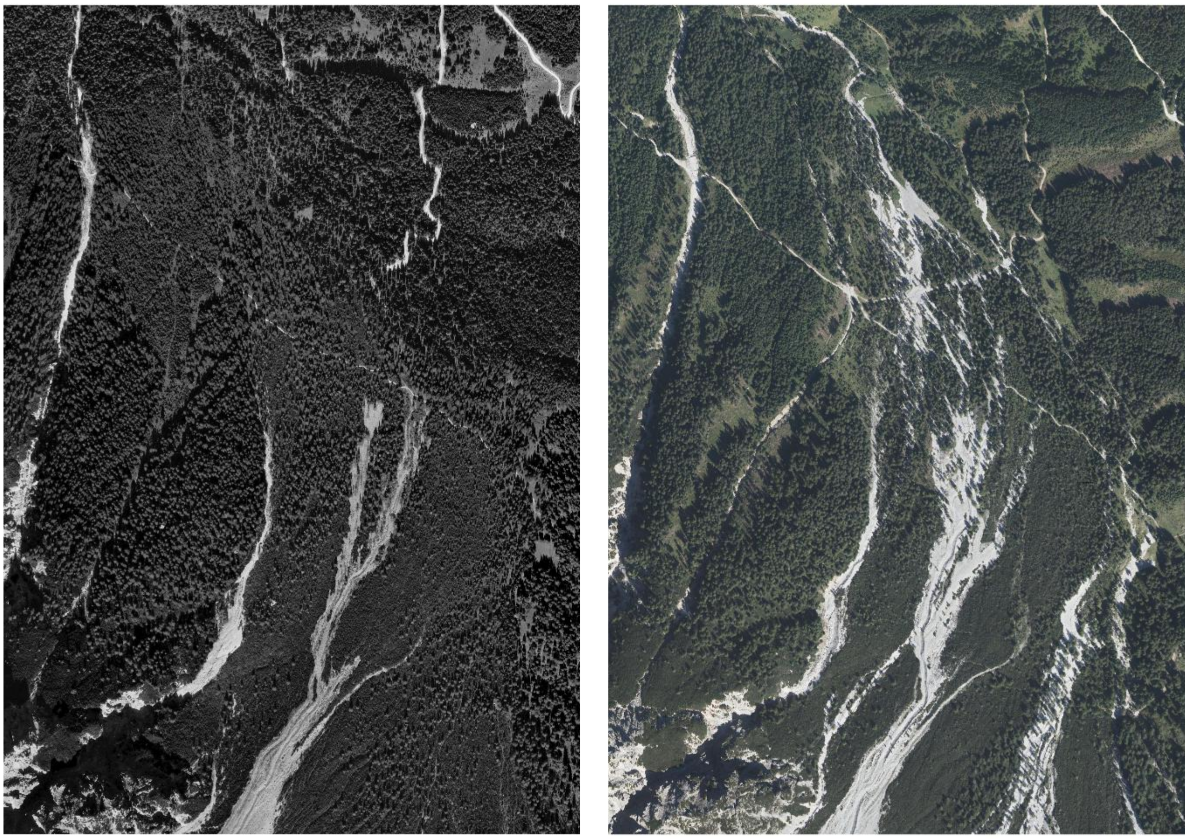


Figure 12: Orthophotos of the mid-section of the Mühltalbach channel in 1970 (left) and 2023 (right) (source Land Tirol, 2024); a comparison of the two images shows that a debris flow channel has formed during this observation period.

Figure 13: Debris flow channel of the Margaretenbach above the mitigation measures, showing the loose material source and large boulders - the biggest block has about 20 m³ (left); mitigation measures in the Margaretenbach (right) (source BFW).

Oberbergbach (municipality Neustift im Stubaital)

The Oberbergbach has a long history of events. The key hazards in the subcatchments are erosion, debris flows, in the main channel hyper-concentrated flows and flood events. The latter may potentially affect the settlement area in the valley bottom; however, a series of sediment retention basins offer efficient protection.

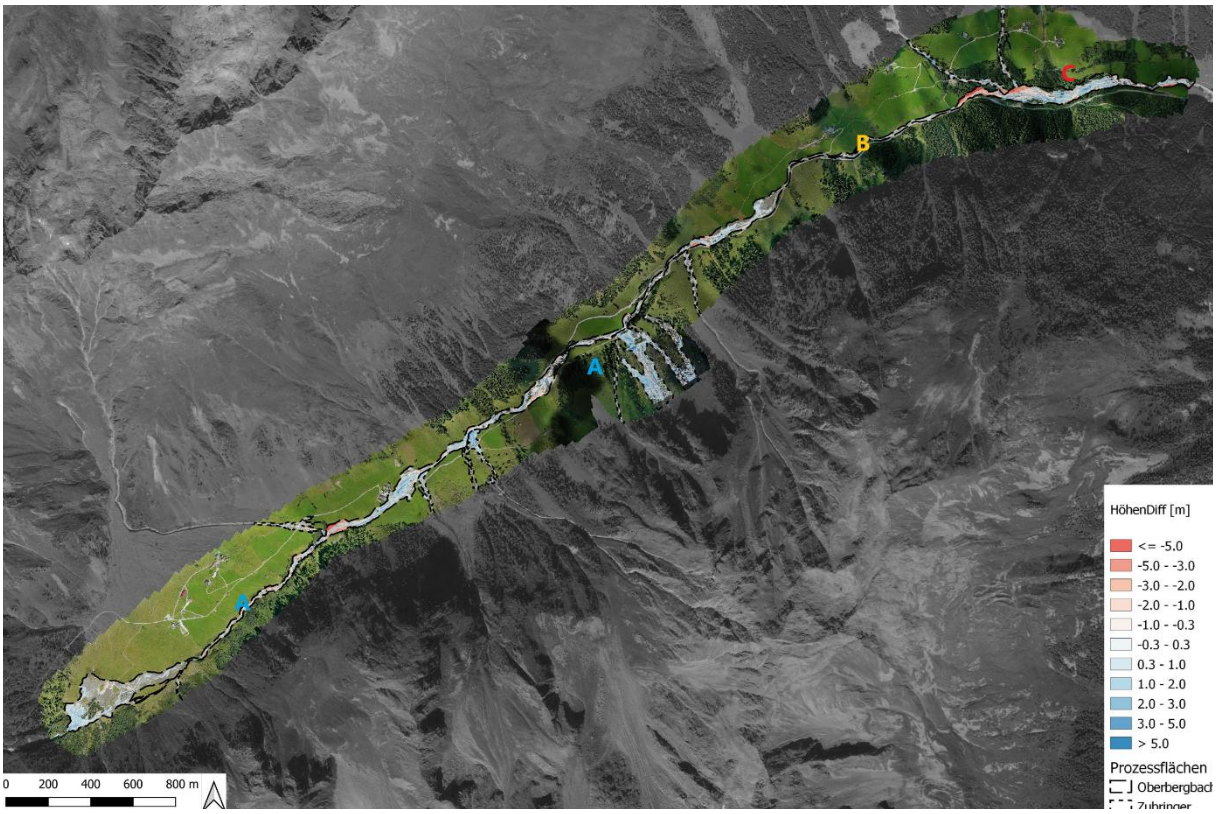


Figure 14: Oberbergbach, differences in altitude caused by the events during the summer 2022 (sediment erosion and deposition in reds and blues, respectively) (BFW, 2023).

Since the catchment reaches up to a high altitude, it is affected by the rise of the permafrost-line, an upward shift of the snow line (and thus a lack of snow cover with seasonal buffering effects on the glaciers) and glacier retreat, which causes increasing sediment availability (Figure 14, area A). In the upper parts of the catchment, erodible sediment is readily available. With a higher frequency and more intense precipitation, more and larger debris flow events are probable. However, the long, flat and wide middle channel section (Figure 14, area B) minimize the sediment transport to the lower parts of the Oberbergbach. The crucial area is below this flat part, where a great but not "unlimited" quantity of loose sediment can be mobilised. This is on the one hand old alluvial fan material from the subcatchment Tiefenbergbach and on the other hand material which is also permanently deposited from other subcatchments in this area (Figure 14, C).

Several scenarios were modelled by the WLV for the discharge of the Oberbergbach, where two scenarios turned out to be crucial:

1. Precipitation hot spot in C: Subcatchments may deposit large amounts of sediments in the channel of the Oberbergbach due to the decreasing slope. The discharge in this scenario results in peak discharges.

2. Intense precipitation in the western parts of the catchment cause peak discharges, which is assumed to increase in the future, due to less snow cover and solid precipitation. From this

area, only moderate sediment transport to the lower catchment-parts is possible, but material can be mobilized at the hot spot C, as far as available.

For compound events, increasing magnitudes reaching the retention basins and partly also the settlement of Neustift, are assumed. If and how often they will occur is difficult to determine at this point in time. Hence, the frequency of extreme events is assumed to be constant, whereas the frequency of small and medium events may increase.

The change of forest cover is assumed to have moderate effects, due to the discharge and sediment supply and low coverage percentage (16%). However, the increasing accumulation of woody debris negatively affects the function of the protective measures (retention basins) and increases the affected areas. In contrast to the two catchments mentioned above, in which debris flow events were the main danger, in this area the main danger results from fluvial events with woody debris.

Grawanockbach (municipality Neustift im Stubaital)

The key hazard in the Grawanockbach is debris flow, affecting the road leading to the glacier ski area Stubaier Gletscherbahnen. It was opened in 1973 and since this time until the summer 2022, there have not been any debris flow event impacting the road. There are also no debris flow events documented before the construction of the road. However, old aerial photos show a debris flow channel at the debris fields below the glacier, which indicates earlier events. In 2022 and 2023, a series of large debris flow events heavily impacted the road, back-filling and partially eroding the avalanche dam. Since then, the mitigation structures in the deposition area were heavily modified and upgraded (Figure 15).

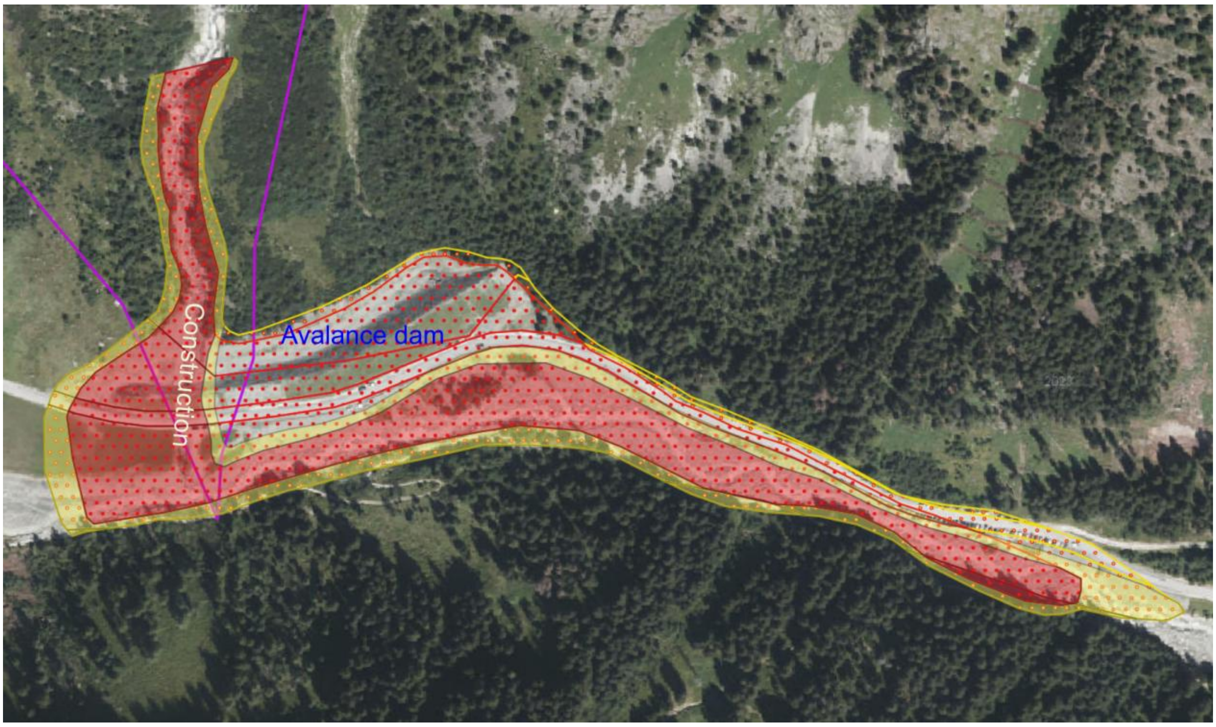


Figure 15: Estuary of the Grawanockbach into the Ruetz, redesign of construction measures and adapted hazard zone maps (dotted/before, transparent/after 2023).

Due to the high altitude of the catchment, the role of forest cover is negligible. The catchment is affected by the rise of permafrost and glacier retreat, which causes increasing sediment availability, but there has been plenty of erodible material throughout. With a higher frequency and more intense precipitation, more and larger debris flow events are probable. However, the endangered area will decrease due to the above-mentioned, modified mitigation structures in the area.

Mutterbergbach (municipality Neustift im Stubaital)

The key hazard type in the Mutterbergbach is hyper-concentrated flow. There is only one non-defined event (1987) documented before 2022 in the Mutterbergbach affecting the estuary into the Ruetz. The Stubaier Gletscherbahnen opened in 1973, and since then infrastructure is close to the estuary of the Mutterbergbach into the Ruetz (Figure 16).

In the catchment there are several debris flow channels. There are large debris bodies, whose infiltration causes subsurface flow. It is assumed that these areas currently do not contribute to the discharge of the Mutterbergbach via surface flow (and will also not in case of potentially increasing precipitation in the future). Due to the catchment's altitude, it is affected by the rise of the permafrost line, the upward shift of the snow line and glacier retreat, which causes increasing sediment availability. However, plenty of erodible material is already available. With a higher frequency and more intense precipitation, more and larger hyper-concentrated events as key hazard are probable at the estuary area.

Figure 16: Parking space affected during the 2022 event - estuary Mutterbergbach (source BFW).

ANALYSIS OF KEY RISK PATHWAYS

IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

a) Past/present and potential future exposure and impacts

i. Directly exposed elements

Exposed elements at risk are determined through the intersection of hazard zones with land use information. While several sources are available in the pilot area, only one is up-to-date and specifically designed for risk analysis, the Basic European Assets Map (BEAM, Figure 17 & Figure 18), which has been developed to estimate real and potential damages caused by natural hazards across Europe and was applied to Austria in 2022 (EMSN123, 2022).

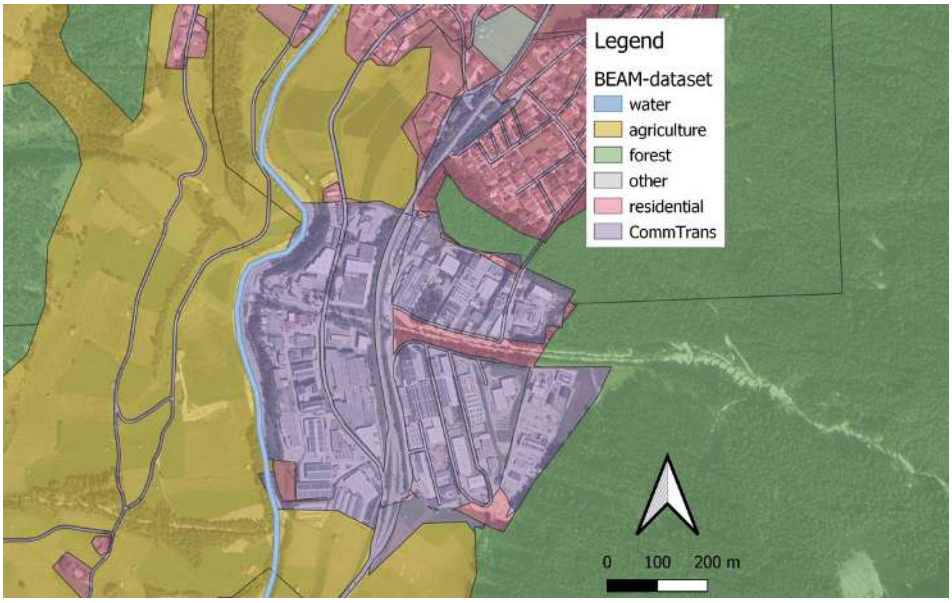


Figure 17: Excerpt from the BEAM dataset, Margaretenbach, land use classes.

The dataset offers information on the population density, values of buildings, households, industry, agriculture and forestry, amongst others, at a regional scale. Local data to specify values, construction details or the use of buildings from which the vulnerability can be derived, were not available in the pilot area. However, as soon as they are available, they could potentially be included to refine the dataset.

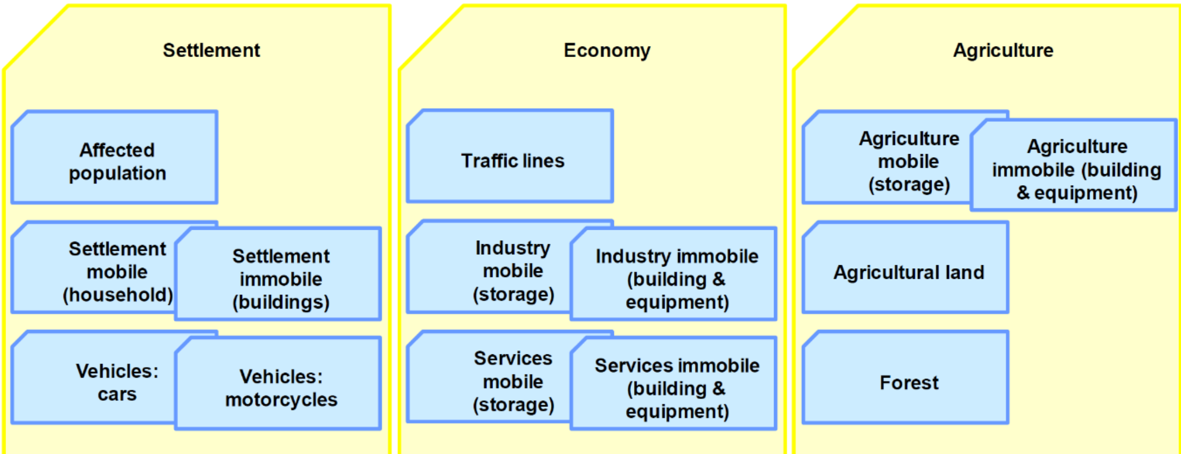


Figure 18: Structure of the BEAM dataset, values are population density: people/m², other €/m² (source EMSN123, 2022).

Based on the BEAM data, the value of directly exposed elements is determined step by step, applying equation 2:

$$\textbf{Cost [€]} = A_{aff}[m^2] * E\ [€/m^2] * p * Pr * Vu \qquad 2)$$

A_{aff}: affected area
E: value in €/m²
p: probability of occurrence (annuality)
Pr: presence of the elements in the area
Vu: Vulnerability, described by the degree of destruction

Area and value are calculated via a GIS (Table 5 & Table 6). The probability of events is given through the annuality of the design event of the hazard zone maps (1/150). The approach determines the direct costs of events as an annual average, indirect costs need to be calculated separately.

The presence of immobile elements at risk (e.g., buildings) is 1. The values for mobile elements at risk (e.g., vehicles) may change with the season, day of the week or even the daytime. However, this varying presence is not included in the BEAM dataset, which displays average values. Thus, we assessed the value of presence for these elements at risk with 1.

The direct costs were estimated by the degree of destruction of the elements at risk. In the BEAM dataset, the values are displayed, but there is only sporadic information on vulnerability through classification. However, the area is classified on a regional scale, which matches only roughly with the local situation. Torrential channels with mitigation measures (repair and clearance after events may cause substantial costs) are not classified as such. Hence, in a first expert-based approach, we chose an average degree of destruction in the red zone of 0.8 and in the yellow zone of 0.3, which can be easily changed in the case of improved knowledge.

Based on available data and the applied method, a quantitative assessment of likelihood for fatalities was not possible. The BEAM-dataset includes information on the population density but seems to be derived from the residence of the citizens. Thus, industrial zones, leisure facilities or roads have a population density of zero (Table 4), while there may be a lot of potentially endangered people in these areas.

Table 4: Population densities (and other values) for several classes – excerpt from the BEAM-dataset (Margaretenbach).

ln_label	popdensity	building	household	vehicles	nav_agricu
industrial, commercial, public, military, privat	0	0	0	17,9452920...	0
other roads and associated land	0	0	0	0,71781168...	0
other roads and associated land in urban areas	0	0	0	0,71781168...	0
sport and leisure facilities	0	0	0	0	0
sport and leisure facilities	0	0	0	0	0

Furthermore, the hazard zone maps do not cover the areas completely, as they are limited to settled areas (*"raumrelevante Bereiche"*). Roads and trails outside of settlements are not covered by hazard zone maps, but particularly the former are relevant to determine the likelihood of casualties.

However, we suggest a semiquantitative assessment of its development based on the previous analysis according to equation 3

$$P_{cc} = p_{haz} * 3 + \Delta A_{rel} \qquad 3$$

where P_{CC} is the degree of change, p_{haz} is the endangerment of the current hazard zones (unknown and thus set to 1) and ΔA_{rel} is the difference between the area under CC-conditions and the actual hazard zone map in relation to the current hazard zone map. We recommend calculating P_{CC} separately for red and yellow zones (Table 7), because of the different degrees of endangerment of people and the varying development of the zones in the different areas. In this project, the infrastructure (elements at risk) in the potentially endangered areas remained unchanged due to the lack of detailed information.

Areas already endangered nowadays may have a changed event frequency as shown in Chapter III, Table 1. Since all five catchments have (more or less) unlimited sediment sources, the frequency in current hazard zones is assumed to increase by about a factor of three (p = 1/50, Figure 6). New endangered areas are added with p = 1/150).

The results determined by the introduced method are shown in Table 5 (affected areas – red/yellow zone), Table 6 (affected values – red/yellow zone) and Table 7 (development of likelihood of casualties). Since the current likelihood of casualties is unknown or not determinable with currently available data, only its development can be determined. As soon, as there is proper information on the current likelihood available, the future values can be quantified on this basis.

Table 5: Affected area (m²) of events in the five catchments, hazard zones (red/yellow) and the current frequency/magnitude (GZP), the frequency/magnitude estimated 2050 (xrisk) and the calculated difference (Diff).

[m^2]	GZP red	GZP yel	sum	*xrisk red*	*xrisk yel*	*sum*	*Diff*
Grawanockbach	51355	16847	**68202**	30629	16716	**47345**	**-20857**
Margaretenbach	11120	2352	**13472**	27535	43638	**71173**	**57702**
Mühltalbach	11904	40162	**52066**	15649	38003	**53652**	**1586**
Mutterbergbach	34565	20499	**55064**	38184	16953	**55136**	**72**
Oberbergbach	305192	227297	**532489**	320264	227297	**547561**	**15072**

Table 6: Annual direct average costs of events in the five catchments for the hazard zones (red/yellow) and the current frequency/magnitude (GZP), the frequency/magnitude estimated 2050 (xrisk) and the calculated difference (Diff).

[€/year]	GZP red	GZP yel	sum	*xrisk red*	*xrisk yel*	*sum*	*Diff*
Grawanockbach	1916	310	**2226**	1935	129	**2063**	**-162**
Margaretenbach	35553	2915	**38468**	68462	53900	**122362**	**83894**
Mühltalbach	7365	5252	**12617**	11092	4575	**15666**	**3049**
Mutterbergbach	66483	15155	**81638**	68635	14348	**82983**	**1345**
Oberbergbach	55976	24407	**80383**	58808	24407	**83214**	**2832**

Table 7: Semiquantitative estimation on the development of endangered persons (P) in the red and yellow zones in 2050.

	A GZP red	A GZP yel	Δ A red	Δ A yel	rel. red	rel. yel	**P red**	**P yel**
Grawanockbach	51355	16847	-20725	-132	-0.40	-0.01	**2.6**	**3.0**
Margaretenbach	11120	2352	16415	41286	1.48	17.55	**4.5**	**20.6**
Mühltalbach	11904	40162	3745	-2159	0.31	-0.05	**3.3**	**2.9**
Mutterbergbach	34565	20499	3618	-3546	0.10	-0.17	**3.1**	**2.8**
Oberbergbach	305192	227297	15072	0	0.05	0.00	**3.0**	**3.0**

At the catchment Grawanockbach, the affected area was recently reduced due to mitigation measures, hence the annual costs are stable (Table 6). This shows the influence and importance of mitigation measures in the area and the need of its adaptation and maintenance. However, the presence of people during events in endangered zones (Table 7) and thus the probability of casualties will increase, despite the decreasing affected area due to more frequent events if there will be no additional mitigation measures as for example road closures controlled by an early warning system.

The necessary rezoning in Margaretenbach resulted in a significant increase of potentially endangered areas (Table 5), and thus in increasing annual costs (Table 6). The presence of people during events (Table 7), especially in the enlarged yellow zones is caused by a clear rise of endangered zones (Figure 5).

The process-change in the Mühltalbach causes only moderately increased costs (Table 6), due to the low value of additionally affected areas, just as in Mutterbergbach and Oberbergbach. The increase of people in endangered zones during events (Table 7) is mainly caused by the increase of the event-frequency.

In the Oberbergbach, costs might be underestimated, since the retention basins are classified in the BEAM dataset as pastures with low value, whereas their clearance and the maintenance of the mitigation measures may incur increasingly high costs. This also applies partly to the Margaretenbach and to the construction measurement in the Grawanockbach and Mühltalbach.

To check the results, event costs were recalculated, based on these values and compared with available information. For the Mühltalbach, the sum of actual costs (event 2022) was stated with € 1.5 Mio by the municipality, the recalculation yields € 1.89 Mio.

ii. Indirectly exposed elements

Following the nomenclature put forward by Meyer et al. (2013) in their review article on the cost of natural hazards, indirectly exposed elements, or rather non-direct costs from natural hazards can be further subdivided into the following categories:

- Business interruption costs: Occur in affected areas because of natural hazard event(s) interrupting economic processes, e.g., people not being able to carry out their work, as their workplace was destroyed, or agricultural or industrial production being limited. Indirect costs: These costs may be incurred either within or outside the affected area and may include production losses of suppliers of companies that have been directly affected.
- Intangible costs: Include those costs, which are not measurable in monetary terms, e.g., the impacts of natural hazards on health, the environment or cultural heritage.

A wealth of methodologies and procedures have been published on how to calculate these non-direct costs for a range of different types of natural hazards (e.g., earthquakes - Zhang et al., 2017; drought - Martin-Ortega et al., 2012; floods - Penning-Rowsell and Fordham, 1994; Alpine hazards - Papathoma-Köhle et al., 2011). However, all these approaches have in common that detailed, site-specific socio-economic data is required. Unfortunately, no or too little such data was available for the Stubaital.

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

a) Current vulnerability factors

To determine the costs of the event (see equation 2), it is necessary to assess the vulnerability of affected elements at risk. This vulnerability depends on the one hand, on the impact (type of hazard, unexpected occurrence, forces, etc.) and, on the other hand, on the resilience of the different objects at risk to these various effects. For example, a solid house may withstand the impact of a debris flow and sustain only partial damage, whereas cars are likely to be completely destroyed.

However, based on the information provided by the BEAM data, determining vulnerability in the classified zones is hardly possible. Moreover, in Austria, damages caused by natural hazards such as flooding or debris flows are only partially covered by insurance, and relevant information is usually not available. Event documentation typically does not include spatially allocated costs that could be correlated with the spatial classification of the BEAM dataset.

Hence, the costs of cleaning and refurbishment were roughly determined by the degree of destruction. Due to the lack of adequate information on the resilience against the effects of natural hazards without detailed additional field survey, these costs were estimated as averages: 80% in red zones and 30% in yellow zones. If a more comprehensive data basis becomes available, these estimates can be easily refined within the approach.

b) Potential future vulnerability factors

The exposure of elements at risk and their vulnerability is closely linked in the context of risk assessment. The development of infrastructure influences exposure; however, for accurate risk calculation, the degree of damage to the exposed elements is crucial. Actions taken by responsible actors, the behaviour of citizens and tourists, and the availability of resources during and after the event all impact vulnerability.

Further development of infrastructure: No reliable prognosis is currently available for the further development of infrastructure in the pilot area. Therefore, forecasts of population growth were used, as it has significant influence on the development of infrastructure. Overall, the communities showed a significant increase in the population during the last century, leading to a clear rise in potentially endangered elements. This increase is attributed to the growing population density, the value of buildings, households, industry, vehicles, and other assets (Figure 19). Additionally, summer tourism has developed vigorously from approx. 3 Mio arrivals and 21 Mio overnight stays per annum, to over 6 Mio arrivals and 23 Mio. overnight stays per annum in the region Stubaital (Land Tirol, 2024).

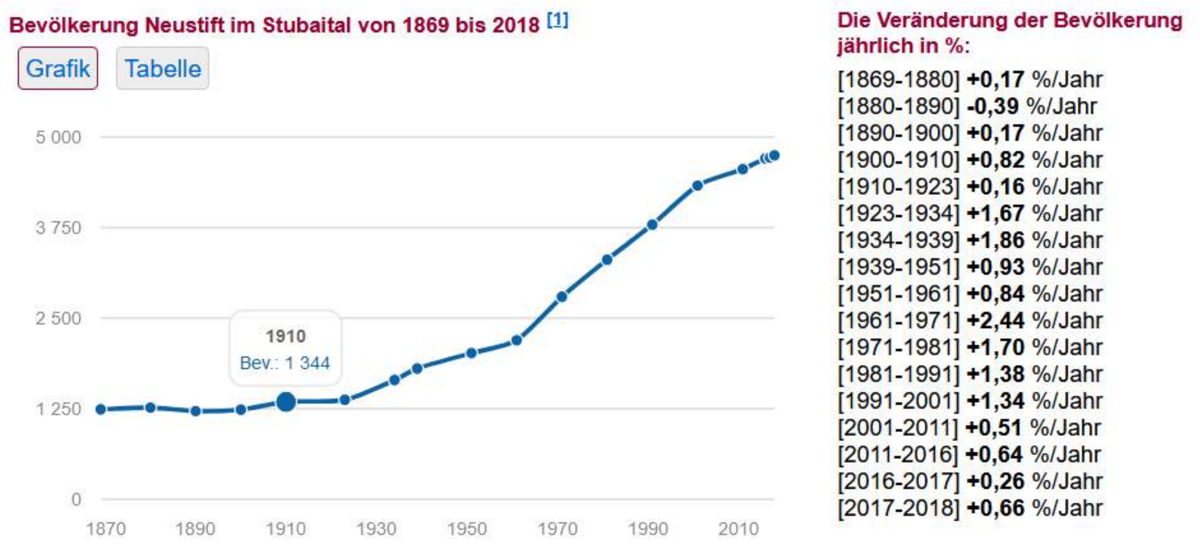


Figure 19: Development of the population in Neustift im Stubaital from 1869 to 2018 (graph on the left), and the percentage change in population (table on the right) (source: http://www.bevoelkerung.at).

Nevertheless, in the pilot areas, responsible actors have largely managed to keep potentially endangered areas free so far, except at Margaretenbach. Furthermore, projections for Tyrol (more detailed analyses for the Stubaital region are not available) indicate a slowing population increase (Figure 20).

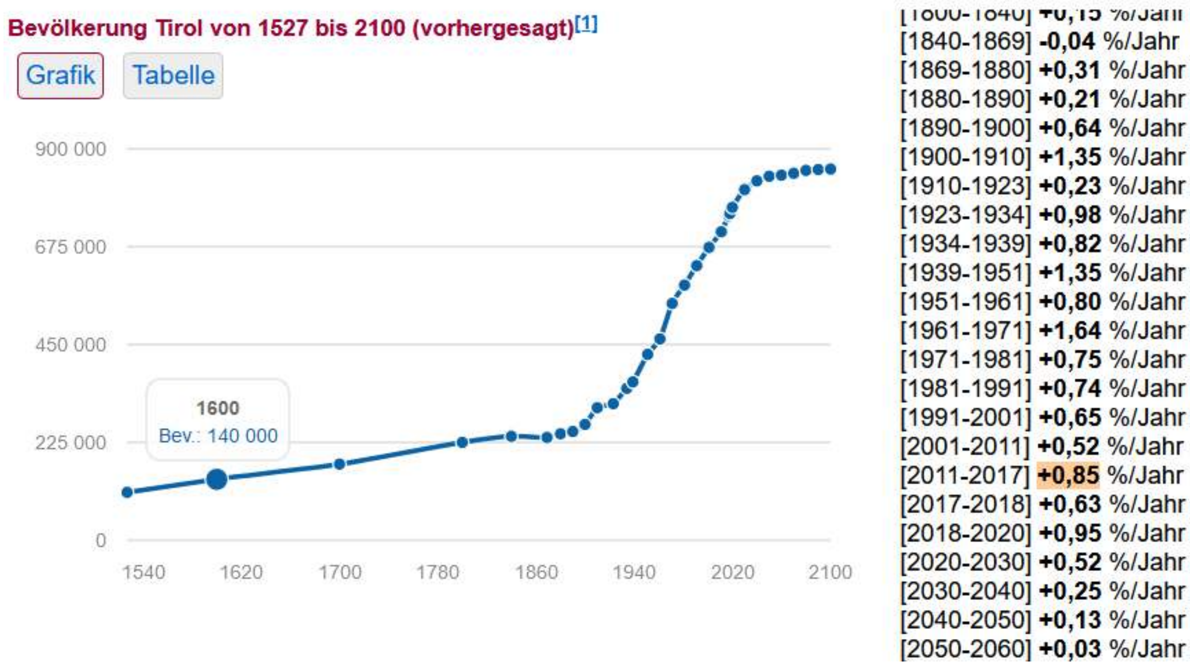


Figure 20: Population development for the Tyrol, including prognosis till 2100, (http://www.bevoelkerung.at).

For the project, it is assumed that the maintenance of mitigation measures will be ensured in the future as well, despite increasing financial challenges due to its high relevance. Analysis showed (Grawanockbach) the significant importance of mitigation measures in reducing the extent of losses.

In summary, we assumed a constant level of vulnerability in the pilot area for our risk forecast.

Settlements, Alpine tourism, traffic

Torrential events mainly affect the mobility and accessibility in Alpine valleys like the Stubaital: Roads and railways might be blocked (Einhorn et al. 2015). The development of the number of citizens and associated infrastructure depends on many factors, especially the socioeconomic development. Climate change is assumed to have a moderate influence as Figure 20 indicates. The change of population density in different Alpine regions under comparable CC-conditions is generally inconsistent. Anyhow, the number of inhabitants in the three municipality, where the catchments are located, is increasing, in Mieders it tripled between 1971 and 2021.

Leisure activities in Alpine terrain show an increasing trend in many regions. For the Alpine areas summertime and selected regions as e.g., the Stubaital, a trend of increasing touristic activities is assumed (BMWFW, 2012) reasoned by the rising temperatures. Time series of overnight stays in the core Alpine regions of North & South Tyrol, show an increase of 10% in the decade between 2005 and 2015. In touristic developed Alpine areas, a continuing trend towards the expansion of facilities and Alpine leisure parks can be observed (https://www.alpenverein.at). As mentioned above, in the main tourist season, for example, there are 8,000 tourists for every 5,000 locals in the municipality of Neustift, and further development is progressing. Every gondola station, restaurant or bike park, which is additionally integrated into the Alpine landscape will cause an increase in exposure of infrastructure and people according to the rising number of visitors, and thus to an intensification of vulnerability. Debris flow and flooding events mainly concern the summer tourism and due to the presence of hikers and cyclers in unprotected areas. However, during extreme precipitation events probably no significant number of people will be outdoors, while the number of people in accommodations or using infrastructure could increase. They are not endangered by debris flow while practicing the sport, but also when travelling to the starting points of their tours.

VI. **Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?**

a) **Current risk management measures**

In Austria and hence in the five catchments, many actors are involved in the case of natural hazard events. On the one hand there are the government part (federal - state - municipal level) and federal companies (like the BFW), and on the other there is the private sector (like forest owners or hunting associations). Figure 21 gives an overview of these actors.

Risk-Prevention

For the damage prevention at the catchments the most important stakeholder is the WLV, who is responsible for protective measures and the so-called hazard zone maps. Others are avalanche commissions, forest supervisors, geological services and research centres (like the BFW).

Hazard Zone Maps (GZP)

In general, Austrian hazard zone maps are based on event chronicles and -documentations, field surveys (silent witnesses) and increasingly on modelling. The WLV maintain their own event register (WLK), where damage events can be entered at different levels of detail. In some cases, however, (smaller) damage events are also recorded by unsystematised file notes and event logs. In the case of major events, usually more detailed analyses are carried out, often with the help of external teams of experts.

Hazard zone maps are area-wide expert reports with predictive character, which support the WLV as tool for planning, prioritizing and the realisation of mitigation measures as well as information for the responsible institutions regarding spatial planning (at federal and municipal level). They focus on hazards, while risks are only partially considered due to potential damage amounts (Pichler, 2019). These hazard maps are – due to state legislation - legally binding for spatial planning in Austria. Settlement development is regulated according to the type and degree of endangerment. Future endangerments can be mitigated by keeping settlements and infrastructure away from endangered zones or reduce vulnerability due to constructional adaptations.

Since approx. 1970 (with ongoing continuous updates) experts of the WLV turn all these sources into the final GZP. Maps are freely accessible at the communities, partially already implemented in the federal state GIS. The maps are available at the slope scale (at least 1:5,000) for relevant areas around settlements in Austria. Areas endangered by avalanches and torrential processes (flooding, sediment transport, debris flows in channels) are identified either as *yellow zones* (settlement development with restrictions) or *red zones* (building prohibited). Other hazards such as landslides and rockfall are shown as *brown reference areas*, indicating the need for further investigations.

The hazard maps are a proven instrument that has been generally accepted, implemented and used after decades of effort. Due to their well-established status as a planning tool, a lot of actors show little interest in introducing new instruments (such as e.g., risk planning), especially as changes in hazard zone maps can have significant socio-economic impacts and therefore lead to serious conflicts of interests.

Hazard zone maps are the basis for decisions of emergency services as they indicate different degrees of danger and thus the need of measures (nature and urgency, e.g., evacuation). A careful balance is essential when determining danger zones. It is important that mistakes from the past are not repeated, but a simple STOP to all construction measures cannot be the solution either. Communities also need development opportunities for business.

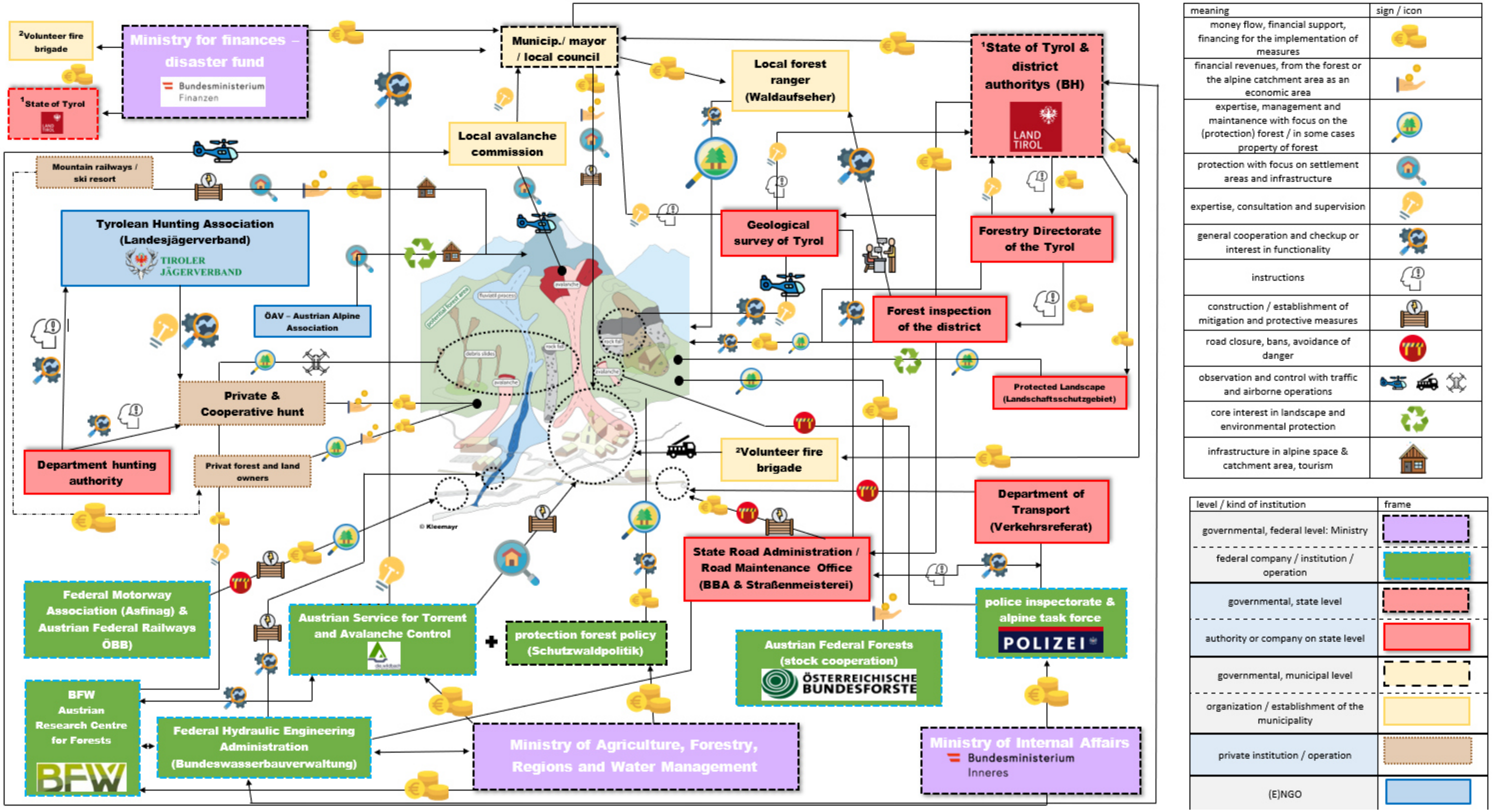


Figure 21: Actors on the topic "Natural Hazards" in Austria (BFW, Plörer, 2020, adapted 2024).

Disaster prevention plan of the municipality

In the case of regional natural hazard events, municipalities are responsible for local security, local rescue and local disaster mitigation. It is also their responsibility to raise resources and to train the staff. In Austria, several actors (torrent and avalanche control, state geology, responsible persons in communities and district authorities) are involved in all phases of the natural hazard management cycle. In many municipalities, the fire station serves as the operations centre, where usually decades of experience are bundled.

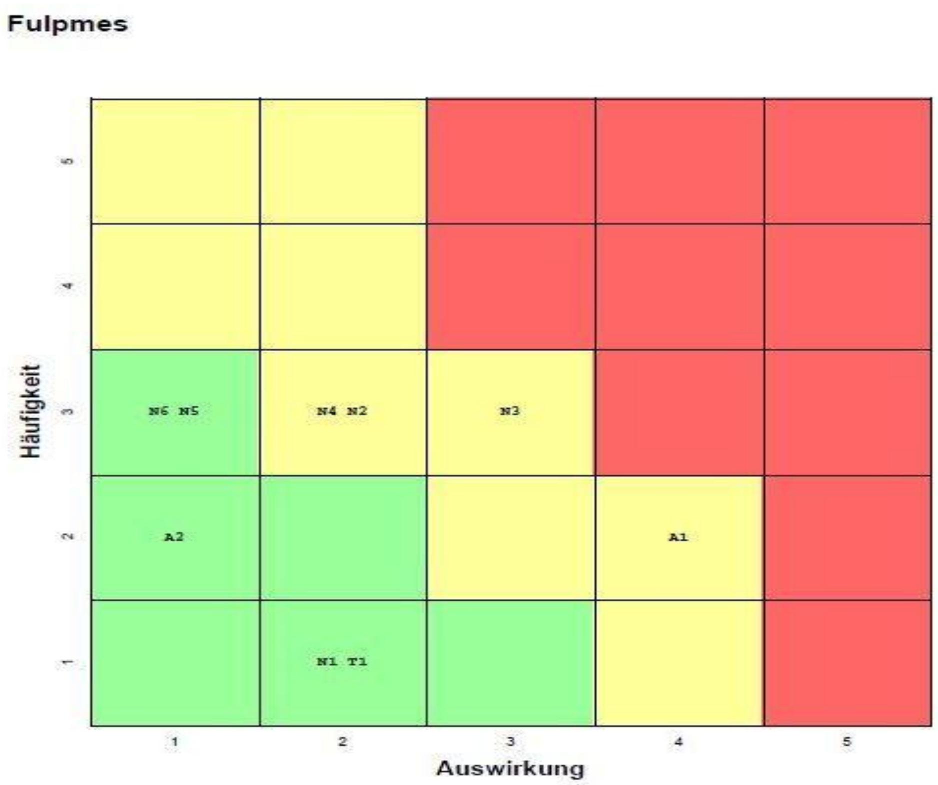
The municipality's emergency plans form the link between preparedness and response in the risk management cycle. Fire brigades and civil protection organisations are primarily engaged during the damage events but also on preparation shortly before events and indirectly through their members to the rise of awareness. This is why the preparatory networking of stakeholders and coordination between the responsible authorities is crucial.

The Tyrolean Centre for Crisis and Disaster Management of the Tyrolean Government provides a model table of contents for a disaster prevention plan for municipality, which is intended to ensure that all necessary points are covered in the plans of the municipalities. However, the sample table of contents is a generic template to be adapted to local conditions by the municipality. Hazard survey and risk analysis are an essential basis for the content of the disaster prevention plan. Torrents are inspected by local forest rangers ("Waldaufseher") yearly and after heavy precipitation events. The inspection contains an overview of necessary maintenance work on technical measures, structures or the need of action at the course of the stream (e.g., to keep it free of tree wood).

The disaster prevention plan contains:

- a general description of the local and special features of the municipality (such as accessibility and specific challenges in terms of the economy, tourism, etc.)
- a hazard catalogue with a risk assessment and risk analysis of general risks, natural hazard risks and technical risks, assessing frequency and the extent of damage
- the legal basis for the organisation of civil protection
- checklists and flowcharts for the individual risks (e.g., epidemics, blackouts, earthquakes, storms, floods, traffic accidents)
- contact details of the emergency response centres, the state warning centre for experts and surveyors. Good communication is particularly important since decisions must be made under great pressure by the emergency manager (in most cases) the mayor
- warning and informing of the population, press and public relations work
- a chapter, where the emergency and support personnel resources, (e.g., for flood operations) and objects for the accommodation are listed
- information on activities for the planning of evacuations
- an inventory of buildings and operational support (hospitals, aerial platforms etc.) and protective structures
- special alarm plans and sample forms

The risk assessment was carried out for all Tyrolean municipalities around 2015. Figure 22 shows an example of the risk matrix for the municipality of Fulpmes.



Legende

rot	hohe Priorität
gelb	mittlere Priorität
grün	niedrige Priorität

Risiken

Abk.	Name	Master Risiko	Häufigkeit	Auswirkung
A1	Gefährliche Stoffe Fa. Galvanik Schmidt (Fulpmes)	Gefährliche Güter und Öl, Transportunfälle, Boden- und Wasserverseuchung	2	4
A2	Gefährliche Stoffe Transportunfälle B183 (Fulpmes)	Gefährliche Güter und Öl, Transportunfälle, Boden- und Wasserverseuchung	2	1
N3	Hochwasser & Geschiebe Schlickerbach (Fulpmes)	Hochwasser, Murbrüche, Flutwellen	3	3
N4	Hochwasser & Geschiebe Margretenbach -> Verklausung Brücken Industriegebiet (Fulpmes)	Hochwasser, Murbrüche, Flutwellen	3	2
N6	Hochwasser & Geschiebe Griesbach -> B183, Alte Landesstrasse, Klärwerk (Fulpmes)	Hochwasser, Murbrüche, Flutwellen	3	1
N5	Hochwasser Ruetz -> Bereich Medraz-Auenweg (Fulpmes)	Hochwasser, Murbrüche, Flutwellen	3	1
N2	Omesberglawine -> Siedlung Omesberg (Fulpmes)	Lawinen	3	2
N1	Lähntallawine -> Industriezone A (Fulpmes)	Lawinen	1	2
T1	Brand Umspannwerk TIWAG Industriegelände -> Auswirkung Medraz-Stille (Fulpmes)	Brände	1	2

Figure 22: Risk matrix of the municipality of Fulpmes.

However, this risk matrix does not consider ongoing changes. Therefore, the province of Tyrol recommends reviewing this matrix every five to six years. Seminars on municipal crisis and disaster management are offered several times a year as part of a training program, provided by the province of Tyrol.

In addition to the legal basics, the principles of working in a municipal emergency management team are also taught, as well as tips on structuring the emergency management team and drawing up the disaster control plan. Joint exercises by all organisations are carried out in the pilot area to ensure that the people involved know each other well and that the urgently needed calm can be maintained when a damaging event occurs. In the Stubaital, several municipalities have proper emergency plans due to their extensive experience in dealing with natural hazard damage events. Nevertheless, some processes are still (too) heavily dependent on the people who act in the event and are not yet institutionalised. However, relevant persons may not be spontaneously available if required. Therefore, written, person-independent operational checklists are necessary.

Stable forest stands

Small-scale differentiated, locally adapted forest stands usually have a positive, damage-preventing effect on torrential processes. In the Stubaital, the local forest rangers are strongly integrated in this process, liaising with and being managed by the Forest Inspection of the District (BFI) and the Forest Directorate of Tyrol (LFD), especially in advising forest owners. The BFI provides technical and financial support to build up resilient forest communities. In the catchments, the introduction of mixed tree species (everything except spruce) is being promoted, with the focus on conifers such as larch, pinus cembra and abies alba, and hardwoods such as acer montanus, prunus avium and walnut. Erosion can be reduced with shrub vegetation (hazelnut!), especially the mixture of shrubs with mixed tree groups has proven successful. Reforestation with spruce is not financially supported anymore, due to its non-natural dominance in the Stubaital and its susceptibility to bark beetle calamities.

Due to the protective effects of forests, landowners are legally obligated to reforest stands after damaging events. The formerly common practice of pasturing between clearcut and reforestation is forbidden now, as even short-term (3-4 weeks) use of forest areas as pasture for small animals can have very negative long-term consequences for these areas. Today, these areas can also be easily protected from grazing by electric fences.

The existing small-scale distribution of forest ownership in the pilot area (communal property-agricultural communities, communal property forests) is a limiting factor for the uniformly organised forest management. Nevertheless, development measures to create good conditions for forest management and the processing of damage events are also addressed together with the BFI. The BFI's support advisory activities and assistance with funding applications. Cooperation with the authorities works well in the Stubaital.

Weather forecast

Weather forecasts generally provide information on extreme weather events such as heavy precipitation and are thus an important basis for risk management. In the pilot area they are provided in the weather data portal *Tyrol Weather Box*, which is coordinated by the Tyrolean State Warning Centre. The data also includes analyses of exceptional weather situations by experts from the national weather service GeoSphere Austria (GSA). These are evaluated in coordination with the Tyrolean warning centre which cab take further measures. The data from the *Tyrol Weather Box* can be accessed by various departments of the province, decision-makers at municipal level and the fire departments. However, not all relevant stakeholders in the pilot area, (e.g., the Stubaier Gletscherbahnen), have access to this data. Additionally, GSA maintains more than 200 meteorological stations and the INCA-system (Integrated Nowcasting through Comprehensive Analysis), which has been developed for use in mountainous terrain. Analysis and nowcasting fields include among others the spatial distribution of precipitation amounts and precipitation type in a 1 x 1 km² resolution.

However, the forecast quality is comparatively low for precipitation, because of the limited representativeness of station data in mountainous terrain (Haiden et al. 2011).

In the event of potentially dangerous weather conditions (e.g., thunderstorms), responsible persons receive warnings via SMS or the Tyrolean warning centre contacts them directly. For liability reasons, however, *Tyrol Weather Box* is not a warning system per se - the further procedure in the event of warnings must be determined in detail in each individual case. In particular, it is difficult to predict small-scale heavy precipitation events. For example, during the damage event in the Stubaital in July 2022, there was a weather warning of level "yellow" on the morning of the 20th, which was raised to "orange" for the entire Stubaital in the afternoon. However, the actual occurrence of the small-scale thunderstorm cells that caused the major damage only became evident directly during the event.

Collaboration between responsible persons and organisations

The availability of competent personnel is essential and applies both, the own staff of the responsible institutions and external experts or persons (mountain rescue, ambulance, police, armed forces). Fire brigade and rescue services in Austria are to a high degree based on volunteering. There are 340,000 volunteers with the fire brigades and almost 60,000 volunteers with the Red Cross in Austria. Therefore, it is essential to maintain and expand this volunteer system by creating appropriate political framework conditions (e.g., free time off work for employees in case of damage). Fire brigades and civil protection organisations focus on awareness-raising and preparation as well as operations directly during the damage events.

If natural disasters exceed the local and regional resources of civilian forces, the military provides additional assistance. State crisis and disaster management is coordinated by the Ministry of Internal Affairs. The crucial task is convening and coordinating the operations management or the emergency services. Many actors are subject to an official procedure. The respective heads of operations are basically on duty from the beginning to the end of the operation/immediate danger. Fire brigades and regional geologists are usually active in this phase, focusing on mitigation and damage repair. Therefore, the flow of information between emergency management and the emergency services needs to be frictionless to implement roadblocks, evacuations and bypasses. Mobile phone and on-board-communication, barrier materials, tools (including heavy equipment such as trucks, excavators, caterpillars and helicopters) also provided by private construction companies are essential. The responsible persons in the test areas do have the relevant contacts.

b) (Potential) future risk management measures

In addition to the expertise available at the BFW, literature research and detailed discussions and inspections of the catchments together with the WLV, further sources were used to answer this part of the questionnaire:

- Workshops (12.2023) were held by the WLV in each of the three municipalities in the pilot area, to analyse the risk management during the events of July 2022, identify possible deficits and develop measures to improve hazard management in the future. The workshop participants worked in subgroups using a questionnaire to discuss their positive and negative experiences of hazard management during the event. The results were presented in plenary and the most important lessons learned were identified.
- Based on the results of this workshop, the BFW started individual discussions with all three mayors during the summer of 2024 to obtain their personal assessment and expertise.

- The minutes of the municipal authority meetings held after the damaging events in 2022 were also available.
- The assessment of the situation of the forest areas in these municipalities was obtained in personal discussions with the BFI.

Scenarios

Hazard maps are, from the conceptual point of view, static plans designed for spatial planning and therefore only represent the status. Thus, it is not the intention to consider changes (climate change, land use changes) or sketch scenarios. However, additional modules to extend the hazard focused maps by information on risks scenarios (e.g., climate change related scenarios) are interesting in terms of providing additional information for decision-makers. However, the inclusion of (uncertain) scenarios into the hazard zone maps complicate the implementation of such maps in practice. Decision-makers need clear information, as their decisions are associated with monetary effects. Event documentation, use of improved assessment methods, and more accurate spatial information can enhance hazard zone maps.

Early warning systems

As shown above, technical protective measures based on design events and historical experience will inevitably become insufficiently dimensioned in many areas. Expanding flow profiles or retention areas is often hardly feasible. An alternative can be temporary protective measures (Sättele et al., 2015), which, however, requires reliable and timely warnings.

For debris flows, two types of early warning systems are available:

- Early warning through the activation of sensors (trip wires, geophones, level sensors) in the upper catchment area, triggered by an already initiated debris flow. These offer high accuracy but only short lead times (minutes), which is enough time to, for example, control traffic lights but not enough time to set up protective structures or evacuate people.

- Early warning based on specific thresholds for rainfall intensity. These systems can be fed with both measured data (rain gauges, weather radar) and forecasted rainfall amounts. The latter allows longer lead times depending on the forecast period, although with decreasing accuracy. Currently, warnings from this kind of early warning systems are generally quite broad in terms of location and type, actions are undertaken to specify the warning spatially (e.g., Hagen and Lechner 2022).

Both systems are currently not in use in the catchments. They would however be an appropriate method to increase safety for roads, as soon as they can provide warnings with high positional accuracy and precision.

Information and involvement of the local population

Overall, the need for civic participation has increased significantly in recent years and is a useful addition in several areas. Involving the (local) population addresses many different issues. On the one hand, risk communication is about raising public awareness of risk management issues, also regarding possible changes due to climate change. On the other hand, measures need to be presented, and the population needs to be involved in disaster control exercises. Furthermore, citizens are often a source of event documentation (e.g., to complete damage event chronicles). Success usually depends on the commitment of the local stakeholder (e.g., mayor). Educational involvement of young people (school projects) helps, to increase the awareness for danger and risk.

However, there is a gap between the increased need for information and possibilities (document upload and download, workshops, etc.) and a lack of individual responsibility. It is challenging to address groups of the population that have no history of dealing with local natural hazard risks.

In this context, all efforts to provide the population with comprehensive information must clearly communicate the residual risk, which will always remain despite all safety measures. In all these discussions, it is to consider that people do not calculate in probabilities in their daily lives.

Information on advance warning and the behaviour during an event is important to minimize damage and casualties in municipalities with a high number of tourists (e.g., Neustift im Stubaital 5,000 citizens, up to 8,000 tourists on given peak season day). This requires a wide variety of information channels, with booking platforms and tourism newsletters playing an increasingly important role.

Recent events showed an increasing number of spectators, hindering the emergency services. Closures of roads were sometimes ignored, despite the probability of casualties. However, after appropriate warnings have been issued to onlookers, they must also take personal responsibility. In connection with informing the population, the symbolic effect of present emergency managers (mayor) on site, is often helpful. This is the best way for all the people involved and affected by the event to gain the impression that someone is taking care of them in this difficult situation.

Strengthening risk awareness by ensuring the availability of equipment and deposit areas

The emergency plans of the municipalities should ensure that the necessary (heavy) equipment capacities are available for immediate measures in the damage event (excavators to open the channels, trucks to transport the material, etc.). In this context, municipalities often work well with local transportation companies. The financial requirements should be clarified to minimize administrative efforts in the case of events. To work efficiently and effectively, it is helpful to take a holistic approach to certain matters on a cross-regional basis. Equipment and vehicles (including those of the fire department) could be shared in assistance operations. However, the corresponding framework requirements for such assistance operations must be organised in advance.

In the Stubaital with limited spatial resources, the availability of areas for the (temporary) deposit of debris flow material needs to be planned, since solution had to be found just in time in the case of events. If areas are not owned by the municipality, negotiations with landowners are often difficult and time-consuming. Moreover, financial aspects of compensation payments and legal aspects of environmental protection need to be considered. A solution is to define depositional areas in advance in the spatial plannings. The availability of adequate disposal areas is also of great importance for the of (temporary) deposition for timber from windthrow areas. In addition to the areas themselves, their accessibility and the necessary facilities of the transport routes are of course also a key factor.

Strengthening risk awareness by reviewing past events and the development of best practice examples

Most of the actors and institutions in risk management create operational protocols, in the form of inspection reports, findings, expert opinions or in the form of standardised procedures (e.g., at the central fire station). Additionally, often lessons learned protocols are derived, which are incorporated into future work plans. In the context of the WLV this is frequently not executed in a systematic way, but is incorporated into thought processes, which mostly relate to the concrete measures, but not the organisational structure as such.

These protocols are usually created internally or with the involvement of the participating actors. Statements by external persons (eyewitnesses, experts from other disciplines) may be included.

Processes are reviewed in the context of informal exchanges and non- or little standardised debriefings directly after the assignment. Key points will be derived from this for further training. In the case of the fire brigades, feedback is sent to the mayor.

Municipalities that are frequently affected by natural hazard disasters have a sound the knowledge how to manage such events. Municipalities that will face previously unknown challenges in the future (because of climate change) could benefit from this experience. In the pilot areas, the willingness to share them was stated.

Strengthening risk awareness by better preparation for financial risk management

The financial aspects of the immediate countermeasures required in the event of damages are in many cases already in the municipalities' emergency plans (Figure 22). However, most losses can only be assessed monetarily after the event and possible financial assistance for those affected can only then be agreed upon. A wide variety of funding and in some cases additional municipal decisions are also necessary. Furthermore, there are sometimes very different schemes for covering damage to private and public property. From minor damage to the complete loss of property, everything is divided between several different actors.

Almost all those directly affected by a damage event, consider the municipal administration to be the first point-of-contact. However, these authorities are often overwhelmed by the large number of requests; this is further complicated by the fact that regulation regarding access to funding and eligibility are subject to ongoing changes. With large time intervals between the events, the knowledge on how to handle such events may get lost. To avoid this, a superordinate unit for the financial management, managing loss events, by aiding the entire settlement process would be desirable. In this way, real structural support could be provided in conflicts between centralized, holistic thinking and the concrete operational processing of the individual actors.

Generally, investing more money in sound measures in earlier phases of the risk cycle saves money on recovery. The financial support of damage management and recovery differs from region to region and is to a certain extent random. The establishment of a uniform mandatory insurance for natural hazards (already existing in Switzerland) could also help to reduce the (economic) vulnerability of the population.

Another way to offer funding for damage recovery are the *Kontokorrent* loans, which are also recommended by the Tyrolean government for municipalities. This form of loan is made available by a bank for a limited period and is capped to a certain amount to cover short-term liquidity bottlenecks by. If there is a need to take out the loan, very low interest (approx. 0.15%) is charged.

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

Compound events are either linked to the same meteorological trigger or incidentally occur simultaneously because the region has a high susceptibility to multiple hazards. Examples of possible interactions for multi-hazard risk scenarios in the catchments are:

- Impact of debris flow material into the receiving water - bed load loading up to blocking rivers with the danger of dam breakage scenarios
- Blocking of channels because of rockfall or landslides and therefore triggering of debris flows
- Windthrows may lead to a high proportion of woody debris, which can cause blockings
- Deforested areas due to windthrows, forest fire or bark beetle can lead to:
    - increasing erosion and landslide activity, impacting the torrent channel system with additional sediment
    - increased surface runoff causing higher discharges and thus, higher sediment-transport capacities

Difficult reforestation will most likely extend the timespan of increased susceptibility to natural hazard events. The current probability and relevance of compound events is assessed for the catchments in Chapter III as this is part of the creation of hazard zone maps.

b) Potential future impacts of compound/cascading hazard events

The probability of compound events under the assumed future climatical conditions in the catchments were part of the estimated future hazard zones, considering the climate change and are described in Chapter III as well.

Rise of temperature - degradation of permafrost

An average worldwide temperature rise of about 2°C means an increase over large landmasses and thus for the Stubaital of about 4°C (UBA, 2023). Under the greatly simplified assumption of a linear relationship between permafrost distribution and air temperature, the lower permafrost limits would rise by around 600-800 m (Schrott et al., 2012b). The general permafrost limit in the Alps is currently around 2500 m above sea level (www.slf.ch), mostly in northwest over north- to northeast exposed terrain. The underlying assumption would therefore cause a shift in the permafrost limit from 2500 m to 3100-3300 m.

For debris that is located at altitudes above 2500 m, the influence of permafrost depends on the sediment availability. Torrential systems can be classified into two main categories:

- Transport capacity limited torrents: show +/- unlimited sediment supply. Debris flows are limited by the amount of available water and its transport capacity. Only an increase of runoff may lead to an increase in debris flow activity, additional sediment will not change the frequency or magnitude of debris flows.

- Debris limited torrents: in such torrents, the transport capacity of debris flows exceeds the debris supply. Debris flows are limited by the amount of sediment, which can be mobilised. Additional sediment due to thawing permafrost can increase both the frequency and the magnitude of events. Thus, the influence of permafrost on debris flow intensity or frequency will strongly depend on the type of control driving the torrential system.

The way permafrost and permafrost degradation may influence debris supply to torrential systems can be classified as follows:

- Debris supply by rock walls
- Debris supply by rock-glaciers or other permafrost creep processes: rock glacier destabilization or even collapse
- The melting of interstitial ice will lead to a loss of cohesion of the previously frozen debris, which will become available for mobilisation by surface processes
- Permafrost can influence the water supply, either by limiting infiltration or by providing additional water volume

Rise of temperature – reduced buffering of snow cover

The decrease of snow cover in high altitudes during the thunderstorm season usually accelerate the runoff and thus the peak discharge. Irrigation experiments (100 mm/h, Figure 23) showed that the delay of runoff under snow cover strongly depends on the snow depth (increased runoff delay with increasing snow depth), whereas the amount of surface runoff depends on whether the soil was frozen or not (lowest runoff coefficients -not frozen). The snow water equivalent, liquid-water content and the snow density influence both moderately (Kohl et al. 2001).

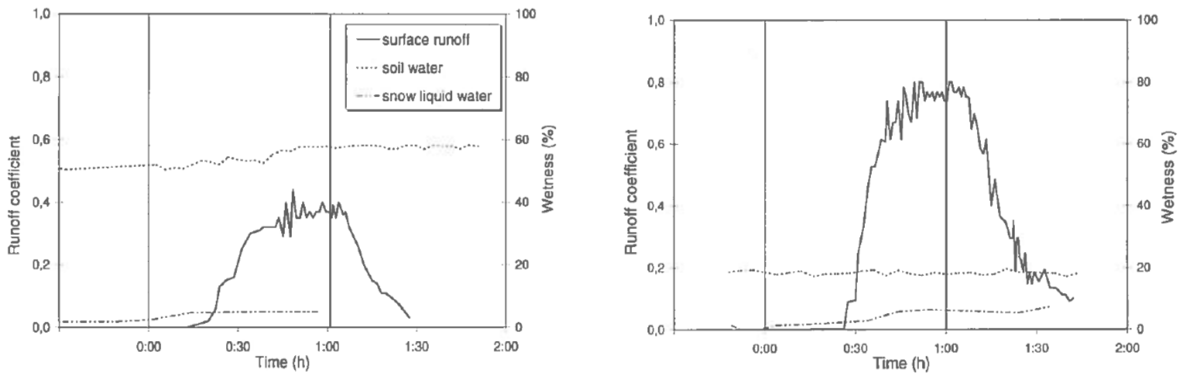


Figure 23: Surface runoff under snow cover: Monitoring of soil and snow liquid-water contend during irrigation experiments, starting-point and end of irrigation are marked by vertical lines (Kohl et al. 2001).

The runoff coefficients within the experiments were between 0.4 and 0.8, Thus the reduction depends beside the mentioned snow-parameters not only on the area covered by snow but also on the difference of the runoff coefficients of snow-covered and snow-free areas.

Rise of temperature and drought – destabilisation of forests and disturbances in the forest structure

The rapid rise in temperature weakens forest stands as they become increasingly unadopted to site conditions. At the same time, reproduction conditions for various insects may improve. The cascade of windthrows and resulting mass reproduction of destructive insects cause a significant hazard potential (Halla et. al., 2024). Figure 24 shows the increase of damage caused by bark beetles in connection with the temperature development. Consequently, in the pilot area, where spruce trees (picea abies) cover wide areas, problems with the spruce bark beetle (Ips typographus) are already observed to increase.

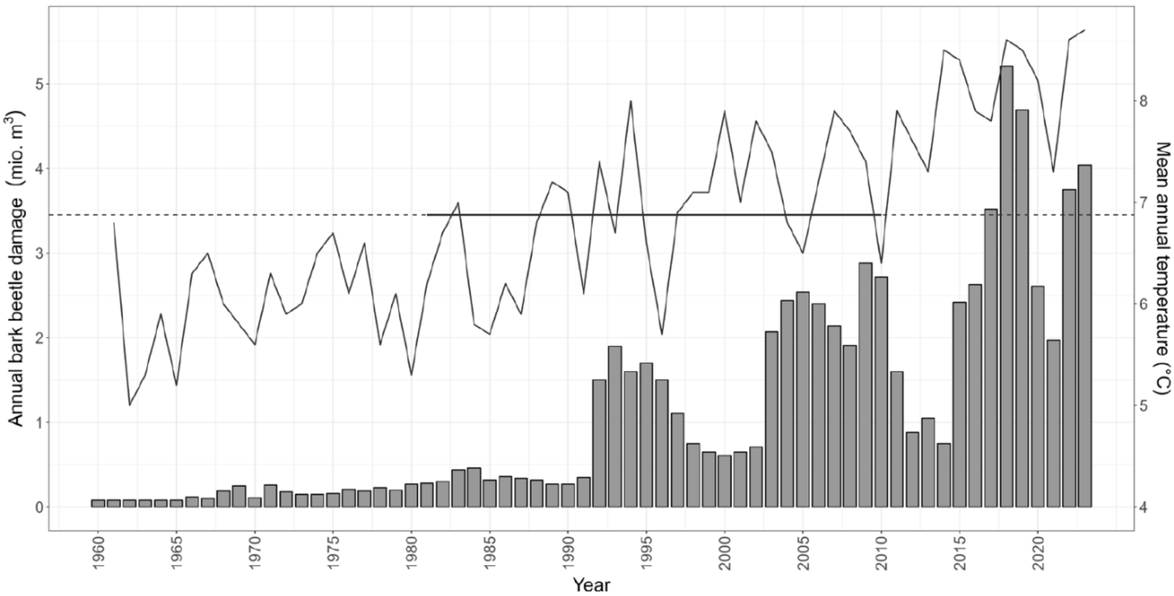


Figure 24: Annual damage by bark beetles and annual mean temperature in Austria. The horizontal line indicates mean temperature for period 1981–2010. Damage data based on documentation of forest damaging factors, temperature from GeoSphere Austria (2023); figure modified and updated from Hoch & Steyrer (2020).

Also, longer drought periods weaken the trees, especially if the forests are already not optimally adapted to the site conditions. A decrease of root reinforcement caused by beetle calamities, wind throws, wildfire, and delayed reforestation due to high population of game can be expected. However, these chains of effects are seen as multi hazard risks. Widespread loss of forest cover (due to windthrow, forest fire, pest infestation (bark beetle, fungal infestation (Hymenoscyphus fraxineus)) – may increase the risk potential for debris flow. Not directly, but through other impacts, like increased landslide activity and their possible influence on the bedload transport of torrents or the high proportion of woody debris (also due to rootstocks often remaining on the area after the clearing of forest stands).

Since 2017, windthrows have occurred frequently and very regularly in the Stubaital. In the border area between Fulpmes and Neustift, around 35 ha of forests were damaged by windthrow events on July 18, 2023. Around 20,000 m³ of damaged wood were caused by windthrow in the municipality of Neustift, affecting forest areas whose vitality had already been impaired by climate change. Windthrow scenarios that had never been recorded in this region with downdrafts of up to 240 km/h, indicate the already ongoing impact of climate change in the area.

The increase of windthrows support the mass reproduction of the large brown beetle (Hylobius abietis), as its larvae develop particularly well in the roots of dying conifers. This is additionally favoured by higher temperatures. The beetles cause extreme damage, especially in newly afforested conifers. Depending on possible source protection areas (in the pilot area approx. 200 ha are designated as such), often the only option is chemical control.

Furthermore, in the Stubaital, snow breakage occurs at higher altitudes than in the past due to newly very wet snow at higher altitudes. In 2018, oaks, which are heavily laden with snow in winter due to their foliage, have been heavily affected.

The high quantities of damaged timber in the pilot area also cause considerable economic losses due to higher harvesting costs and reduced timber price. If long-distance cable cranes must be used, the costs are currently almost €80 per cubic meter. Together with the costs for transporting the timber to stores or timber store or temporary disposal sites, the timber revenue that can be generated is already used up. If timber harvesting does not generate a profit, areas that are not (quickly) processed can contribute to an increase in the hazard potential for natural disasters.

Increased risk of forest fire, increased fire severity

Forest fires play a subordinate role in the Stubaital. Reforestation in these areas, especially on south-facing slopes is difficult, and may reduce the protective effects for long periods. The general risk of forest fires will increase due presumably more frequent, longer-lasting droughts (IPCC 2022).

Just after wildfires, the root reinforcement is usually still available (Gehring et al 2019), it decreases continuously in a period of several years. Hence, mitigation measures can be applied in time, however there will be a long-time span with reduced root reinforcement effects, even if reforestation is successful. In the pilot area, wildfires are not assumed to have significant impacts on torrential processes, also in the future.

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4. Wipptal, Italy

RISK QUESTIONNAIRE

WIPPTAL (IT)

October 2024

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

a) Past/present weather extremes

In the Stubaital/Wipptal pilot area the main weather extremes considered are heavy precipitation events, especially short-duration rainfall occurring during the summer period. In fact, South Tyrol precipitation maxima are more frequent in summer, when more convective processes occur and are particularly influenced by orographic effects. Such meteorological events are found to trigger several gravitational mass movements in the area, especially debris flow processes.

By analysing the annual and summer 1-day precipitation maxima over the last 40 years (1980-2022) based on available station observations in the area and close surroundings, an overall increase of precipitation intensity is found, especially for Wipptal, even though no trend is statistically significant. The trends in the annual frequency of 1-day precipitation extremes are positive at almost all sites up to + 14 % per decade with respect to the long-term averages. The greatest increases are reported in the eastern portion of the pilot area, where trends turn out to be statistically significant.

b) Potential future weather extremes

In the future, the intensity of 1-day precipitation maxima is projected to increase throughout the area with the magnitude of change depending on the level of global warming reached by the end of the century. The increases with respect to the current period (1991-2020) are almost similar in Stubaital and Wipptal and range between + 4 %, in the best-case scenarios, i.e., with a global warming limited to +1.5 °C or + 2 °C, and + 16 % under the worst-case scenarios, i.e., reaching + 3 °C or + 4 °C of warming.

In the future, the frequency of heavy precipitation is projected to increase throughout the area with the magnitude of change depending on the level of global warming reached by the end of the century. The increases with respect to the current period (1991-2020) range between + 6 % and + 46 % in Wipptal, and between + 3 % and + 23 % in Stubaital.

The projected changes in return levels of 1-day precipitation extremes corresponding to 10, 20, 50 and 100-year recurring intervals were also analysed for future 50-year periods corresponding to different global warming levels and compared to the current values (1971-2020). The intensity of 1-day precipitation extremes is projected to increase for all return periods and under all global warming levels in both Stubaital and Wipptal. As spatial average over each subregion, the projected increases of precipitation intensity for 20-year recurring event are in the range of + 5 % and + 15 % for Stubaital, depending on the warming level, while for Wipptal they are between + 4 % and + 18 %, under the worst-case scenario of a global warming of + 4 °C by the end of the century.

Sub-daily precipitation data was analysed by applying the Clausius-Clapeyron relationship to precipitation data from stations on wet days. Results indicate that the 99th percentile of hourly precipitation totals increase by 7.6% ± 1.1% per °C of warming (scaling between temperature and logarithm of precipitation). Historical data show that the Alpine space warms at roughly double the rate compared to the global mean near-surface temperature. Using Alpine space warming levels as twice the amount of global warming levels, and 1991 to 2020 as reference period, it yields increases, for the current 99th percentile, from 8.2 [mm/hour] to (11.0 ± 0.5) [mm/hour] for the Global Warming Level (GWL) 1.5°C. For GWL 2°C, (12.83 ± 0.86) [mm/hour], GWL 3°C (17.44 ± 1.99) [mm/hour], GWL 4°C (23.71 ± 3.81) [mm/hour] and for GWL 5°C (32.32 ± 6.7) [mm/hour].

II. Which hazard processes can be triggered by current and future weather extremes?

a) Past/present weather extremes

The Wipptal area is morphologically characterized by steep narrow lateral catchments merging into one main valley i.e., the Fleres valley. The major part of these lateral valleys is drained by streams and small rivers, which are the tributaries on the left or right side of the Fleres river. The steepness of the slopes and the shortness of the concentration time, together with the heavy short summer precipitation events, make the valley prone to mass movements such as debris flow.

Debris flows are usually triggered by an extreme rainfall event following an antecedent long duration precipitation, bringing soil to saturation [Armanini et al., 2006]. Debris flows commonly occurring in mountainous areas, such as the Wipptal area, concern especially small basins and their alluvial fans. Since debris flows are very local phenomena, their predictability is difficult and often their triggering is unexpected

In the past years, several debris flows have been registered in the regional events register ED30. In particular the focus pf this pilot area is a debris flow occurred on the 16th August 2021 on the Toverino river, a tributary of the Fleres river. This event was triggered by a heavy rainfall (summer storm) occurred in the afternoon of the 16th August, causing widespread erosion in all the Toverino catchment.

In the upper part of the Toverino basin, existing incisions were reactivated, with a mobilized debris mass of ca. 25000 m³ - 35000 m³ deposited on the plain meadows at an altitude of approx. 1580 m a.s.l. Further downstream, the flood wave eroded the slopes as well as the river bed, from an altitude of 1425 m a.s.l. up to the apex of the alluvial fan, at about 1200 m a.s.l.; the erosion rates reached depths of 2 - 2.5 m. According to estimates, between 35000 and 45000 m³ of debris were deposited on the fan of the Rio Toverino, and in addition also large quantities of timber were mobilized and transported by the river till the alluvial fan. Due to the huge amount of material deposited by the Toverino debris flow at the Fleres confluence, the Fleres river flooded on the left orographic side, causing damages to private buildings, agricultural land and infrastructures, roads, bridges and the hydroelectric plant.

This unexpected flood event is the result of the combination of multiple cascading impacts i.e., the debris flow on the Toverino river causing flood on the Fleres river, all triggered by the heavy precipitation event. The relationship between the different processes is explained qualitatively by the following hazard interaction matrix.

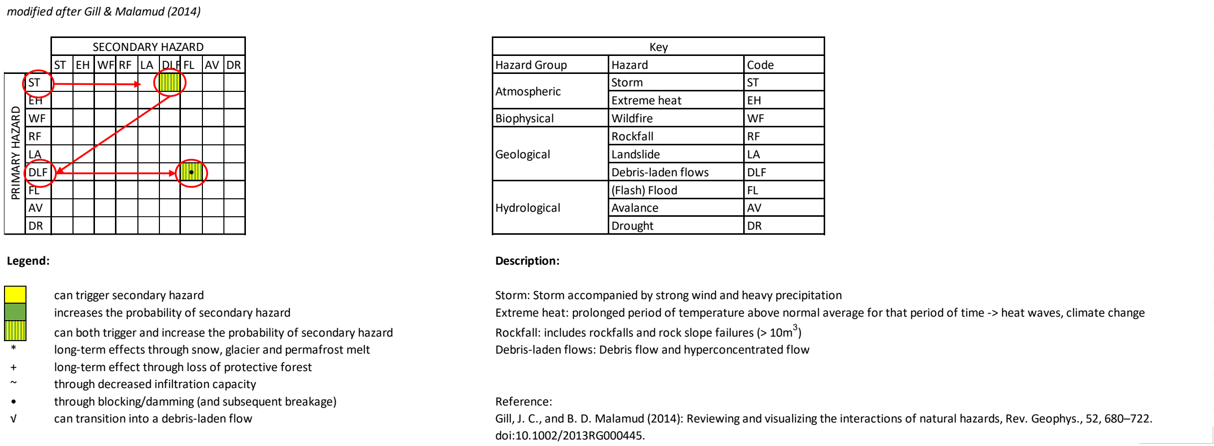

Figure 1: Hazard interaction matrix of the 16th August 2021 event.

Moving horizontally (first row of the table), it can be seen that the heavy rain event can both trigger and increase the probability of debris flow on the Toverino river. But the Toverino debris flow can also trigger and increase the probability of floodings on the main river (Fleres in this case) through the blocking/damming of the Fleres river.

b) Potential future weather extremes

It is clear that an intensification of precipitation extremes and an increase in their frequency can lead to a higher probability of hazardous processes in the next decades in the area. For instance, due to more frequent and intense triggering rainfall, also associated in mountainous areas with permafrost thaw due to warming (causing an increase in availability of solid material), debris flow and landslide events might become more frequent in the future or increase in their magnitude.

Following this consideration, the hazard interaction matrix for the future events might have the same feature of the one for the past, with some small modifications, as shown below.

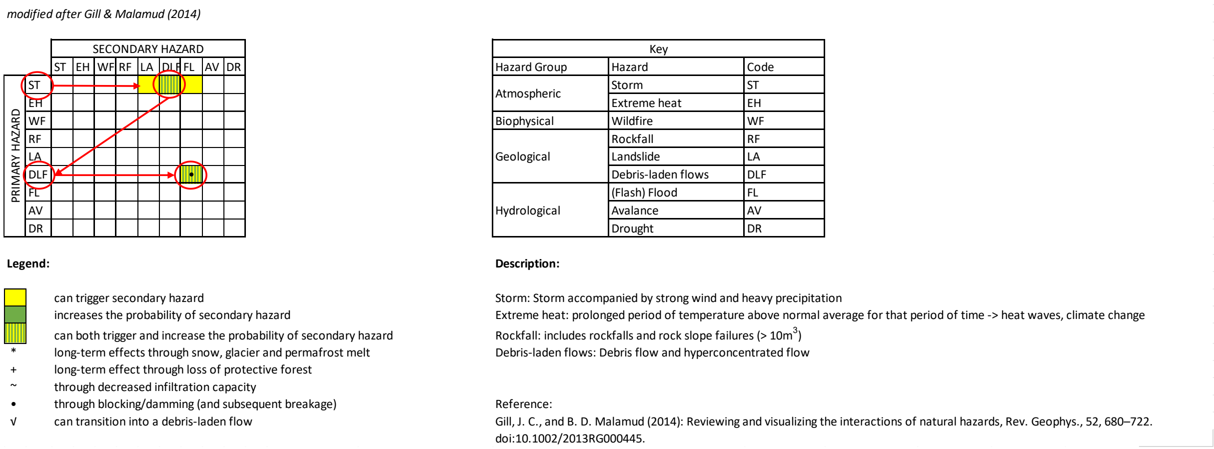

Figure 2: Hazard interaction matrix for the potential future weather extremes.

The matrix shows the same cascade of impacts of the past/present matrix. However, in the future the intensity of the summer storms is expected to increase, probably triggering not only debris flow, but also landslides on the slopes and floodings on the main river.

Sources

Armanini A., Fraccarollo L., and Larcher M. (2006). Debris Flow. In Encyclopedia of Hydrological Sciences (eds M.G. Anderson and J.J. McDonnell). https://doi.org/10.1002/0470848944.hsa149

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III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

a) Past/present frequencies and magnitudes

The available recordings of debris flow and flood events for all the South Tyrol region is contained in the ED30 register. The register contains flood, flash flood and debris flow occurrences since the XVIII Century; however, a systematic and complete registration of the events starts from year 2000.

In the period from 2000 to 2023 in the Wipptal area have occurred 66 events, from which the major part are debris flows happening mainly in the summer season (graph below).

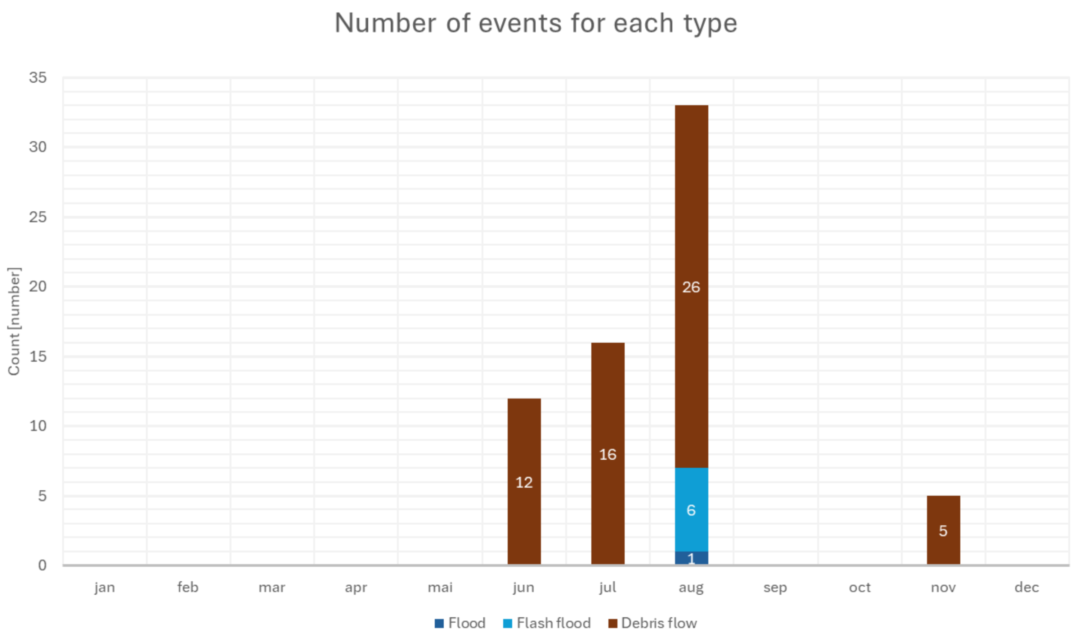

Figure 3: number of events for type and month in the pilot. Source: ED30 inventory, from year 2000 to 2023.

The ED30 register contains also an indication of the volume of deposited material, especially for mass movements like debris flow. Although this is only an estimation of the debris deposited volume based on the retention basins capacity and on the debris removed after the event, this data permit to group the events into the following magnitude classes:

1. Deposited volume between 0 and 1000 m^3;
2. Deposited volume between 1000 and 10 000 m^3;
3. Deposited volume between 10 000 and 50 000 m^3;
4. Deposited volume between 50 000 and 100 000 m^3.

The graph below shows the frequency of the different classes calculated as the number of registered events belonging to one class, divided by the years of observations i.e., 23 years for Wipptal.

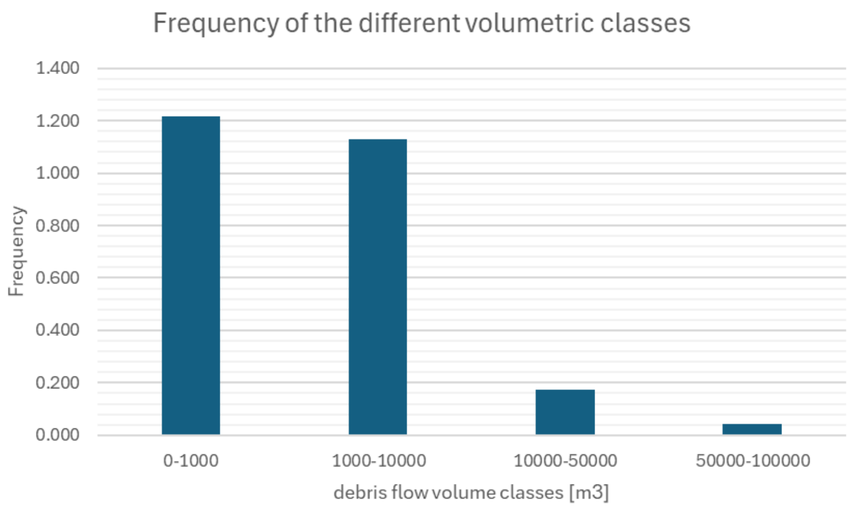

Figure 4: Calculated frequency of the different debris flow volumetric classes in the pilot area.

As shown in the plot, the most frequent events are the ones in the first two volumetric classes i.e., the debris flow events become “rarer” as their magnitude increases.

b) Potential future frequencies and magnitudes

Projected precipitation has been calculated from 11 EURO-CORDEX simulations and spatially adjusted for the Fleres station. Since the projected precipitation is on daily scale, a further temporal downscaling was needed [Simonovic et al., 2015].

In the following chapter will be analysed the impact of the projected precipitation on the Toverino river debris flow according to the scenario RCP 8.5, as “worst-case scenario”. We considered in particular the projection for the next 50 years i.e., from 2021 to 2070.

The Intensity Duration Frequency curves calculated for the Fleres station from observed sub daily maxima (1995-2020) and for projected data from RCP 8.5 (2021-2070) show an increase of the intensity and frequency of the maximum sub-daily precipitation, as represented in the figure below. We also compared the calculated curves with the IDF calculated from the projections for the end of the century (2051-2100).

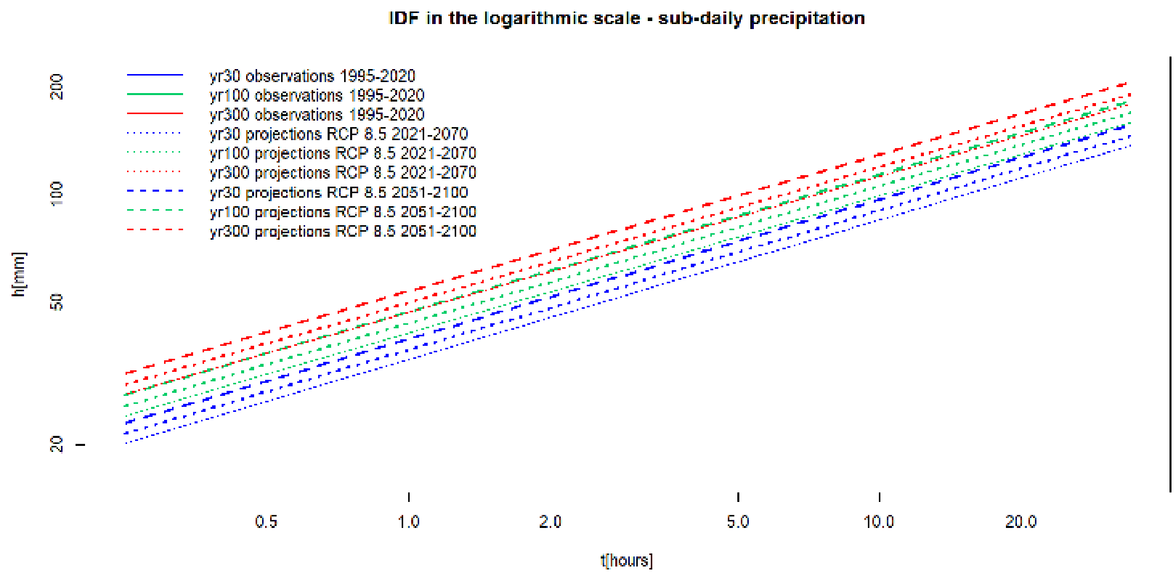

Figure 5: Intensity Duration Frequency curves for the observed and projected precipitation in the Fleres valley. Projections are calculated according to the RCP 8.5 scenario for the mid and end of the century.

The picture shows a shift upwards of the curves, meaning that given the recurrence interval, the expected precipitation height could be potentially higher i.e., climate change is expected to modify heavy precipitation intensity and its occurrence probability. For instance, the precipitation height corresponding to a 300-year recurrence interval in the observation period (red solid line), might become a 100-year recurrence interval precipitation at the end of the century (overlapping green dashed line).

This variation is then visible already in the mid-term period hydrograph, calculated with the software Peakflow [Bertoldi et al., 2009], represented in the next figure. The hydrographs show an amplification of the peak discharge and consequently a bigger runoff volume, which in turn has a potential effect on debris flow runout areas.

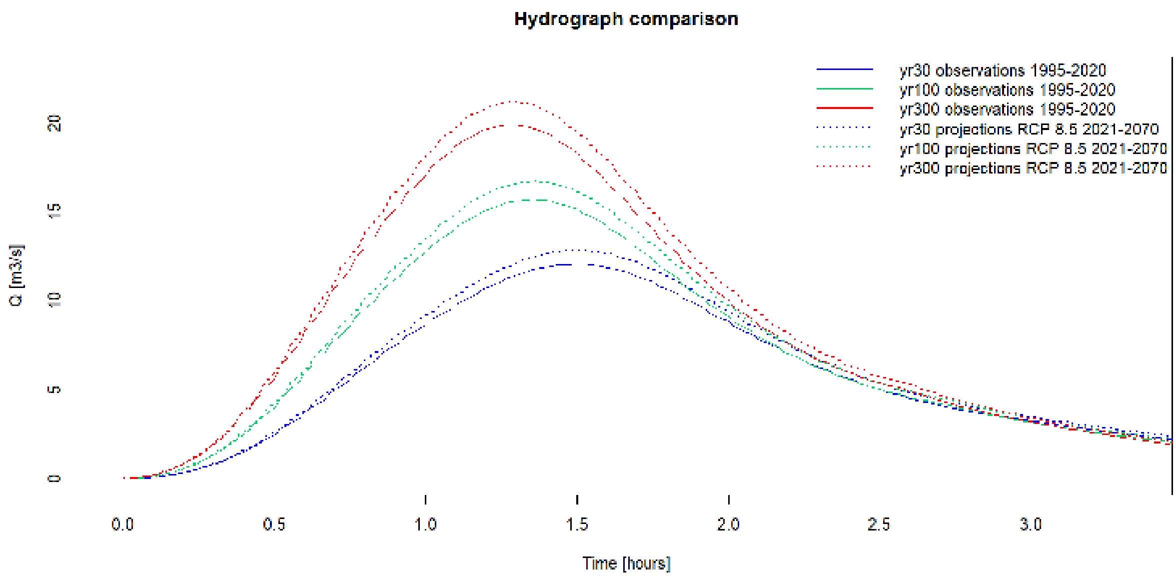

Figure 6: Hydrographs from observed data and projections for the scenario RCP 8.5 for the period 2021-2070.

The increase in peak discharge and runoff volume causes phenomena like the 16th August to become more intense and frequent i.e., increasing the runout area and the intensity of the phenomenon.

The debris flow simulation was done through the software WEEZARD [Rosatti et al.,2018]. The next figure shows an example of one of the results derived from the runout simulation of the Toverino river debris flow i.e., the deposition height.

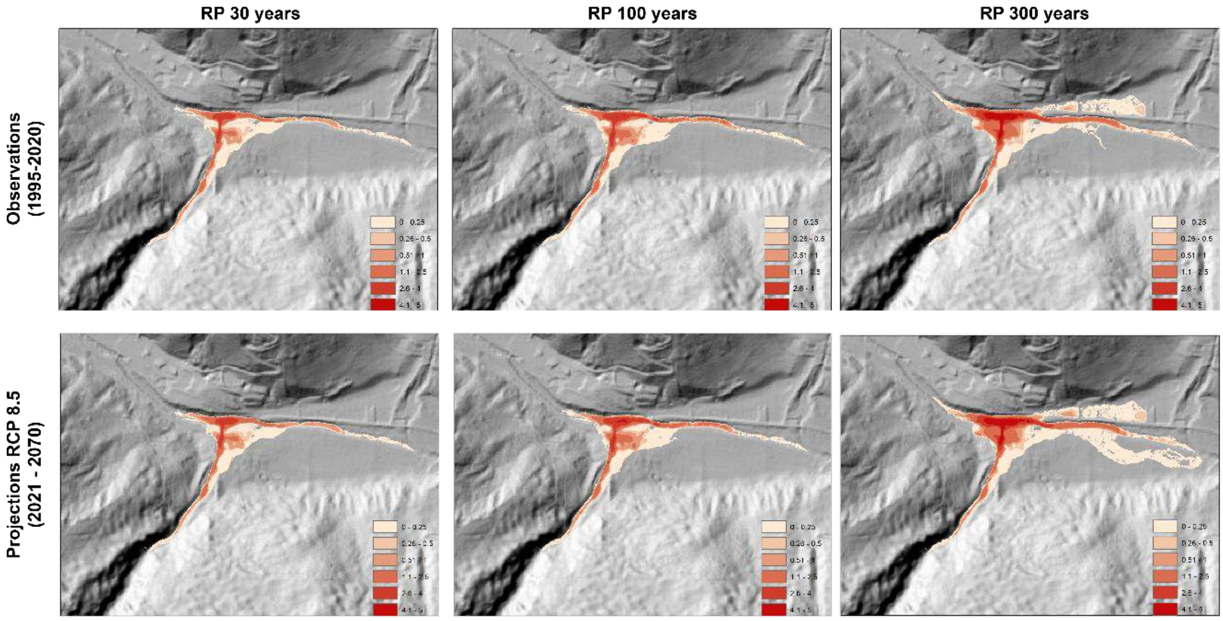

Figure 7: Simulated debris flow deposition height [meters] from observations and projections.

Comparing the pictures in the columns i.e., given the recurrence interval, the figure shows an increase of the deposition height and of the runout area. This intensification is more evident for the 300 years recurrence interval, while it is slightly evident for the 100 years recurrence interval and negligible for the 30 years.

Sources

Bertoldi G. Rigon R., D'Odorico P. The peak-flow and its geomorphic structure. 2009.

Giorgio Rosatti, Nadia Zorzi, Daniel Zugliani, Stefano Piffer, Alessandro Rizzi, A Web Service ecosystem for high-quality, cost-effective debris-flow hazard assessment, Environmental Modelling & Software, Volume 100, 2018, Pages 33- 47, ISSN 1364-8152, https://doi.org/10.1016/j.envsoft.2017.11.017.

Simonovic, S.P., A. Schardong, R. Srivastav, and D. Sandink (2015), IDF_CC Web-based Tool for Updating Intensity-Duration-Frequency Curves to Changing Climate – ver 7.0, Western University Facility for Intelligent Decision Support and Institute for Catastrophic Loss Reduction, open access https://www.idf-cc-uwo.ca.kk. DOI: 10.1016/j.envsoft.2016.03.016

ANALYSIS OF KEY RISK PATHWAYS

IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

The exposed elements map is part of the risk map (*Carta del Rischio*) created recently by the Autonomous Province of Bozen – Bolzano in compliance with the legislation at national and provincial level (see also question nr. VI). The identification of the elements at risk constitutes the **Potential Damage Map**, based on the municipal urban plan (i.e., a management plan at the municipality level where each land use class is regulated by a specific legislation) integrated with other territorial information. The map is created through the reclassification of the land-use classes identified by the urban plan, integrated and summarized in a single layer, that describes four potential damage classes, from E1 to E4.

- E0 - absent: comprehends water, natural areas, glaciers, meadows and pastures
- E1 - low: comprehends the agricultural land
- E2 - medium: comprehends ski slopes and secondary roads
- E3 - high: comprehends intensive agriculture, cycle-paths, railways, ski-slopes and cable cars, refuges and agricultural buildings, roads and main roads and industrial areas
- E4 – very high: comprehends residential areas, touristic infrastructures, city centres, industrial areas, sport infrastructures.

The following picture is an example of the expose elements map for the pilot area Wipptal.

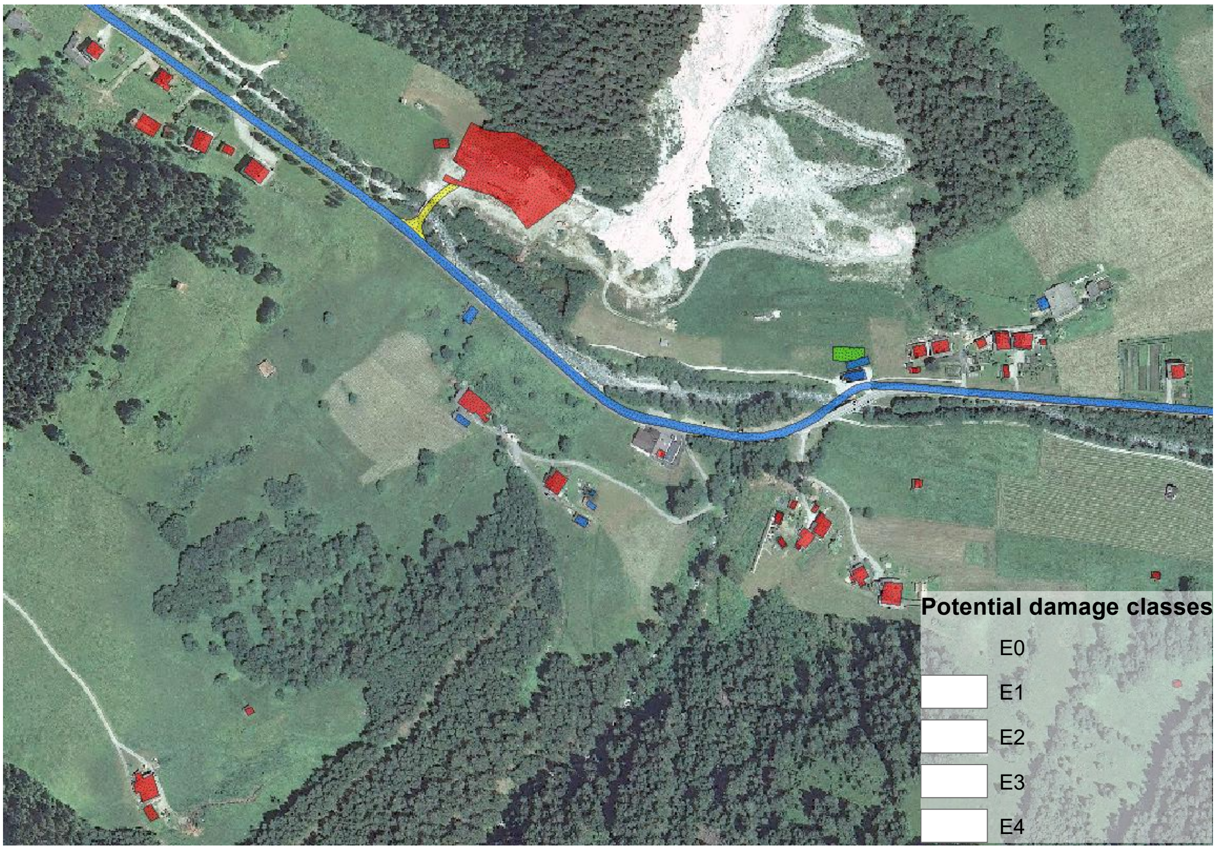

Figure 8: Extract of the Potential Damage Map for the Wipptal area.

a) Past/present exposure and impacts

The Wipptal area is an alpine valley characterized mainly by small villages alternated with agricultural areas at the bottom of the valley and managed meadows and pastures at higher altitudes. The valley is also touristic.

Therefore, the exposed elements are mainly related with private properties and buildings, agricultural land and infrastructures and touristic facilities, located in the valley, where also the floodings and the debris deposition take place during the most extreme events. In addition, all the infrastructures connecting them, such as roads, bridges and energy supply infrastructures, are key exposed elements, potentially causing indirect impacts to the other assets, if damaged.

The following exposure checklist lists the exposed assets which have been damaged during the 16th August heavy rainfall event. In the next chapters the directly and indirectly exposed elements will be analysed more in detail.

Exposure Checklist			Comment	Exposure							
				Relevance	Description of direct consequences	Description interactions with other exposure types and indirect consequences	affected assets	affected area/ length	asset value	affected population	affected tourists
Category	#	Type					[# / other]	[m²/ m]	[Mio. €]	[#]	[#]
Settlement	1.1	Private properties		☑	direct damages to private properties due to mud and deposited material		5				
	1.2	Healthcare and social facilities		☐							
	1.3	Tourism and accomodation		☐							
	1.4	Cultural property		☐							
	1.5	Educational facilities		☐							
	1.6	Administrative facilities		☐							
	1.7	Commercial facilities		☐							
	1.8	Industrial facilities		☐							
	1.9	Service		☐							
		...									
Environment	2.1	Natural environment		☐							
	2.2	Air		☐							
	2.3	Water bodies		☐							
		...		☐							
Mobility	3.1	Road infrastructure		☑	12 hours of road closed (main road and 3 access road)	isolated villages	1+3				
	3.2	Railway infrastructure		☐							
	3.3	Lifts		☐							
	3.4	Airports		☐							
	3.5	Bridges		☑			2				
Essential services	4.1	Energy		☑	power plant flooded	energy loss due to the direct damages to the power plant	1				
	4.2	Communication		☐							
	4.3	Potable water		☐							
	4.4	Waste water		☐							
	4.5	Waste		☐							
		...									
Public Safety	5.1	Protective structures		☐							
	5.2	Public safety organisations		☐							
	5.3	Public safety communication network		☐							
	5.4	Monitoring systems		☐							
		...									
Agriculture	6.1	Agricultural lands		☑	agricoltural land submerged by mud and deposited material			5260.91			
	6.2	Agricultural equipment		☐							
	6.2	Agricultural infrastructure (buildings)		☑	direct damages to agricoltural buildings due to mud and deposited material		5				
	6.3	(Cultivated) Forest		☐							
		...									
Mobile Assets	7.1	People		☑	☐	evacuated				30	
	7.2	Vehicles		☑	vehicles directly involved into the flow		4				
	7.3	Livestock									
	7.4	Wildlife		☐							
		...									

Figure 9: Exposure checklist for the 16th August 2021 event.

i. Directly exposed elements.

The directly exposed element are those elements which can be directly damaged by a flood, flash flood or mass movement. In the following chapter the exposed elements identified for the Wipptal area will be described. The spatial location of the different elements has been intersected in a GIS environment with the available hazard maps, to assess the presence/absence of the element in a hazard zone.

People. The Brenner municipality and the Fleres valley are residential areas. In general, the population data for the last 20 years show an increase of the number of people living steadily in the municipality area, as displayed by the graph below.

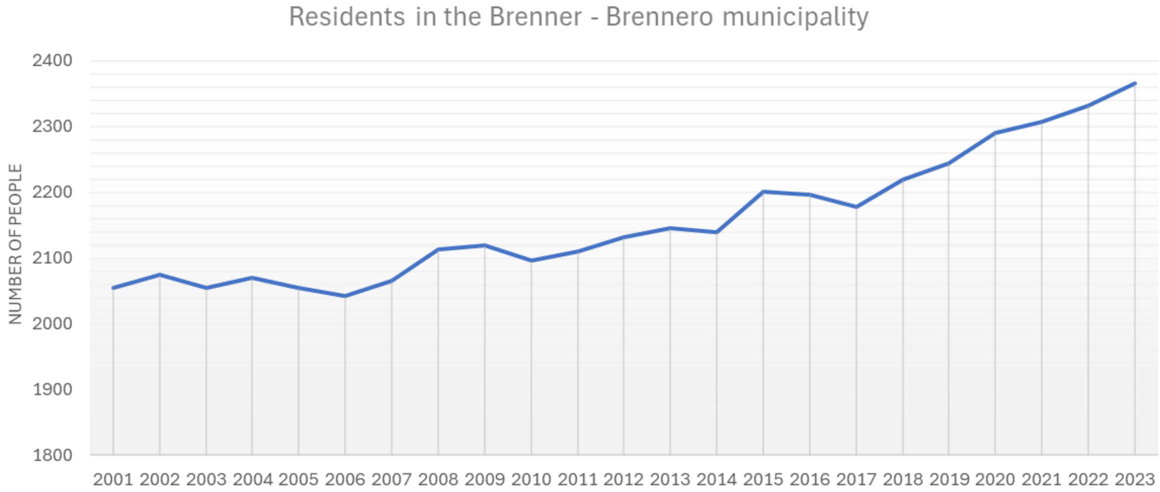

Figure 10: Residents in the Brenner - Brennero municipality from 2001 to 2023. Source: ASTAT data.

However, people are a mobile asset, since they can move differently according to their age, job and to the time of the day, therefore their real-time actual number is difficult to predict. In addition to residential people are tourists; in fact, the Brenner municipality, and especially the Fleres valley, are popular touristic destinations hosting every year hundreds of people. In the last 20 years the number of tourists visiting the Brenner municipality has been increasing, with no significant seasonal variation, as shown in the graph below.

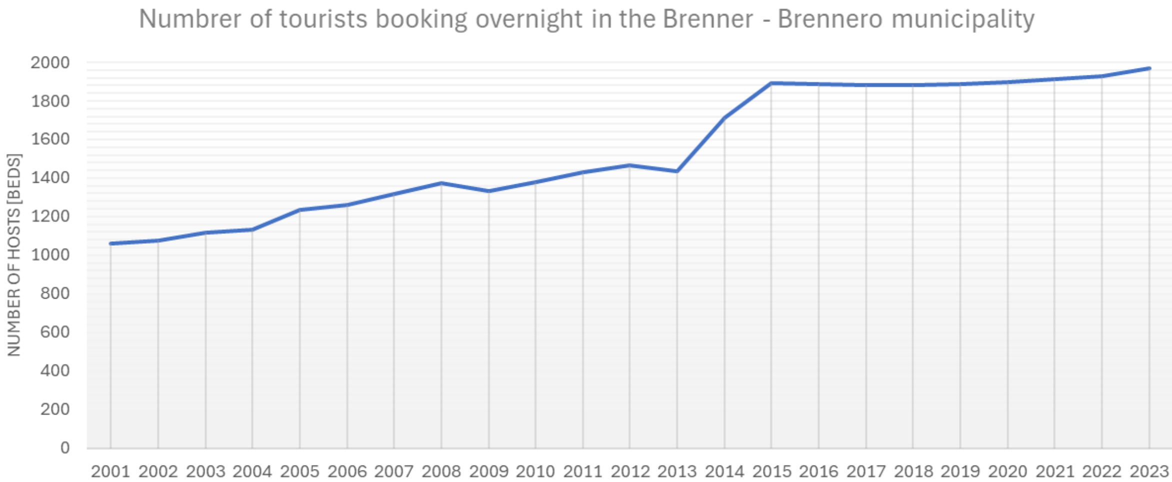

Figure 11: Number of tourists booking overnight in the Brenner - Brennero municipality from 2001 to 2023. Source: ASTAT data.

Comparing the number of tourists with the resident population, it can be seen that in the touristic seasons i.e., summer and winter, the population in the municipality doubles.

On the 16th August 2021 event 30 people have been quickly evacuated from the Fleres valley as precaution. [Alto Adige, 17th August 2021]

Vehicles. Like people, also vehicles are mobile and thus difficult to predict. On the 16th August 2021 event four vehicles have been directly involved and damaged by the debris flow.

Roads and bridges. Roads are fundamental connections among villages and between the mountain villages and the main cities. In the Fleres valley one main road, the LS/SP35, connects all the villages located in the valley; in addition, many secondary roads connect the sparse buildings (mountain farms) and further forestry roads and trails connect the pastures, managed meadows and forests. The total length of the road network in the Wipptal pilot area is about 264 kilometres, of which the 45% intersects at least one hazard area. In addition, 34 bridges permit to cross the main river, its tributaries or other roads. In the 16th August event the main road, blocked by the debris transported by the Toverino, remained closed for the cleaning operations, thus causing the isolation of the villages in the upper part of the valley.

Buildings. The total number of buildings in the Fleres valley is 630, which have been classified according to their main functions i.e., residential, agriculture, commerce and industrial. As shown by the graph below, the most abundant category is the one of the commercial and service buildings, which comprehends also the touristic facilities and the agricultural sales points.

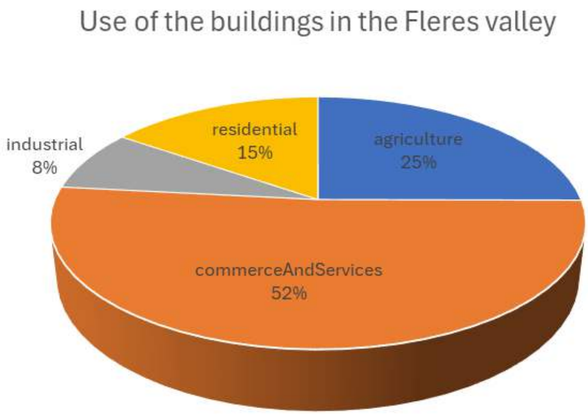

Figure 12: Percentages of use of the buildings in the pilot area.

Another important data is the number of buildings located inside and outside the hazard areas. As shown by the isogram at the end of the chapter, only the 32% of the buildings are in a “no hazard” area; this fact can be explained considering that most of the buildings in the valley have been constructed long time before the hazard plan approval, when the hydrogeological hazard and related risk was considered only basing on the past experience of presence/absence of phenomena. Moreover, due to the changing climate, also the hazards intensity and affected areas are changing, potentially involving areas that before where not considered hazardous. In the 16th August 2021 event 5 buildings have been directly damaged by the debris.

Infrastructures and energy supply. Infrastructures are located in the valley bottom to connect the villages and provide them the necessary water, energy and electricity supply. In total, about 50 kilometres of infrastructural lines are present in the Fleres valley, comprehensive of aqueducts, sewerages and high voltage lines. Moreover, in the valley are located 3 power plants, 4 public drinking water supply, 5 antennas and 12 water intakes. Most of these punctual and linear infrastructures are in a hazard area. In the 16th August event the power plant was directly damaged by the Toverino flooding and debris flow, with consequent interruption of electricity for some villages.

Touristic and free time infrastructures. About 7 hectares of the Fleres valley area are dedicated to touristic infrastructures and free time / sport infrastructures, frequented by locals and tourists. Most of these infrastructures are located in hazard areas, however the major part is settled in low hazard areas.

Agricultural land and infrastructures. The agricultural land comprehends many areas in the valley bottom, where the cultivations take place, as well as in the mountains, where pastures and managed meadows are located. The most exposed areas are those sited at the valley bottom and in proximity of steep slopes, the main river or its tributaries. These areas can be directly interested by the hazards, causing the loss of production and therefore economic damages to the owner. Moreover, about 70% of the livestock farms are located in hazard areas and consequently can be directly damaged by an event. The 16th August Toverino debris flow and flood involved 5260.91 square meters of agricultural land and 5 buildings dedicated to agriculture.

To conclude, the different exposed assets have been classified according to their location outside or within the hazard areas and according to the severity of the hazard. A summary of all the hazards (mass movements, hydraulic and avalanches) has been considered, giving to each asset the highest hazard class in case of overlapping hazard layers. The result is showed by the histogram below, displaying the percentages of the exposed assets located in the different hazard/no hazard areas.

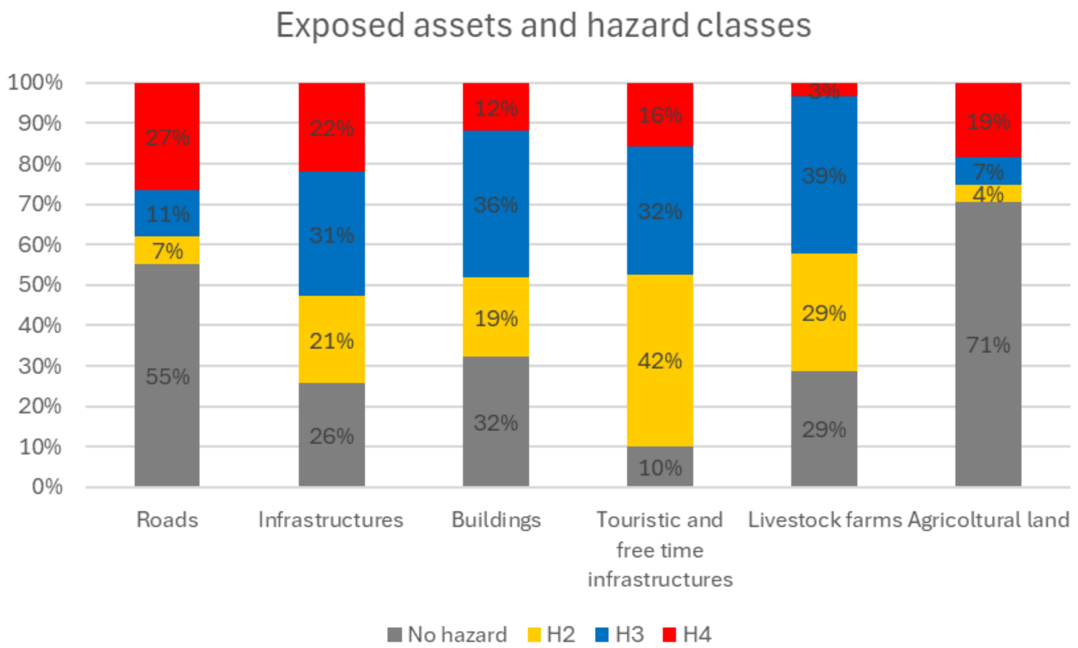

Figure 13: Percentages of exposed assets in the hazard / no hazard areas for the pilot Wipptal.

The graph shows that the major part of the buildings, infrastructures and livestock farms (about 70%) are located within hazard areas. This is true, considering that the buildings and infrastructures are mainly located in the valley bottom, where most of the hazards (especially hydraulic) occur. Differently, the other two categories, roads and agricultural areas, are more widespread in the study area.

ii. Indirectly exposed elements

The exposed elements listed in the previous chapter can be affected directly or indirectly by the different hazards. In the following paragraph the potential indirect consequences on the exposed elements are listed.

People and villages. People move from one point to another using roads connecting the different villages and the villages with the main cities. Therefore, if the main road is damaged or flooded, people are indirectly affected by the closure of the road for the cleaning operations and villages remain isolated. In the 16th August event 30 people were evacuated from their houses.

Tourism. The touristic sector can be indirectly affected in two ways:

- as consequence of the direct damages to the touristic host infrastructures such as hotels, private hosts and agritourism;
- as a consequence of direct damages to the road network and/or the hiking trails and paths.

In the second case the indirect effect lasts for shorter time i.e., some hours, than in the first case, where the cleaning and rebuilding operations could potentially last months.

Economic activities. Economic activities depend on the energy supply, therefore if the energy infrastructure or connection is damaged, also economic activities are affected, especially those related with livestock and food supply, which depend on energy for the cooling systems.

b) Potential future exposure and impacts

i. Directly exposed elements.

The municipal urban plan contains an indication of the areas dedicated to the development of new constructions, called “completion zones” and “expansion zones”. In Fleres valley 8 areas are designed for this scope with a total surface of about 7.5 hectares. As shown by the graph below, the new expansion areas are still located in hazard areas, but outside the H4 areas, since the local laws forbids new construction in those zones.

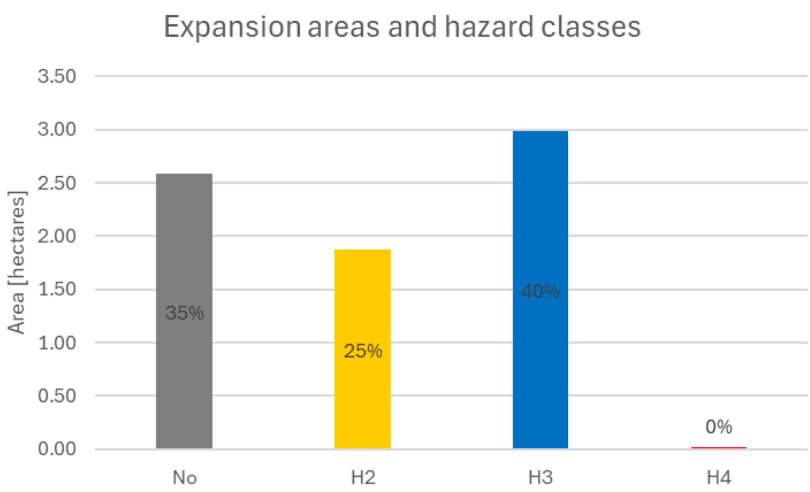

Figure 14: Percentages of expansion sites located into hazard/ no hazard areas.

The presence of a good portion of the new expansion sites in hazard areas can be explained by the fact, that the available space for new construction is limited, also considering the typical alpine valley morphology, with steep slopes and small valley bottom.

Up to now, the 95% of the new expansion and completion areas are built, thus only the 5% is still available and new areas have to be found if the trend of inhabitants continues to increase. Moreover, also the touristic sector in the valley shows an increasing trend, with consequent need for new host structures or an expansion of the existing ones. Considering the lack of new spaces, it is probable that for the touristic sector the existing structures will invest in bettering the quality of their services, with the scope of offering the tourists more qualitative experiences, instead of increasing the quantity of tourists. This could potentially lead to a flatten of the trend, or even a slight decrease.

Finally, an important future threat for the expansion areas is given by the potential intensification of the frequency and magnitude of the hazard events, and consequently of the affected areas, as shown in question number III)b. This is true, especially for those areas that currently fall in the hazard class H3 and which represent the 40% of the new expansion areas. In this case, if the hazard intensity increases, the hazard class of these areas can potentially become H4.

ii. Indirectly exposed elements

As shown in the previous question, the indirectly exposed elements are people (locals and tourists), villages and economic activities, which depend mainly on the direct potential damages to the road and energy supply infrastructures. The ASTAT data show an increasing trend of residents and tourists in the last 20 years, meaning that a bigger number of people can be potentially directly or indirectly affected by the intensification of hazard events.

Sources

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Landesinstitut für Statistik – Istituto provincial di statistica ASTAT
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Provincia Autonoma di Bolzano – Alto Adige. (2021). Report 2021 Pericoli naturali – Relazione riassuntiva Documentazione eventi.

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

a) Current vulnerability factors

The vulnerability depends on many factors, mainly related to physical and social aspects. The physical vulnerability i.e., the predisposing/preparatory factors, take into account for the specific features of the territory (i.e., morphology, presence/absence of forest, availability of sediments, glacier melt) and of the exposed asset (i.e., how buildings, roads and infrastructures are constructed, their age and maintenance status). It also considers the potential damage that the exposed assets can undertake, which in turn depends on the hazard type, intensity and duration. The social vulnerability i.e., the pre-impact vulnerability factors, depends mainly on people i.e., their age, their risk perception and preparedness, their education level and the level of communication with risk managers during the emergency phase.

The quantification of all these aspects is in general not trivial, and in the province of Bozen – Bolzano it has been done only in some specific cases [Kaswalder, 2009]. The threats for the determination of the vulnerability are many. For the physical vulnerability, the hazard intensity and duration can potentially change from time to time, as shown in the previous chapters, as well as the territorial specific features, like the presence of a protection forest or the availability of sediments in the upper parts of the catchments. Moreover, the value and the features of every single building change depending on the location and on the age of construction. A database indicating the shapes of the buildings is currently available, but their economic value and its changes in the future are difficult to forecast. Regarding the social vulnerability, it depends mainly on people's risk awareness and how fast the communication between people and risk managers is during the emergency phase. For these reasons in South Tyrol the **vulnerability is set always equal to 1**. The maximum value of the vulnerability permits to act on the other two components i.e., exposure and hazard, in a "worst case scenario".

The 16th August 2021 event in the Toverino river catchment highlighted some of the predisposing factors characterizing the Wipptal pilot area i.e., the availability of sediments in the upper part of the basin and the steep slopes with the deep channel incisions typical of such alpine valley territories. Other vulnerabilities, individuated in the Wipptal Impact Chain, are the absence of risk management practices dealing with multi-risks e.g., debris flow causing further flood, in the response phase as well as in the prevention phase i.e., protection structures and planning instruments. For example, the existing hazard maps are not considering certain scenarios e.g., river blockage and flood waves, resulting from the compoundnes of two or more hazards or from the unexpected increased intensity and/or frequency of one or more hazard.

b) Potential future vulnerability factors

From a practical point of view, the vulnerability is set to the maximum value i.e., 1, for all the province, therefore its value is not expected to change in the future, unless the calculation procedure changes.

The change in the predisposing factors depends instead on how the land use and the territory evolves e.g., glacier melt or a landslide in the upper part of a catchment can lead to more availability of sediments, and a better forest management could lead to less death-wood in the channels.

The risk management is showing some changes, such as a growing attention towards compound and cascading events, the consciousness about hazard increase in intensity and frequency with future climatic changes and a general increase in people risk awareness. All these elements can contribute to lower the vulnerability factor.

Sources

Kaswalder C. 2009. Schätzungsstudie zur Berechnung des Schadenspotentials bei Hochwasserereignissen durch die Rienz im Abschnitt Bruneck - St. Lorenzen / Studio estimativo ai fini della determinazione del potenziale danno a causa di eventi alluvionali lungo la Rienza, nel tratto Brunico S. Lorenzo. Autonome Provinz Bozen – SüdtirolAbteilung, 30. Wasserschutzbauten, Amt für Wildbach- und Lawinenverbauung Ost / Provincia Autonoma di Bolzano-Alto Adige, Ripartizione 30. Opere idrauliche, Ufficio Sistemazione bacini montani est.

X-RISK-CC project Impact Chain

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

a) Current risk management measures

In the following chapter, the risk management measures will be described according to the four risk management phases i.e., prevention, preparedness, response and recovery.

Prevention measures

Prevention measures are structural and non-structural. Regarding the structural prevention, a total of 317 protection structures are distributed in all the Wipptal area, specifically 185 structures protect against hydraulic hazards, 103 against avalanches and 29 against rockfall. The following graph shows the type of protection structures.

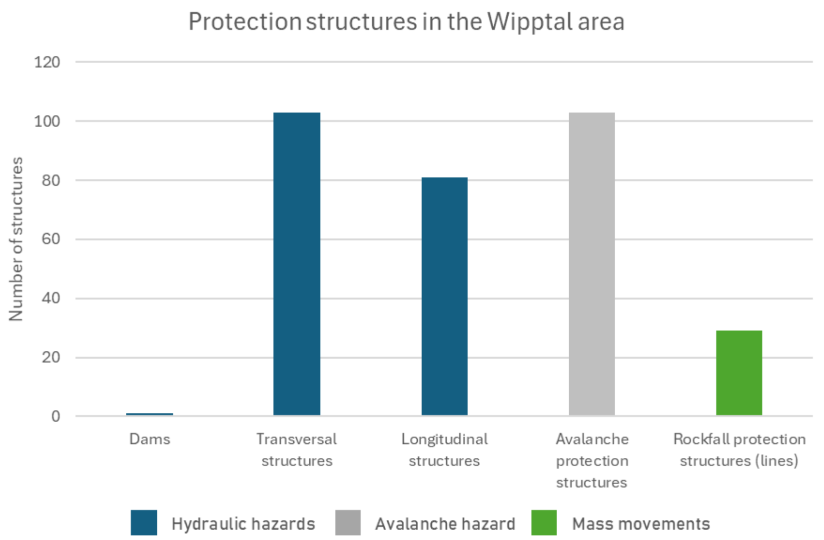

Figure 15: Protection structures for the different types of hazards in the Wipptal area.

The most numerous protection structures are those against hydraulic risk. One possible explanation of this fact is that, among the exposed elements, agricultural land, especially the one connected with industrial activities, is the one with the biggest hydraulic hazard affected area. Therefore, protection structures are built for water management and to protect economic activities and related infrastructures against water-related damages.

The non-structural prevention is done mainly with the planning instruments like the **Hazard Zone Plan,** which analyzes the most relevant hydrogeological hazards (mass movements, hydraulic hazards and avalanches) on municipality level, producing hazard maps and reports. The hazard plan contains specific planning legislation depending on the hazard type and intensity (H2, H3, H4) e.g., building new constructions is forbidden in the H4 red-zone areas.

Preparedness measures

Recently, the Autonomous Province of Bozen – Bolzano created a **Risk Map** in application of the legislation at national and provincial level. The Risk Map aims most of all to protect existing exposed elements and only secondarily at an evaluation in the planning phase. In this way, it proposes priorities of protection to the municipalities and risk managers. Since the position and type of elements at risk varies with the urban development of the territory, the Risk Map "photographs" the situation at the time of drafting the map itself, and must therefore be continuously updated. For this reason, this map is not a planning tool in the strict sense, but more an "indicator for mitigation measures" in the sense of passive, non-structural interventions (urban planning, civil protection plans, etc.) and /or active, structural interventions.

Response phase

The **Civil Protection Plan**, designed during the prevention phase, is the instrument that permits to deal with the emergencies and to protect people, goods and services present in an area affected by disasters, that may derive from one or more residual risks. Every municipality in South Tyrol has a tailored civil protection plan, with clear and direct instructions to organize the knowledge, the resources and the procedures used to deal with the various critical situations, that potentially arise on the municipal territory.
Moreover, different association of volunteers, such as fire fighters, red and white cross and mountain rescue act directly and immediately on the affected territory, securing the impacted area and providing basic supply to the people or evacuating them if necessary.

Recovery phase

The Autonomous Province of Bozen – Bolzano allocated different funds and facilities to support the reconstruction in the recovery phase after an extreme event. Every fund is provided by the specific reference office, e.g., funds related to agriculture are allocated by the Agricultural service. The different funds have also different targets of interventions and specific receivers e.g., municipalities, public associations, private citizens and farmers.

To conclude, the following table summarizes the results of the Rapid Risk Management Appraisal 1st workshop involving the main actors of the risk management in the Vaia pilot area. The positive aspects and the gaps for each of the four phases are highlighted.

	Positive aspects	Gaps
Structural prevention	• good communication between office for torrent control and population	• acceptance of measures by population is critical if private land is therefore needed
Non-structural prevention		• the guidelines for the hazard maps do currently not demand the consideration of complex scenarios; • buildings are built too close to rivers; • acceptance of non-structural measures by population should be enhanced and improved; • hazard maps and civil protection plans do not contain the same scenarios
Preparedness tools	• weather forecast was accurate; • civil protection notification was communicated; • population was warned about forecasted thunderstorms via press	• nowcasting should be developed

Preparedness tool implementation	• excavators were already placed in the valley in expectation of strong thunderstorms (warning); thus, the warning led to preparedness of firefighters	• need for improvement of communication of uncertainties and awareness for natural hazards among population; • procedure for generation of BIS notifications needs to be improved; • need for better definition of what actions should follow after warnings; • critical spots (e.g. bridges) need to be identified and monitored; for monitoring collaboration of different stakeholders is needed
Response tools	• firefighters were quickly on site;	
Response tool implementation	• all involved people put great effort into response and recovery	• communication between locals (e.g. firefighters and municipality) and the provincial offices should be improved (e.g. procedure for civil protection notification)
Structural recovery	• new protection measures planned considering hazard map and the scenario that occurred at the event; • new protection measures built quickly	• system transparency is missing regarding the reconstruction of private buildings --> public contact point would be helpful; • better regulation for special cases such as relocation of buildings, designated landfill areas to deposit the debris flow material should be defined; • need for overall consideration of catchment area in planning of recovery measures
Recovery learning organizations		• a meeting of all involved organizations should be held to define in detail the recovery procedure

Figure 16: Summary of the RRMA 1st workshop results.

b) (Potential) future risk management measures

It is important that future risk management in the Wipptal area takes into account several aspects. Most of all the potential increase of intensity and frequency of hazards (as presented in question number III) should be considered, but also the activation of new processes derived by the modification of the territory upstream (e.g., permafrost melting, increased availability of sediments) or from the compoundness of more different hazards.

Sources

Hazard browser, Autonomous Province of Bozen – Bolzano (https://maps.civis.bz.it/?context=PROV-BZ-HAZARD)

https://pericoli-naturali.provincia.bz.it/it/contributi-e-agevolazioni-in-seguito-a-eventi-calamitosi

Maltempo in Alto Adige: 200 interventi dei pompieri in una notte. 17th August 2021, Alto Adige.

RRMA results of the 1st workshop

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

The 16th August event on the Toverino and Fleres rivers is a concatenation of cascading impacts i.e., the debris flow produced by the Toverino causing the blockage and subsequent flooding of the Fleres river. Due to the combination of the two phenomena, the affected area was different from the one defined by the hazard map for the single phenomena, and therefore unexpected impacts occurred. In fact, the current hazard plan and map do not consider such complex scenarios, made of two or more compound/cascading hazards.

In South Tyrol the procedure for designing the hazard plan is made of a very detailed analysis, which studies all the rivers and tributaries of a municipality also using dynamic simulations for specific cases, such as bridge blockage. However, hazard plans consider only one single phenomena at a time, thus not studying the potential effect of the compoundness of two or more impacts, or the possible cascading effects of one impact. In general hazard plans have a strong connection with the urban plan legislation, putting strong limitation on the construction areas and design of the buildings and infrastructures, but since the potential damage of compound and cascading hazards is not considered, construction is permitted where potential compound / cascading hazard can occur.

b) Potential future impacts of compound/cascading hazard events

In the next years extreme precipitation is expected to increase in intensity and frequency, and therefore compound/cascading hazards will be potentially more intense. Predicting the occurrence of such complex events and the potential cascading impacts of the tributaries on the main river is still challenging, because it depends on sediment production and river connectivity.

In general, compound/cascading events make more damages than a single event, because they are complex phenomena, in which different hazards combine together amplifying their impacts.

5. Val d’Ega/Carezza, Italy

RISK QUESTIONNAIRE

Carezza/Ega Valleys (South Tyrol, IT) October 2024

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

a) Past/present weather extremes

In the pilot area, the main weather extremes considered are precipitation and wind. These elements, when combined, can lead to a variety of hazards, especially in a mountainous area with complex terrain and high density of forest coverage. In the short term, precipitation and wind extremes can lead to fallen trees, flooding and gravitational mass movements, such as debris flows. Over time, cascading effects can follow, such as higher slope instability due to reduction of forest coverage, or enhanced forest damage due to the proliferation of parasites on fallen or weakened trees during subsequent favourable conditions, e.g. during heatwaves and persistent high-temperature periods.

The intensity of heavy precipitation in Trentino – South Tyrol exhibits distinctive spatial patterns in both magnitude and seasonality. The most intense precipitation events occur in Trentino and central part of South Tyrol. In Trentino, the annual maxima of precipitation occur mostly in the autumn, probably due to a higher exposure to moist air masses from the Mediterranean Sea, while in South Tyrol precipitation maxima are more frequent in summer, when more convective processes occur and are particularly influenced by orographic effects.

In the last decades, the intensity of heavy precipitation has increased throughout the region, with the most significant trends in South Tyrol being in the order of + 5 % per decade (with respect to average heavy precipitation intensity over reference period 1991-2020). In particular, the intensity has increased in summer and autumn, which are the seasons when heavy precipitation occurs most frequently in the region.

b) Potential future weather extremes

In the future, overall increases in the intensity and frequency of extreme events are expected to occur in Trentino – South Tyrol, including the pilot area considered for the Vaia event analysis. The intensity of 1-day precipitation extreme is projected to increase in the pilot area between + 3 % and + 18 % compared to the period 1991-2020, depending on the global warming level reached, or, in other terms, depending on the effectiveness of mitigation actions. 1-day precipitation extremes could become more frequent: on a regional scale, a Vaia-like precipitation event is expected to halve its return period under the worst-case scenarios, i.e. if the global warming will exceed + 3 °C or + 4 °C by the end of the century.

No remarkable changes are projected for the intensity and frequency of wind speed extremes in the future over the region. However, due to the overall intensification of precipitation extremes, the probability of a compound occurrence of high precipitation and wind speed conditions can increase throughout the region in the future years.

II. Which hazard processes can be triggered by current and future weather extremes?

a) Past/present weather extremes

The Vaia storm happened in two different phases, distributed over three days i.e., from the 27th to the 30th October 2018, with exceptional precipitation registered in all the province and especially strong wind. One of the main impacts of the Vaia storm was the huge windthrown forested area, with direct and indirect consequences also on the other hazards. The following hazard interaction matrix explains qualitatively the relationship between the different processes.

modified after Gill & Malamud (2014)

		SECONDARY HAZARD								
		ST	EH	WF	RF	LA	DLF	FL	AV	DR
PRIMARY HAZARD	ST				+	+ ~	+ ~	+ ~	+	
	EH									
	WF									
	RF									
	LA									
	DLF									
	FL									
	AV									
	DR									

Key		
Hazard Group	Hazard	Code
Atmospheric	Storm	ST
	Extreme heat	EH
Biophysical	Wildfire	WF
Geological	Rockfall	RF
	Landslide	LA
	Debris-laden flows	DLF
Hydrological	(Flash) Flood	FL
	Avalance	AV
	Drought	DR

Legend:

can trigger secondary hazard
increases the probability of secondary hazard
can both trigger and increase the probability of secondary hazard
* long-term effects through snow, glacier and permafrost melt
+ long-term effect through loss of protective forest
~ through decreased infiltration capacity
• through blocking/damming (and subsequent breakage)
√ can transition into a debris-laden flow

Description:

Storm: Storm accompanied by strong wind and heavy precipitation
Extreme heat: prolonged period of temperature above normal average for that period of time -> heat waves, climate change
Rockfall: includes rockfalls and rock slope failures (> 10m^3)
Debris-laden flows: Debris flow and hyperconcentrated flow

Reference:
Gill, J. C., and B. D. Malamud (2014): Reviewing and visualizing the interactions of natural hazards, Rev. Geophys., 52, 680–722. doi:10.1002/2013RG000445.

Figure 1: Hazard interaction matrix of the Vaia event.

Moving horizontally (first row of the table), the matrix shows that the storm event increased the probability of some secondary hazards such as landslides, rockfall, debris flow, floodings and avalanches. Part of these impacts occurred during the event or right after, due to the heavy rainfall (see also next chapter); another part increased its probability of occurrence in the long term, due to the loss of protective forest and the decreased infiltration capacity. Moreover, the damaged forest created the habitat for the spread of parasites like the bark beetle, triggered by a heatwave in the long term.

b) Potential future weather extremes

It is clear that an intensification of precipitation extremes and an increase in their frequency can lead to a higher probability of hazardous processes in the next decades in the area. However, since no data or very little time series are available for the wind, make a clear forecast is challenging. On the other side, the extreme precipitation is expected to increase, therefore Vaia – like events can potentially become more frequent.

Following this consideration, the hazard interaction matrix for the future events might have the same feature of the one for the past, as shown below.

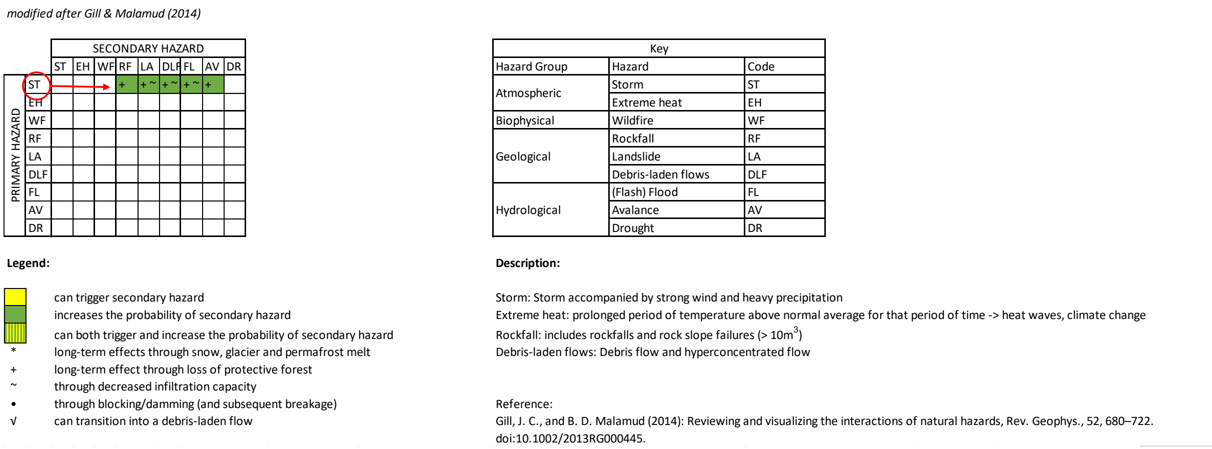

Figure 2: Hazard interaction matrix for the potential future weather extremes.

Also the secondary effects are expected to change: in the closest future i.e., the next 10-20 years without forest, the probability of the secondary hazards is expected to increase, while the windthrown hazard is almost absent, due to the absence of the forest. In a second time, when the protective forest is grown and has resumed its functionality, the probability of all the secondary hazards will decrease.

Sources

Amt für Meteorologie und Lawinenwarnung / Ufficio meteorologia e prevenzione valanghe – Autonome Provinz Bozen / Provincia Autonoma di Bolzano. 2018. TiefTief „Vaia“ sorgt für Hochwasser und Sturm / La depressione “Vaia” provoca piene e venti estremamente forti 27.-30.10.2018. Clima Report Extra Südtirol - Alto Adige, n. E14.

Geokatalog, Autonomous Province of Bozen – Bolzano
http://geokatalog.buergernetz.bz.it/geokatalog/#

Hazard browser, Autonomous Province of Bozen – Bolzano (https://maps.civis.bz.it/?context=PROV-BZ-HAZARD)

III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

a) Past/present frequencies and magnitudes

The pilot area Vaia has been characterized since the past by different types of hazards, which have been progressively registered since the XVIII Century, even if a systematic and complete registration of the events starts from year 2000. Every type of phenomenon is recorded in specific registers:

- ED30 for water related hazards i.e., floods, flash floods and debris flows;
- IFFI for the mass movements i.e., landslides and rockfalls;
- LAKA for the avalanches

In the period from 2000 to 2023 in the pilot area have occurred over 400 different events, as shown by the graph below. The municipality that experienced the major number of events is Deutschnofen, which is the biggest.

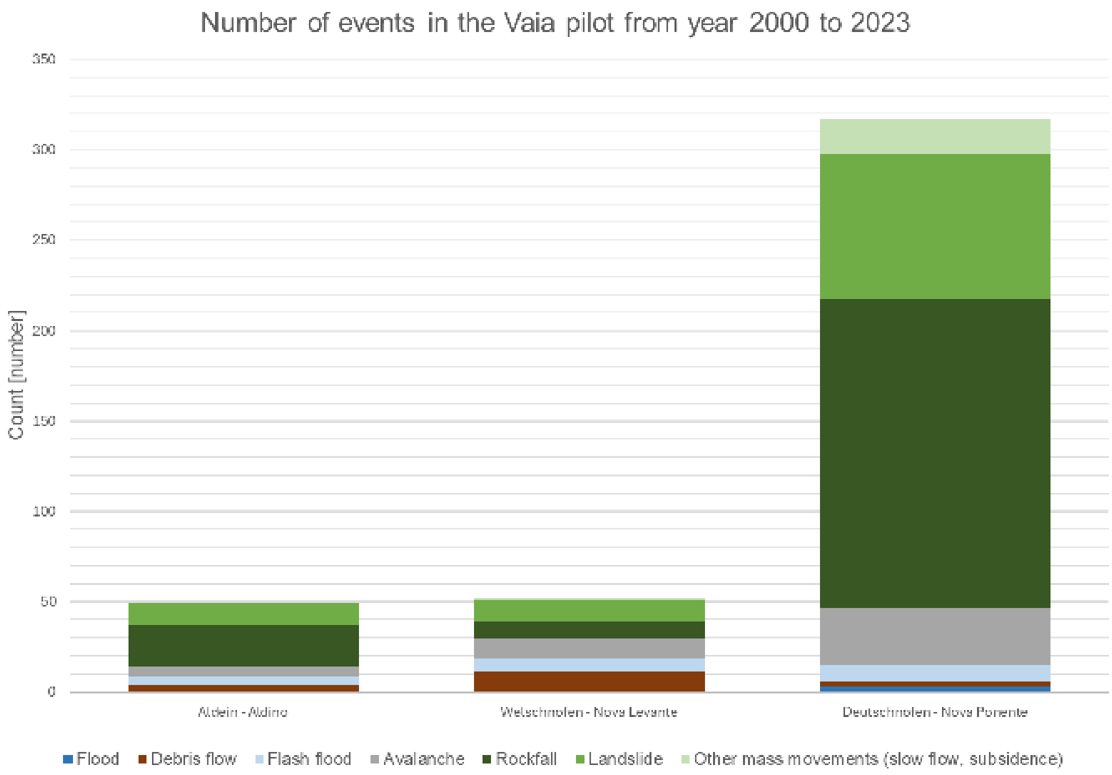

Figure 3: count of snow hazards [source: LAKA inventory], hydraulic hazards [source: ED30 inventory] and mass movements [source: IFFI inventory] in the Vaia pilot area from year 2000 to 2023.

Up to now, there is no database or information about windthrown areas before 2018. This highlights the **unexpected and unique character of the Vaia storm**, which most of all caused the windthrown of several hectares of forest.

Moreover, during the three days, from the 27th October and the 30th October 2018, in the pilot area were registered 11 flash floods, 1 debris flow, 10 landslides/fast flows, and 6 rockfalls/topples. Despite the fact that these phenomena caused several damages in all the municipalities, their magnitude was minor compared to the other phenomena happened in the region in the last 20 years. As an example, the flash floods occurred during the Vaia storm have been compared with those registered during the last 20 years in the ED30 register. The ED30 register contains also an indication of the volume of deposited material. Although this is only an estimation of the debris deposited volume based on the retention basins capacity and on the material removed after the event, this data permit to group the events into the following magnitude classes:

1. Deposited volume between 0 and 1000 m3;
2. Deposited volume between 1000 and 10 000 m3;
3. Deposited volume between 10 000 and 50 000 m3;
4. Deposited volume between 50 000 and 100 000 m3.

The graph below shows the frequency of the different classes calculated as the number of registered events belonging to one class, divided by the years of observations i.e., 21 years. The frequency of the events occurred during Vaia is highlighted in red; the graph shows that the flash floods occurred during Vaia belong to the smallest volumetric class.

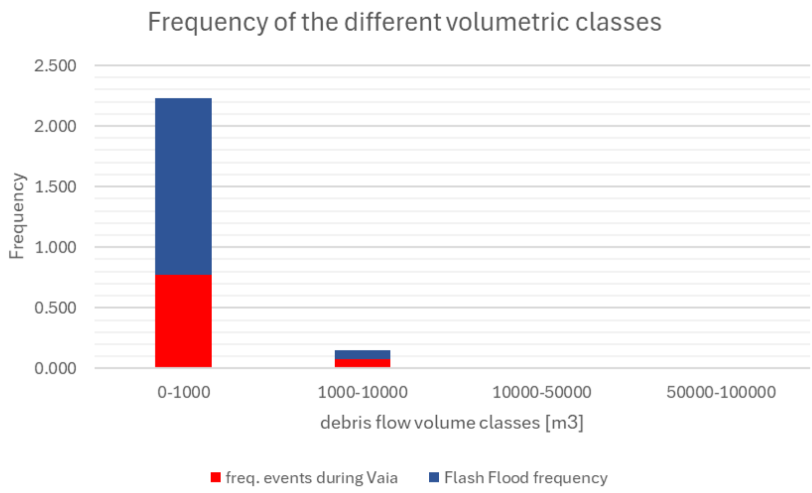

Figure 4: Calculated frequency of the different debris flow volumetric classes in the pilot area. In evidence (red) the frequencies of the events occurred during the Vaia storm.

b) Potential future frequencies and magnitudes

As highlighted in question 1b), no remarkable changes are projected for the intensity and frequency of wind speed extremes in the future over the region. However, due to the overall intensification of precipitation extremes, the probability of a compound occurrence of high precipitation and wind speed conditions can increase throughout the region in the future years. This means a potential intensification of the frequencies and intensities of the hydraulic and mass movement hazards in general. Specifically, the areas which lost the protective forest will be affected.

ANALYSIS OF KEY RISK PATHWAYS

IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

The exposed elements map is part of the risk map (*Carta del Rischio*) created recently by the Autonomous Province of Bozen – Bolzano in compliance with the legislation at national and provincial level (see also question nr. VI). The identification of the elements at risk constitutes the **Potential Damage Map**, based on the municipal urban plan (i.e., a management plan at the municipality level where each land use class is regulated by a specific legislation) integrated with other territorial information. The map is created through the reclassification of the land-use classes identified by the urban plan, integrated and summarized in a single layer, that describes four potential damage classes, from E1 to E4.

- E0 - absent: comprehends water, natural areas, glaciers, meadows and pastures
- E1 - low: comprehends the agricultural land
- E2 - medium: comprehends ski slopes and secondary roads
- E3 - high: comprehends intensive agriculture, cycle-paths, railways, ski-slopes and cable cars, refuges and agricultural buildings, roads and main roads and industrial areas

- E4 – very high: comprehends residential areas, touristic infrastructures, city centres, industrial areas, sport infrastructures.

The following picture is an example of the exposed elements map for the village of Welschnofen - Nova Levante.

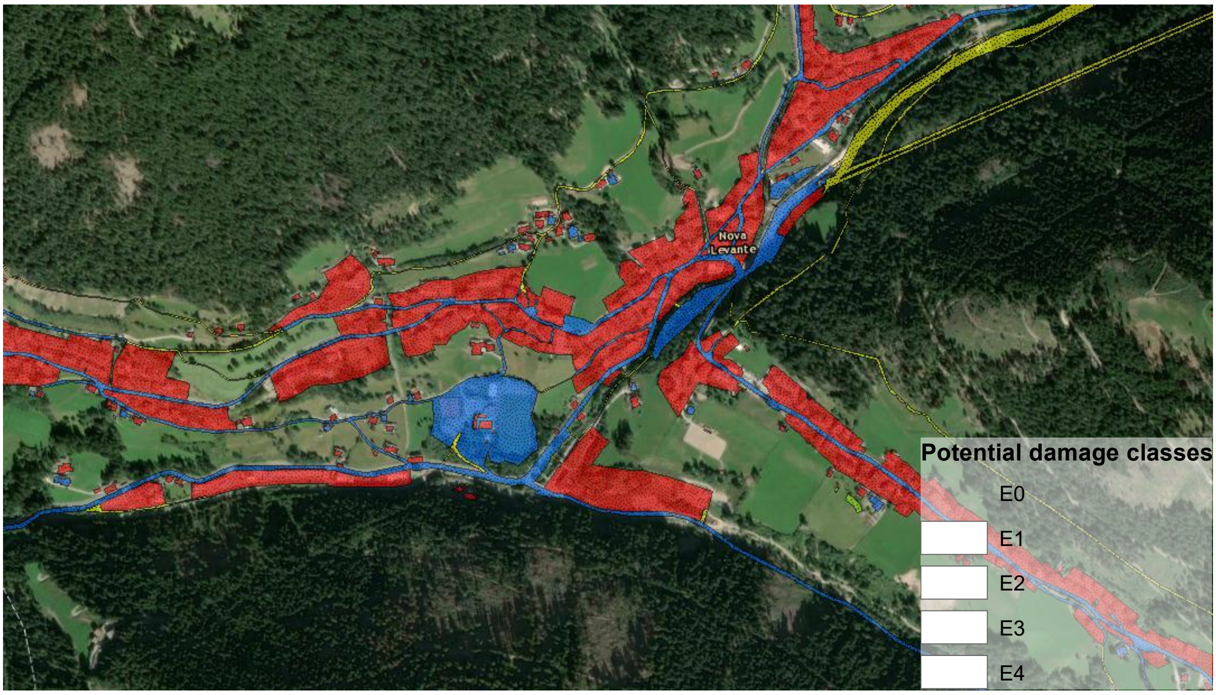

Figure 5: Extract of the Potential Damage Map for the village of Welschnofen - Nova Levante.

a) Past/present exposure and impacts

The Vaia pilot area comprehends three municipalities located in a mountainous area, characterized by small villages alternated with agricultural land, forests and pastures. The area is also a well-known touristic destination in winter as well as in the summer period, with the municipality of Welschnofen – Nova Levante hosting the major part of touristic infrastructures and ski slopes.

Therefore, the exposed elements are mainly related with private properties and buildings, agricultural land and infrastructures and touristic facilities. In addition, all the infrastructures connecting them, such as roads, bridges and energy supply infrastructures, are key exposed elements, potentially causing indirect impacts to the other assets, if damaged. The following graph summarizes the damages caused by the Vaia storm [Report pericoli naturali 2018]: no impacts have been reported on buildings and people, but some roads and infrastructures were damaged by floods, debris flows and mass movements. No avalanches have been registered.

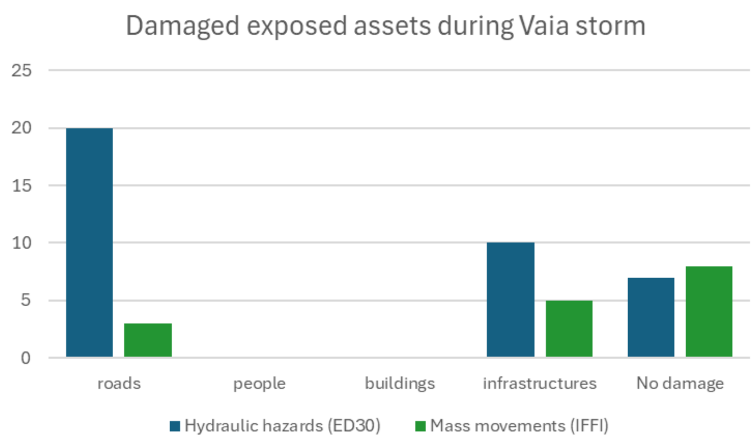

Figure 6: Damages for hazard type during the Vaia storm. Source: ED30 inventory.

Moreover, between the 70% and 75% of the municipalities area is covered by forest, which plays an important role for the related economic activities and for the protection against other hazards. During the Vaia storm, about 25% of the forested area was damaged by the wind, the direct and indirect impacts will be explained in the next chapter.

i. Directly exposed elements.

The directly exposed element are those elements which can be directly damaged by wind, flood, flash flood or mass movement. In the following chapter the exposed elements identified for the Vaia pilot area will be described. The spatial location of the different elements has been intersected in a GIS environment with the available hazard maps, to assess the presence/absence of the element in a hazard zone. For the municipality of Welschnofen/Nova Levante the hazard map is still in development, but the information available is complete enough for the current explorative analysis.

People. The tree municipalities are residential areas, with some differences in the number of people living steadily there, as shown by the following graph, representing the number of residents in the last 20 years.

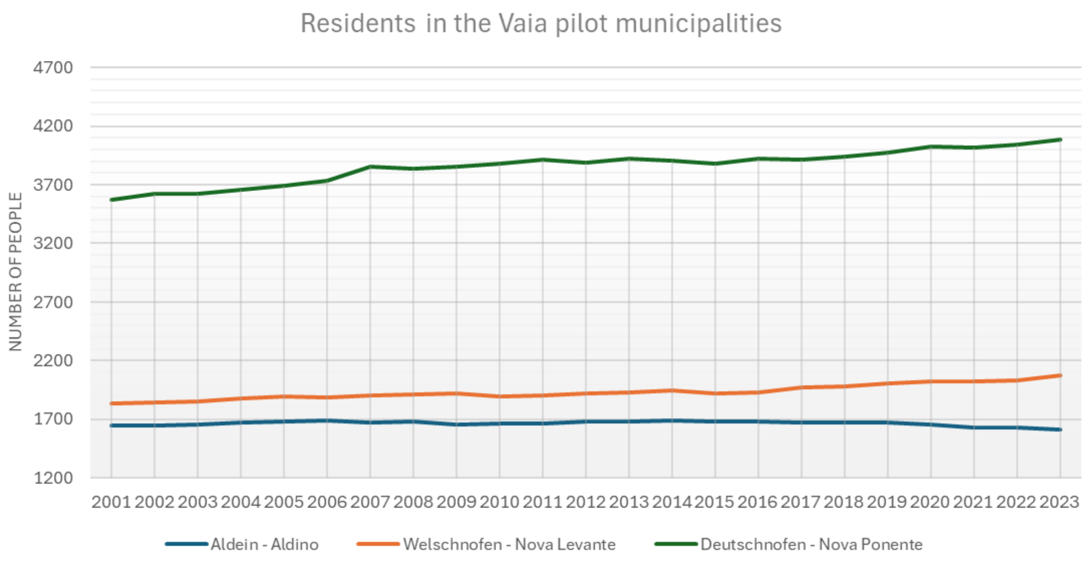

Figure 7: Residents in the Vaia pilot municipalites from 2001 to 2023. Source: ASTAT data.

The municipality of Deutschnofen is the one with the highest population, having also the biggest area. The graph also shows in increasing trend of residents for the municipalities of Deutschnofen and Welschnofen, while for Aldein the trend is slightly decreasing.

However, people are a mobile asset, since they can move differently according to their age, job and to the time of the day, therefore their real-time actual number is difficult to predict. In addition to residential people are tourists; in fact, all the Vaia pilot area, is a popular touristic destination hosting every year thousands of people. In the last 20 years the number of tourists visiting all the tree municipalities has been strongly increasing, as shown in the graph below.

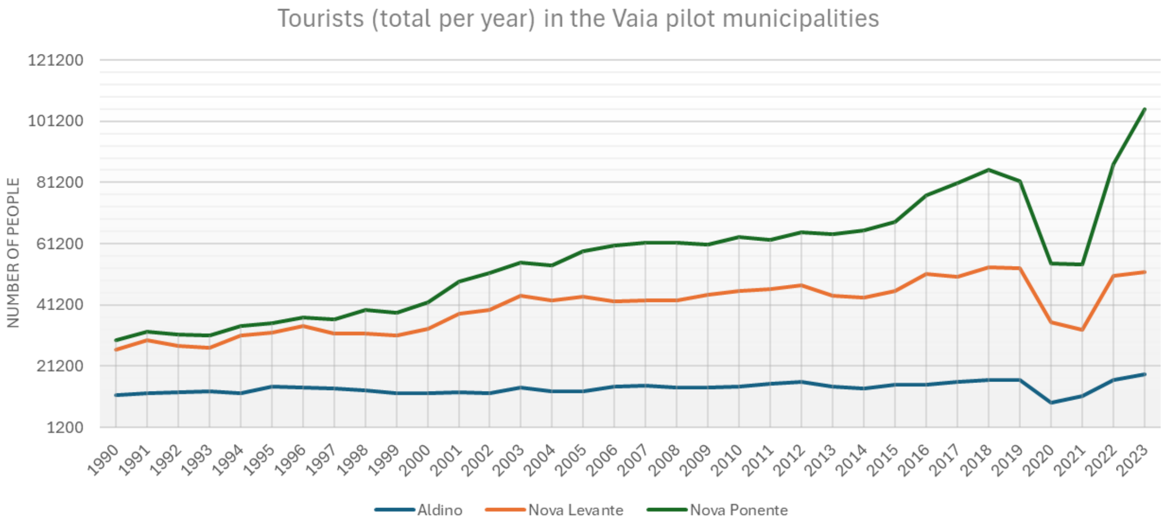

Figure 8: Number of tourists booking overnight in the Vaia pilot municipalities from 2001 to 2023.

Comparing the number of tourists with the resident population, it can be seen that in the touristic seasons i.e., summer and winter, the population in the municipalities grows by a factor of about 10, with the number of tourists being much higher than the resident population.

Vehicles. Like people, also vehicles are mobile and thus difficult to predict. During the Vaia storm event some roads have been damaged or closed, but no data are available on damaged vehicles.

Roads and bridges. Roads are fundamental connections among villages and between the mountain villages and the main cities. The pilot municipalities are connected to the main valley, i.e., the Adige valley, through two main roads: i) the SP72 connects the village of Deutschnofen with Aldein and goes down to the Adige valley reaching the village of Auer – Ora and ii) the SS241 connects the village of Welschnofen with Bozen – Bolzano through the Eggental – val d'Ega. The area is also linked to the Fiemme valley in the neighbour Trentino region through the Passo Lavazè and Passo Costalunga. In addition, many secondary roads connect the sparse buildings (mountain farms) and further forestry roads and trails connect the pastures, managed meadows and forests. The total length of the road network in the Vaia pilot area is about 1556 kilometres, of which only the 15% intersects at least one hazard area. During the Vaia storm the main roads have been damaged in many points and also some bridges blockages occurred, thus making more difficult the connections among the villages.

Buildings. The total number of buildings in the Vaia pilot area is 4198, which have been classified according to their main functions i.e., residential, agriculture, commerce and industrial. As shown by the graph below, the most abundant category is the one of the commercial and service buildings, which comprehends also the touristic facilities and the agricultural sales points.

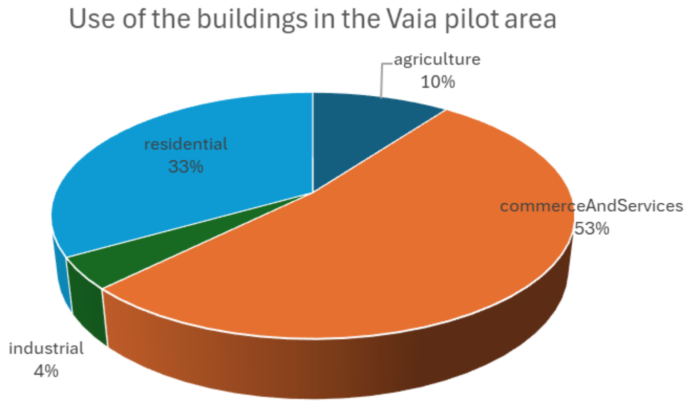

Figure 9: Percentages of use of the buildings in the pilot area.

The percentage of buildings located inside the hazard areas is shown in the graph at the end of the chapter. Only the 18% of the buildings are located in a hazard area. No data have been found about damages to buildings caused by the Vaia storm.

Infrastructures and energy supply. Infrastructures are located in the valley bottom to connect the villages and provide them the necessary water, energy and electricity supply. In total, about 278 kilometres of infrastructural lines are present in the Vaia pilot area, comprehensive of aqueducts, sewerages and high voltage lines. Moreover, in the three municipalities are located 6 power plants, 4 public drinking water supply, 11 antennas and 19 water intakes. Most of these punctual and linear infrastructures are outside the hazard area. In total 15 linear and punctual infrastructures were damaged by the Vaia storm.

Touristic and free time infrastructures. All the three municipalities of the Vaia pilot area are well-known touristic destinations, hosting every year thousands of tourists, as shown before. Therefore, the touristic infrastructure is highly developed in all the municipalities. About 39 hectares of the Vaia pilot area are dedicated to touristic infrastructures and free time / sport infrastructures, frequented by locals and tourists. Most of these infrastructures are located outside the hazard areas.

Agricultural land and infrastructures. The agricultural land comprehends many areas in the valley bottom, where the cultivations take place, as well as in the mountains, where pastures and managed meadows are located. In the Vaia pilot area, the agriculture has an industrial character and the fields are mainly located close to the villages to ensure the connection with the selling points. Moreover, the 90% of the agricultural land and livestock farms are outside the hazard zones.

Forest. The forested areas have many functions, ranging from the economic function, the protection against natural hazards, the ecologic function and the recreational value. The forested area in the Vaia pilot covers up to 75% of the municipality area, which makes forest one of the most abundant and significant asset. With its exceptional wind, reaching velocities of 120 km/h [Amt für Meteorologie und Lawinenwarnung, 2018], the Vaia storm caused high impacts on the forest of the pilot area, especially on the protective forest The forested surface damaged by the Vaia storm in the different municipalities of the pilot area ranges from the 5% to the 18% of the total municipality forested area.

To conclude, the different exposed assets have been classified according to their location outside or within the hazard areas and according to the severity of the hazard. A summary of all the hazards (mass movements, hydraulic and avalanches) has been considered, giving to each asset the highest hazard class in case of overlapping hazard layers. The result is showed by the histogram below, displaying the percentages of the exposed assets located in the different hazard/no hazard areas.

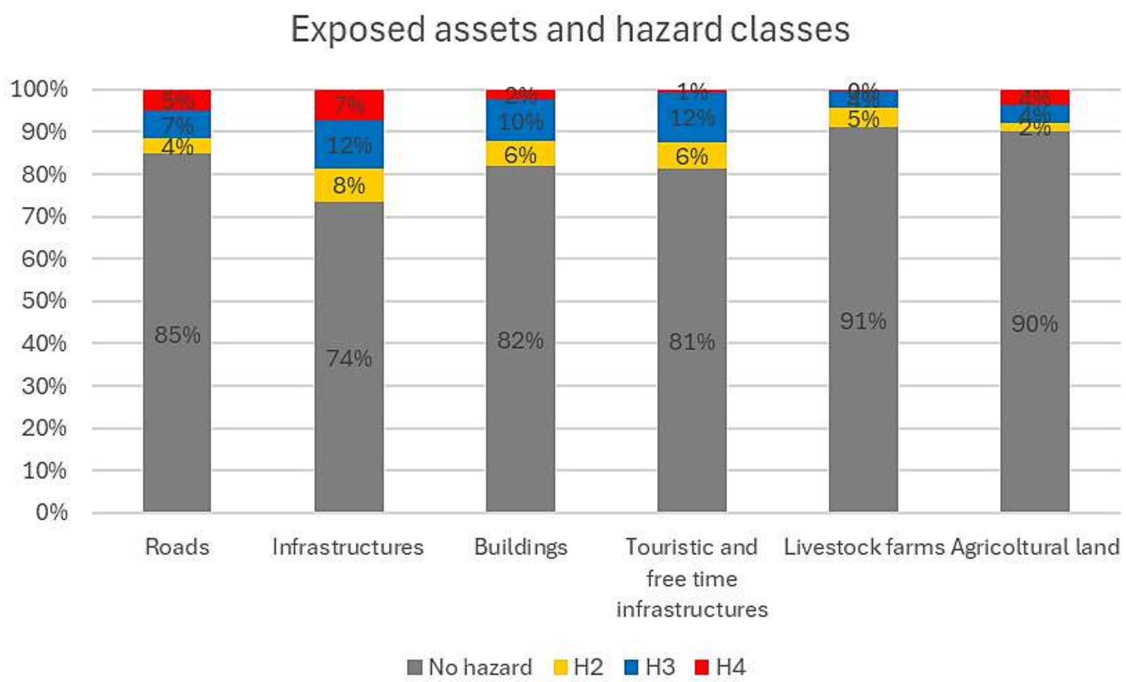

Figure 10: Percentages of exposed assets in the hazard / no hazard areas for the pilot Vaia.

The graph shows that the major part of the buildings, infrastructures and livestock farms (about 80%) are located outside the hazard areas.

ii. Indirectly exposed elements

The exposed elements listed in the previous chapter can be affected directly or indirectly by the different hazards. In the following paragraph the potential indirect consequences on the exposed elements are listed.

People and villages. People move from one point to another using roads connecting the different villages and the villages with the main cities. Therefore, if the main road is damaged, people are indirectly affected by the closure of the road for the cleaning operations and villages remain isolated.

Tourism. The touristic sector can be indirectly affected in two ways:

- as consequence of the direct damages to the touristic host infrastructures such as hotels, private hosts and agritourism;
- as a consequence of direct damages to the road network and/or the hiking trails and paths.

In the second case the indirect effect lasts for shorter time i.e., some hours, than in the first case, where the cleaning and rebuilding operations could potentially last months.

Economic activities. Economic activities depend on the energy supply, therefore if the energy infrastructure or connection is damaged, also economic activities are affected, especially those related with livestock and food supply, which depend on energy for the cooling systems. Moreover, as shown in the previous chapter, many economic activities in this pilot are related to the forestry sector, therefore are affected by the direct damages to the forested areas.

b) **Potential future exposure and impacts**

i. **Directly exposed elements.**

The municipal urban plan contains an indication of the areas dedicated to the development of new constructions, called “completion zones” and “expansion zones”. In the pilot municipalities a total surface of about 84 hectares has been dedicated to this scope. As shown by the graph below, the new expansion areas are located mainly outside the hazard areas, with only a small percentage in the coloured yellow and blue zones.

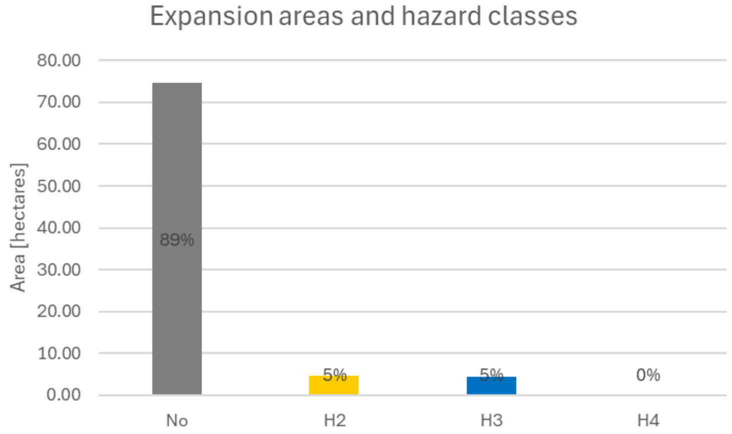

Figure 11:Percentages of expansion sites located into hazard/ no hazard areas.

However, up to now the 93% of the new expansion and completion areas are built, thus only the 7% is still available and new areas have to be found if the trend of inhabitants continues to increase. Moreover, also the touristic sector in the valley shows an increasing trend, with consequent need for new host structures or an expansion of the existing ones.

Moreover, an important future threat for the expansion areas is given by the potential intensification of the frequency and magnitude of the hazard events, and consequently of the affected areas. This is true, especially for those areas that currently fall in the hazard class H3 or are close to a hazard area. In this case, if the hazard intensity increases, the hazard class of these areas can potentially become worse.

Finally, the exposed assets located close to the windthrown areas are now element at risk due to the loss of the protective forest, therefore some artificial protection structures have been built to cover this gap till the forest is grown.

ii. **Indirectly exposed elements**

As shown in the previous question, the indirectly exposed elements are people (locals and tourists), villages and economic activities, which depend mainly on the direct potential damages to the roads, the energy supply infrastructures and the forest, due to its protective and economic value. The ASTAT data show an increasing trend of residents and tourists in the last 20 years, meaning that a bigger number of people and economic activities can be potentially directly or indirectly affected by the intensification of hazard events.

Sources

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V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

a) Current vulnerability factors

The vulnerability depends on many factors, mainly related to physical and social aspects. The physical vulnerability i.e., the predisposing/preparatory factors, take into account for the specific features of the territory (i.e., morphology, presence/absence of forest, availability of sediments, glacier melt) and of the exposed asset (i.e., how buildings, roads and infrastructures are constructed, their age and maintenance status). It also considers the potential damage that the exposed assets can undertake, which in turn depends on the hazard type, intensity and duration. The social vulnerability i.e., the pre-impact vulnerability factors, depends mainly on people i.e., their age, their risk perception and preparedness, their education level and the level of communication with risk managers during the emergency phase.

The quantification of all these aspects is in general not trivial, and in the province of Bozen – Bolzano it has been done only in some specific cases [Kaswalder, 2009]. The threats for the determination of the vulnerability are many. For the physical vulnerability, the hazard intensity and duration can potentially change from time to time, as shown in the previous chapters, as well as the territorial specific features, like the presence of a protection forest or the availability of sediments in the upper parts of the catchments. Moreover, the value and the features of every single building change depending on the location and on the age of construction. A database indicating the shapes of the buildings is currently available, but their economic value and its changes in the future are difficult to forecast. Regarding the social vulnerability, it depends mainly on people’s risk awareness and how fast the communication between people and risk managers is during the emergency phase. For these reasons in South Tyrol the **vulnerability is set always equal to 1**. The maximum value of the vulnerability permits to act on the other two components i.e., exposure and hazard, in a “worst case scenario”.

With its exceptional wind, the Vaia storm highlighted an important vulnerability of the pilot territory, and specifically of the forest system which is the structure and composition of the forest, made of old even-aged trees of mainly one species.

The storm caused high impacts on the protection forests, which play a key role in protecting settlements, people, and infrastructures from gravitational hazards [Hillebrand et al., 2023] and are fundamental in those territories affected by multiple hazards like the Vaia pilot area, avoiding the need for artificial defensive structures or reducing their maintenance costs. The following graph shows the forested surface damaged by the Vaia storm in the different municipalities of the pilot area; about the 25% of the damaged forest area was protection forest.

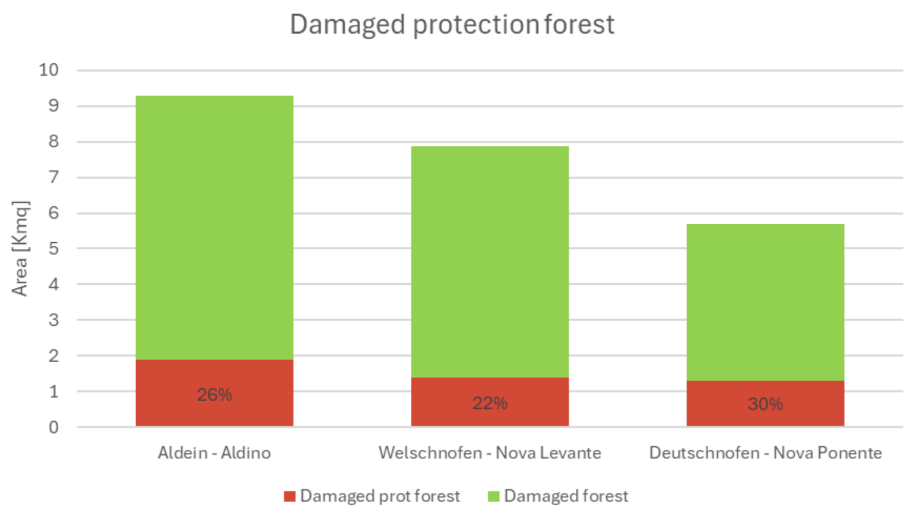

Figure 12: damaged forested area in the pilot municipalities. In evidence, the percentage of damaged protection forest.

As a consequence, a new vulnerability has emerged in the windthrown areas, as a result of the loss of protective forest, with accordingly an increase of the need for realization of protection structures (even if temporary) in those hazard areas. This “temporal” vulnerability will last until the forest is grown.

Therefore, for the Vaia pilot area, the main factors of pre-impact social vulnerability, are connected with the spatial and forest planning, which is not resilient against windthrown. This has also highlighted the absence of risk management practices dealing with multi-risks and the overcoming of the risk management capacities by the Vaia storm event, as shown in the pilot impact chain. Moreover, some gaps have been found in the existing organizational methods for the response management and the early warning systems, which currently cannot deal with unexpected events, and in the preparedness and education of the population.

b) Potential future vulnerability factors

As shown in the previous chapter, the vulnerability of the damaged forested areas has increased due to the loss of protection forest, thus requiring the construction of structures to protect those assets which are located in the most hazardous areas. This particular vulnerability factor will decrease in the future, as far as the forest grows.
The change in the other predisposing factors depends instead on how the land use and the territory evolves e.g., glacier melt or a landslide in the upper part of a catchment can lead to more availability of sediments, and a better forest management could lead to less death-wood in the channels.

The risk management is showing some changes, such as a growing attention towards compound and cascading events, the consciousness about hazard increase in intensity and frequency with future climatic changes and a general increase in people risk awareness. All these elements can contribute to lower the vulnerability factor.

Sources

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http://geokatalog.buergernetz.bz.it/geokatalog/#

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X-RISK-CC project Impact Chain

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

a) Current risk management measures

In the following chapter, the risk management measures will be described according to the four risk management phases i.e., prevention, preparedness, response and recovery.

Prevention measures
Prevention measures are structural and non-structural. Regarding the structural prevention, a total of 3406 protection structures are distributed in the Vaia municipalities. Specifically, 3008 structures protect against hydraulic hazards, 5 against avalanches and 393 against rockfall. The following graph shows the type of protection structures.

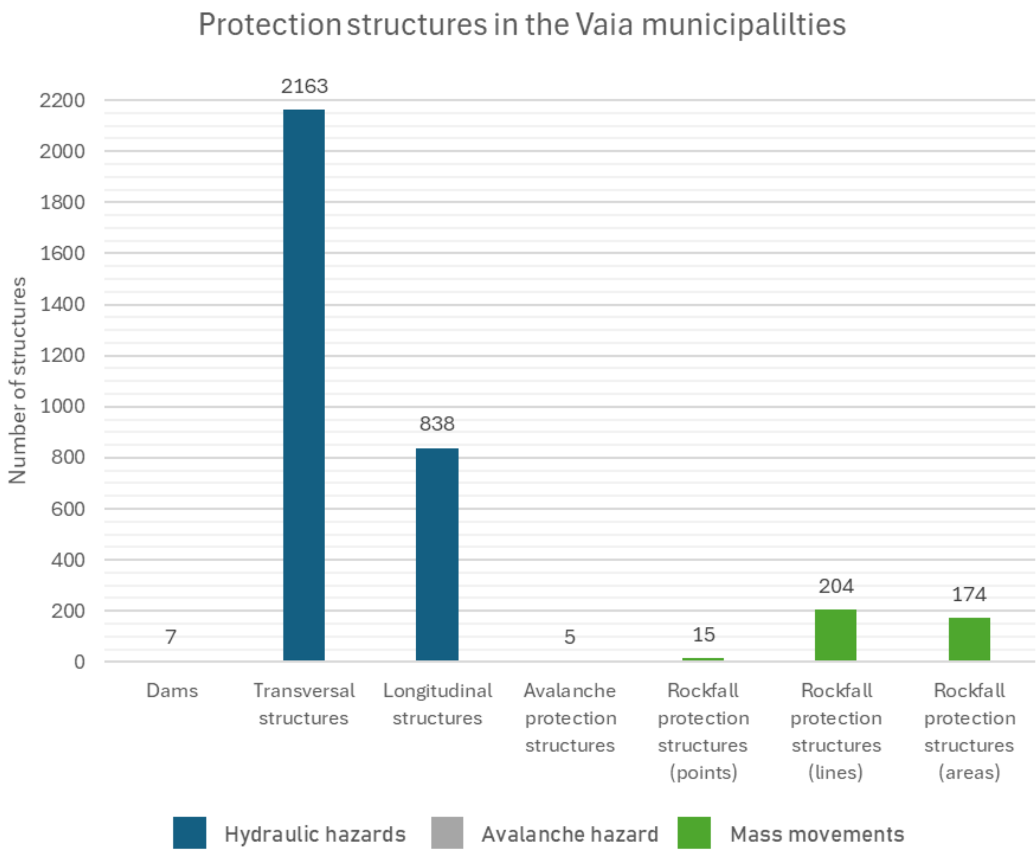

Figure 13: Protection structures in the Vaia municipalities. Source: Hazard browser Autonomous Province of Bozen - Bolzano.

The graph shows that the most abundant category of protection structures is the one related to hydraulic hazards. This was evaluated positively in the RRMA workshop.

The non-structural prevention is done mainly with the planning instruments like the **Hazard Zone Plan,** which analyzes the most relevant hydrogeological hazards (mass movements, hydraulic hazards and avalanches) on municipality level, producing hazard maps and reports. The hazard plan contains specific planning legislation depending on the hazard type and intensity (H2, H3, H4) e.g., building new constructions is forbidden in the H4 red-zone areas.

Preparedness measures

Recently, the Autonomous Province of Bozen – Bolzano created a **Risk Map** in application of the legislation at national and provincial level. The Risk Map aims most of all to protect existing exposed elements and only secondarily at an evaluation in the planning phase. In this way, it proposes priorities of protection to the municipalities and risk managers. Since the position and type of elements at risk varies with the urban development of the territory, the Risk Map "photographs" the situation at the time of drafting the map itself, and must therefore be continuously updated. For this reason, this map is not a planning tool in the strict sense, but more an "indicator for mitigation measures" in the sense of passive, non-structural interventions (urban planning, civil protection plans, etc.) and /or active, structural interventions.

Response phase

The **Civil Protection Plan**, designed during the prevention phase, is the instrument that permits to deal with the emergencies and to protect people, goods and services present in an area affected by

disasters, that may derive from one or more residual risks. Every municipality in South Tyrol has a tailored civil protection plan, with clear and direct instructions to organize the knowledge, the resources and the procedures used to deal with the various critical situations, that potentially arise on the municipal territory.
Moreover, different association of volunteers, such as fire fighters, red and white cross and mountain rescue act directly and immediately on the affected territory, securing the impacted area and providing basic supply to the people or evacuating them if necessary.

Recovery phase
The Autonomous Province of Bozen – Bolzano allocated different funds and facilities to support the reconstruction in the recovery phase after an extreme event. Every fund is provided by the specific reference office, e.g., funds related to agriculture are allocated by the Agricultural service. The different funds have also different targets of interventions and specific receivers e.g., municipalities, public associations, private citizens and farmers.

To conclude, the following table summarizes the results of the Rapid Risk Management Appraisal 1st workshop involving the main actors of the risk management in the Vaia pilot area. The positive aspects and the gaps for each of the four phases are highlighted.

	Positive aspects	Gaps
Structural prevention	• hydraulic protection measures worked well; • rivers are inspected regularly for definition of maintenance measures	• no structural protection measures for wind; • need for strong, healthy, diverse forests to have the best "structural" prevention for wind --> forest management has to be adapted; • trees next to sensitive infrastructure have to be evaluated critically
Non-structural prevention		• hazard maps should be checked and revised after extreme events; • the hazard "wind" is not considered in many civil protection and contingency plans
Preparedness tools	• good precipitation and flood forecast; • Measuring systems available;	• missing nowcasting and monitoring tools for wind, automatic "real time" warning system and definition of procedures; • different data sources difficult to manage altogether: thus, need for a unique monitoring tool (including e.g., info on ongoing fire brigade operations)
Preparedness tool implementation		• missing distribution of warnings and civil protection messages to some "user groups" e.g., tourist; • need for improvement of awareness of population before the event e.g., avoid car trips / movement outdoors, personal responsibility
Response tools		• communication problems due to power blackouts; • contact centres needed; • behaviour of citizens not fully appropriate e.g., curiosity should be avoided; • difficult communication to non-residents; • need for a structured involvement of citizens

Response tool implementation	• good collaboration between civil protection, municipalities, provincial offices in the affected areas; • uncomplicated help from private citizens and companies; • full commitment of all participants over several days and exceptional work from several organizations; • forestry service: flow of information occurred as specified in the organizational structure; • autonomy of fire brigades made their operation easier	• self-protection measures for firefighters in case of strong winds was not trained enough; operational forces stayed too long in risky situation
Structural recovery	• quick removal of windthrown trees and quick restoration of important infrastructure (e.g. roads or touristic infrastructure); • processing of wood was well coordinated, good collaboration with municipalities and forest owners; • quick damage assessment right after the event; • funding was adequate and unbureaucratic; • good collaboration between authorities and municipalities	• capacity of the local wood processing companies too small --> dependency on foreign companies; • coordination between municipalities could be improved for implementation of resilience strategies; • population was not informed enough about recovery measures; • coordination of wood transportation was challenging
Recovery learning organizations		• need for workshops with various stakeholders to be held after each event; • regular meetings to exchange experiences; • importance of transfer of knowledge

Figure 14: Summary of the RRMA 1st workshop results

b) (Potential) future risk management measures

It is important that future risk management in the Vaia area takes into account several aspects. Most of all the potential increase of intensity and frequency of the different hazards should be considered, but also the activation of new processes derived by the modification of the territory (e.g., areas without trees are now more prone to avalanches) or from the compoundness of more different hazards.

Sources

Hazard browser, Autonomous Province of Bozen – Bolzano (https://maps.civis.bz.it/?context=PROV-BZ-HAZARD)
https://pericoli-naturali.provincia.bz.it/it/contributi-e-agevolazioni-in-seguito-a-eventi-calamitosi
RRMA results of the 1st workshop

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

The Vaia storm triggered many compound/cascading impacts, creating a complex scenario overstraining the risk management capacity of the affected municipalities. The complexity was given on one side by the simultaneous occurrence of many hazards i.e., the windthrown, several mass movements and hydraulic hazards, which stressed the existing protection structures at the limit and in some cases caused damages. The compoundness of the multiple hazards and the extent of the affected area amplified the impacts and required much more resources to be managed simultaneously, than the single hazards happening in different times.

On the other side also the secondary cascading impacts played a significant role, in the short term as well as in the long term. Specifically, the cascading impacts occurred in the short term e.g., mass movements due to erosion and debris flow due to the increase of sediments and fallen trees in the streams, added to the already present compound hazards. The long-term secondary impacts instead, influenced the overall vulnerability of the whole territory, and their effects have to be managed over a longer period of time (years). For instance, in the windthrown areas the dead wood remaining on the ground together with a following hot and dry period favoured the spread of the bark beetle, further damaging the forest. Moreover, the areas without trees changed completely their surficial hydrology and roughness, being more vulnerable to erosion, mass movements and avalanches. For this reason, some structural measures have been set in these places e.g., stumps and some trunks have been left on the ground for avalanche protection and barriers have been constructed against rockfall.

Therefore, due to the spread of the damages and their secondary effects, affecting the long-term vulnerability of the territory, the recovery phase after the Vaia storm required many resources for the reconstruction, as well as for the stabilization of the vulnerable areas.

b) Potential future impacts of compound/cascading hazard events

Future projections show a potential increase in precipitation extremes intensity and frequency. Despite no clear trends are observable for the wind storms, the combination of extreme precipitation and wind can potentially trigger more intense compound and cascading hazards in different parts of the pilot area.

In the pilot territory, the vulnerabilities resulting from the Vaia storm cascading impacts will play a significant role in the future occurrence of the hydraulic and mass movement related hazards. For instance, the areas without trees will be more vulnerable to soil erosion, mass movements and in some cases avalanches, but on the other side they will not be vulnerable to windthrown for some years. Among the future vulnerabilities there is also the increased availability of sediments potentially transported by the rivers and streams, due to the absence of the forest and the weathering of the rocks, favoured by the alternance of hot and dry periods and intense rainfalls.

The combination of the triggers and vulnerabilities make future hazards potentially more frequent and destructive, therefore requiring many resources at different levels to be managed and a multi hazard perspective.

6. Val di Fiemme and Val di Fassa, Italy

RISK QUESTIONNAIRE

Fiemme/Fassa Valleys (Trentino, IT) 05 September 2024

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

In the pilot area, the weather extremes considered by the analysis of WP1 are precipitation and wind extremes, whose tendencies are analysed both separately and in combination (compound extremes). They can lead to a variety of hazards, especially in a mountainous area with complex terrain and high density of forest coverage. In the short term, precipitation and wind extremes can lead to fallen trees, flooding and gravitational mass movements, such as debris flows. Over time, cascading impacts can follow, such as higher slope instability or higher avalanche hazard due to reduction of forest coverage, or enhanced forest damage due to the proliferation of parasites on fallen or weakened trees during subsequent favourable conditions, e.g. heatwaves and persistent high-temperature periods (as an example of compound hazards/risks). This could eventually result in higher-severity level hazards being triggered by subsequent weather extremes of intensity comparable with what observed in the past.
Another important weather extreme type to examine in the pilot area is the increase in temperatures, which has various and significant impacts on the Alpine environment: from public health to land use planning, from glaciers' degradation to water resource management, from agriculture to tourist flows, from changes in local flora to alterations in fauna.
Additionally, we consider it noteworthy to delve into aspects related to snowfall (directly stemming from temperature and precipitation trends), hail and droughts.
Please, notice that climate change reference future scenarios for the Trentino region are in preparation thanks to a collaboration with the University of Trento and will be available at the end of October 2024. Projected changes of extreme events indices will be included in the analysis and will allow the present document to be further updated/enriched.

Precipitation

The intensity of heavy precipitation in Trentino – South Tyrol exhibits distinctive spatial patterns in both magnitude and seasonality. The most intense precipitation events occur in Trentino and the central part of South Tyrol. In Trentino, the annual maxima of precipitation occur mostly in the autumn, probably due to a higher exposure to moist air masses from the Mediterranean Sea, while in South Tyrol precipitation maxima are more frequent in summer, when more convective processes occur and are particularly influenced by orographic effects.
In the last decades, the intensity of heavy precipitation has increased throughout the region, with the most significant trends in South Tyrol being in the order of +5% per decade (with respect to average heavy precipitation intensity over reference period 1991-2020). The number of statistically significant trends is limited, with less than 20% of stations showing a trend, mostly confined to South Tyrol; for Trentino, no significant trend can be determined.
The observed trends in the frequency of heavy precipitation are much less pronounced than trends in intensity, although there are some localised areas showing positive trends, with increases in the

number of heavy precipitation days in a year in the order of +10% per decade. The frequency of seasonal precipitation extremes does not show significant changes in the region.
The analysis in the WP1 report is corroborated by previous climate assessments conducted within the Province of Trento (see Sources #3 at the end of the question). Generally, indices representing intense and extreme precipitation events show considerable variability, and, despite some signals of amplification, the statistical evidence is insufficiently robust to suggest a clear, general trend toward either an increase or decrease in the frequency and intensity of intense and extreme precipitation events.
With regard to sub-daily precipitation events (lasting 1-2 hours or less), i.e. extreme short-duration precipitation events, a recent study showed significant increasing trends in annual maxima for the period 1991-2020. For what concerns the frequency distribution of sub-daily precipitation events, there is a trend towards an increase in the proportion of more intense ones at the expense of less intense ones. This change can be attributed to the higher proportion of convective thunderstorms in the summer season. This result confirms the significant increase in the intensity of extreme short-duration precipitation events in recent decades.
According to WP1 analyses, in the future, overall increases in the intensity and frequency of extreme precipitation events are expected to occur in Trentino – South Tyrol, including the pilot area considered for the Vaia event analysis. The intensity of 1-day precipitation extreme is projected to increase by the end of the century in the pilot area between +3% and +16% compared to the period 1991-2020, depending on the global warming level reached, or, in other terms, depending on the effectiveness of mitigation actions. 1-day precipitation extremes could become more frequent: on a regional scale, a Vaia-like precipitation event is expected to halve its return period under the worst-case scenarios, i.e. if the global warming will exceed +3°C or +4°C by the end of the century. Comparable findings are obtained for 3- and 5-day precipitation maxima.
The future scenarios developed by the University of Trento in the framework of the "Trentino Clima 2021-2023" work program specifically for the provincial territory highlight that:

- Despite a marked interannual variability, extreme daily precipitation phenomena will show some significant changes only starting from the second half of the century until 2100 (compared with the 1981-2010 reference period).
- Extreme daily precipitation shows increasing trends in both intensity and frequency of events, with different variations according to different emission scenarios (e.g. greater warming implies a larger increase in daily precipitation intensity).
- The maximum 5-day cumulative precipitation is expected to increase by about 20% (which means about 10-25 mm more by the end of the century).
- In contrast, consecutive dry-day periods show no significant trends.

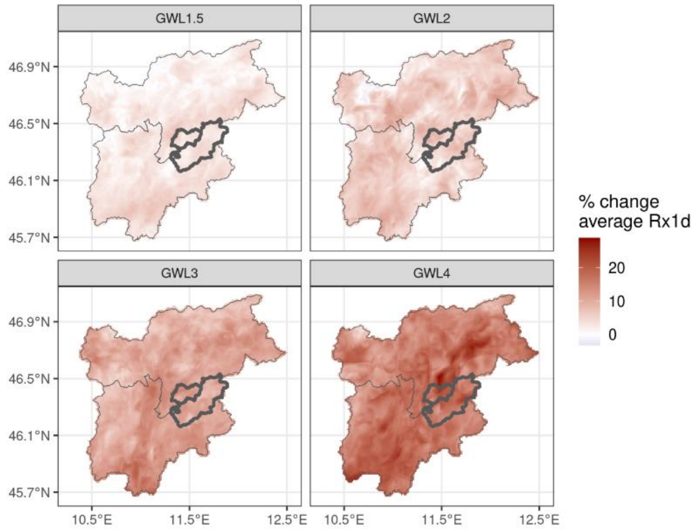

Fig.1 Increase in 1-day precipitation extremes in 2100 with respect to 1991-2020 in different Global Warming Level scenarios (average temperature increase of 1.5°C, 2°C, 3°C and 4°C)

According to X-RISK-CC WP1 analysis, for example, at the Cavalese station, the accumulated precipitation during the Vaia storm was 193.6 mm, corresponding to a return period of 317 years under current climate conditions. However, with a global warming level of +4°C, the return period for this amount of precipitation would decrease to only 61 years by 2100.

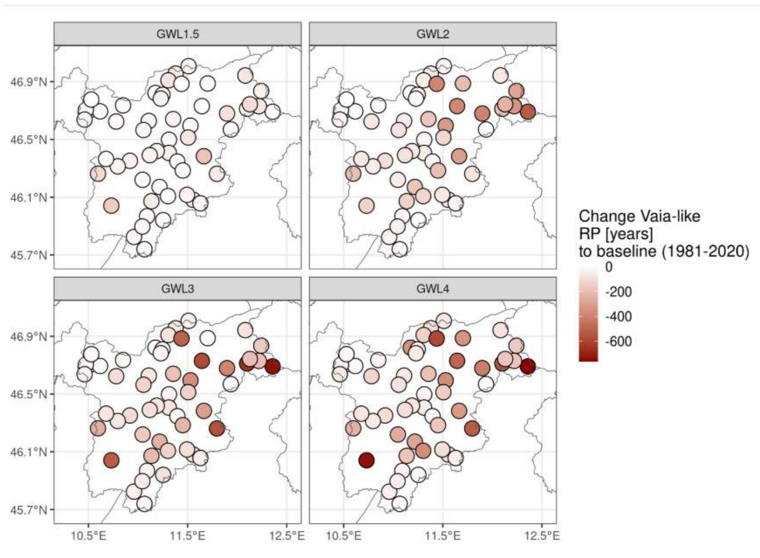

Fig. 2. Absolute changes in return periods associated with a Vaia-like precipitation event at station locations under different Global Warming Levels in 2100 with respect to 1981-2020.

Expected future tendency for Trentino in brief:

Increases in both the frequency and the intensity of extreme precipitation events can be reasonably expected.

Wind

Regarding the wind, the short length of the available observation series (10-20 years) limits the ability to conduct an in-depth analysis of maximum wind speed trends. However, it's worth noting that in several instances, the maximum wind speeds recorded in the pilot area during the Vaia event correspond to or are close to the highest values in the entire station record.

No remarkable changes are projected for the intensity and frequency of wind speed extremes in the future over the region. However, due to the overall intensification of precipitation extremes, the probability of a compound occurrence of high precipitation and wind speed conditions can increase throughout the region in the future years.

Expected future tendency for Trentino in brief:

No increases in the frequency and intensity of wind storm events are expected.

Temperature

A recent analysis of climate indices by APPA (the Provincial Agency for Environmental Protection), based on data provided by Meteotrentino, highlights, over the period from 1961 to 2020, an increase in absolute values and frequency of extreme high temperatures, and a decrease in extreme low temperatures. The number of hot days and nights is increasing, while the number of cold days and nights is decreasing.

For example, observing the Trento Laste station, between the thirty-year period 1961-1990 and the more recent one 1991-2020, the number of summer days increased by 7.7 days, and the number of tropical nights by 2.3, while the number of frost days decreased by as much as 12.8 days, and those without thaw by 3 days. The duration and frequency of heatwaves have clearly increased, a trend confirmed by several scientific studies.

The temperature has significant effects on the territory not only related to its extreme values but also, and especially, due to the increase in its average values.

The overall warming trend in Trentino for the period from 1961 to 2020 has been an average of 0.3-0.4°C per decade over the entire period, with a significant acceleration in the last decades (aligned with data reported at the European and Italian levels, which average around 0.4°C per decade).

The net temperature increases observed between the 1961-1990 and 1991-2020 periods are approximately 1.1°C for daily average temperatures, about 0.5°C for daily minimum temperatures, and around 1.7°C for daily maximum temperatures. For daily minimum temperatures, the rate of warming, previously slower than that recorded for maximum temperatures, has accelerated in the most recent 30-year period. The trend in seasonal temperatures shows minimum temperatures rising more rapidly in summer and winter, while the increase in maximum temperatures is faster in spring and summer.

A study conducted by the University of Trento examined temperatures in Trento from 1816 to 2018, compiling observations from various urban sites. Even after accounting for potential effects related to the degree of urbanisation over time, which may have partially influenced the observed temperature increase due to the urban heat island effect, the results show a clear warming trend, particularly in the last 50 years, with a progressive acceleration. To date (2023) the annual temperature in Trento has increased by about 3.0°C (considering the average anomaly of the last five years) compared to the pre-industrial era, which is roughly double the increase recorded globally on average.

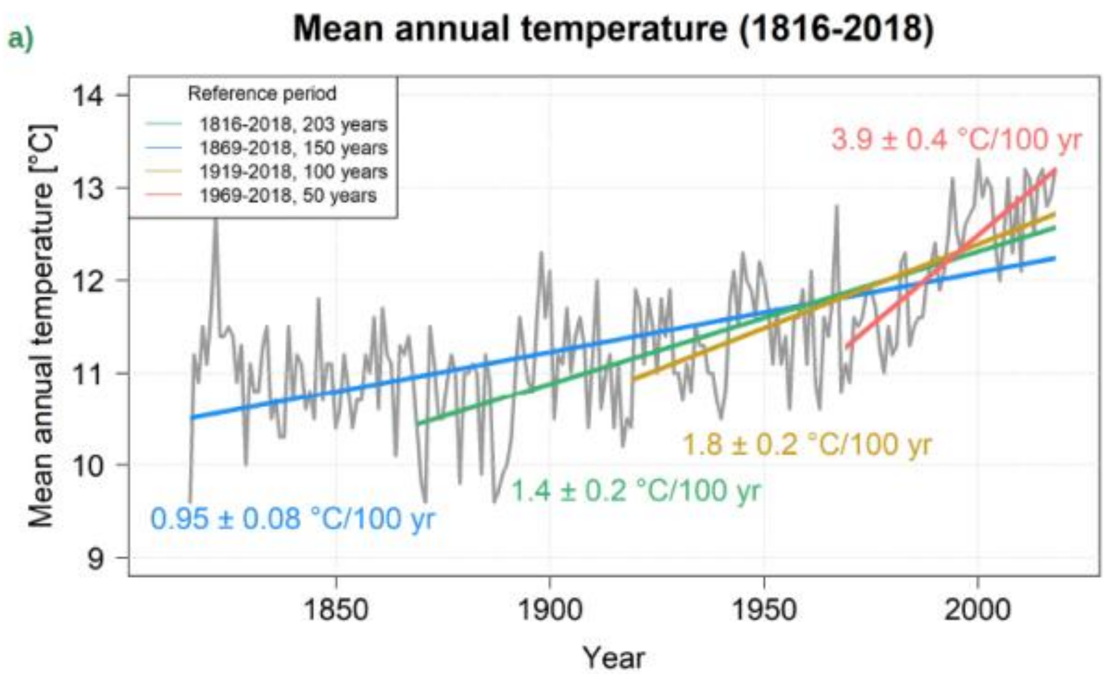

Fig.3 Historical series of the annual average temperature for the city of Trento from 1816 to 2023. The coloured lines represent linear trends in temperature increase estimated for reference periods of different lengths (the last 200, 100, and 50 years), highlighting the ongoing acceleration of warming (data source: DICAM - University of Trento; Meteotrentino PAT; data from the Trento Laste station used from 2003 onwards).

The future scenarios developed by the University of Trento in the framework of the "Trentino Clima 2021-2023" work program specifically for the provincial territory highlight that:

- As far as temperature extremes are concerned, all climate change indices indicate an increase, with values varying according to the emission scenario (e.g. both summer days and tropical nights are expected to increase).

Expected future tendency for Trentino in brief:

Significant increases in both the frequency and the intensity of extreme high temperature events are expected .

Hail

Hailstorms are extreme events that have significant impacts on material assets (such as cars and buildings) and human activities (particularly agriculture), often causing substantial economic damage. A study on hail frequency in the Mediterranean basin from 1999 to 2021, based on satellite data, revealed that in the area encompassing the Alps and the Po Valley during the months of June through August (when hailstorms are typically observed), the average number of events has substantially increased from the 1999-2010 period to the more recent 2010-2021 period. An additional statistical study on the frequency of large and very large hail (greater than 2 cm and 5 cm in diameter, respectively) in Europe from 1950 to 2022 highlighted an increase in hail storms across much of the Italian peninsula. In particular, Northern Italy is the region experiencing the greatest increase in these phenomena: compared to the 1950s, the number of hailstorms with hailstones greater than 5 cm in diameter has tripled.

For what concerns the study area, hail data collected in Trentino by the Fondazione E. Mach for the period 1974-2009 revealed a growing trend for some characteristic parameters of hail precipitation that are notably correlated with damage to agricultural crops, such as the number of more intense events, even though the overall number of hailstorms recorded on average and the affected area did not show similar trends for the analysis period. Updated analyses are not available.

Expected future tendency for Trentino in brief:

No increase in the frequency of hail events is expected, while the intensity of hail events and the associated damages are expected to increase.

Snow

Although it does not strictly pertain to aspects related to extreme weather events, we also include some information about the trend of snowfall in Trentino. Extreme snowfall events tend to become increasingly rare. At the provincial level, in fact, since the 1990s, there has been a significant reduction in both the duration of snow cover on the ground and the average seasonal snow depth; this trend, consistent with the one observed in the whole Alpine region, is significantly influenced by altitude and the altitudinal distribution of temperatures.

During the period from 1980 to 2020, clear negative trends in snow cover were observed at the lowest altitudinal range (below 1,000 m a.s.l.) throughout the entire winter season, which spans from November to May, associated with the general increase in temperatures. Variability is greater in the intermediate altitudinal range. Some positive trends were observed locally above 2,000 m a.s.l. between January and March, due to increased winter precipitation. Significant negative trends, however, were observed at all elevations in the month of April.

Expected future tendency for Trentino in brief:

Interannual variability of snow totals can be expected to increase, although in the long term totals are decreasing rapidly at lower altitudes. Particularly snow-abundant years may represent an amplification factor for liquid precipitation events.

Sources:

1. WP1 pilot area report - Vaia
2. Provincia autonoma di Trento (2024): Lo stato del clima in Trentino. A cura di: Provincia autonoma di Trento, MUSE - Museo delle Scienze di Trento. Ed. Provincia autonoma di Trento.

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4. Manzato A., Fasano G., Cicogna A., Sioni F., Pucillo A. (2023): Trends of sounding-derived indices and observations in NE Italy in the last 30 years. 11th European Conference on Severe Storms, Bucharest, Romania, 8-12 May 2023, ECSS2023-3, DOI: 10.5194/ecss2023-3.
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II. Which hazard processes can be triggered by current and future weather extremes?

Extreme weather events, such as intense rainfall, hail- and windstorms, heatwaves or prolonged droughts, can trigger natural hazards that are typical of Alpine territories, including: floods, inundations, landslides, debris flows, rock falls, snow avalanches and wildfires. Different weather extremes and natural hazards can occur simultaneously (compound natural hazards), leading to more severe overall impacts, or they can cause cascading effects (for example, the combination of the large number of trees felled during the Vaia storm and the subsequent prolonged drought period led to the massive proliferation of bark beetles). We identified the most significant impacts that occurred in recent years in our pilot area that can be expected to be modified in the future due to changes in the triggering extreme weather events described in the previous answer. However, quantitative analyses based on future climate scenarios are not yet available to predict expected future variations in frequency and magnitude of such hazards in Trentino. At present only qualitative assessments can be made on the basis of future projections of extreme weather events and knowledge of the local area and its susceptibility to the investigated hazards.

The tool adopted by the Autonomous Province of Trento to identify areas of land affected by hydrogeological, avalanche, seismic, and wildfire hazards is the Hazard Synthesis Map ("Carta di Sintesi della Pericolosità", CSP), a regulatory map that identifies areas characterised by different levels of restrictions regarding land use due to the presence of hazards described in the Hazard Maps. The CSP is one of the components of the Provincial Urban Plan (PUP) (provincial law of May 27, 2008, no. 5) and serves as a reference tool for urban planning.

Floods and torrential phenomena

The main impact of extreme precipitation on the Trentino territory, and therefore also on the pilot area of the Fiemme and Fassa Valleys, consists of liquid and solid flood phenomena. In the valley floors, the greatest risk is the overflow of watercourses and the consequent flooding of inhabited areas and agricultural lands. In the hillside areas, where the slopes of the watercourses increase, the greatest risk is due to mass transport phenomena.

Water flood occurs when the flow discharge in the watercourse increases , due to a substantial rainfall event or the rapid melting of a snow cover, followed by a decrease, generally slower, and a return to normal conditions. This process is typical of low-slope valley floor watercourses. As the slope increases, the currents accelerate and progressively gain greater erosive capacity and ability to transport solid material incorporated into the flow. Consequently, with increasing slope, the amount of solid material involved in the runoff also increases, which determines different dynamic characteristics of the flow. Based on the solid concentration present, solid transport processes can be classified into bedload (typically <5-10%), hyper-concentrated flow (typically between 10 and 40%), and debris flow (typically >40-50%). The "solid" response to an event, whether it involves ordinary transport (bedload and/or suspended), hyper-concentrated flow, or finally, a debris or mudflow, depends on the availability of sediments readily available from the riverbed and sediment source areas directly connected to the river network.

During the Vaia storm in the Fiemme and Fassa Valleys, the flood of the Avisio stream affected approximately 40 km of riverbed, with recorded flows of 42.4 m^3/s at the Campitello di Fassa gauge, 85.8 m^3/s at Soraga, and 630 m^3/s at Masi di Cavalese. The basin study assigns a return period of approximately 30 years to these flows at Campitello and Soraga, and between 30 and 100 years at Stramentizzo. Outside the riverbed, the flood affected about 80,000 m^2, mostly in floodplain areas. Approximately 100 reports were catalogued (some referring to occurrences of the same phenomenon in different parts of the watercourse).

During the Vaia storm, 8 transport phenomena were reported (Rio Cadino, Rio di Val Stava, Rio Lagorai, Rio Val de Valanza, Rio Val di Gazolin, Rio Valene, Rio Valsorda, Torrente Travignolo), affecting approximately 0.6 km^2 of territory, with over 0.45 km^2 outside the riverbed. Around 100 event reports were catalogued (some referring to occurrences of the same phenomenon in different parts of the watercourse).

During the Vaia storm, 14 hyperconcentrated flow phenomena were reported (right tributary Avisio, Rio Arizzol, Rio Castiller, Rio delle Pozze, Rio di Bocche, Rio di Imana, Rio di Vallaccia, Rio Sadole, Rio San Nicolò, Rio San Pellegrino, Rio Valaverta, Rio Val del Bus, Rio Val della Roda, Tovo Crozi dei Salti), affecting approximately 0.35 km^2 of territory, with over 0.31 km^2 outside the riverbed. Around 20 event reports were catalogued (some referring to occurrences of the same phenomenon in different parts of the watercourse).

During the Vaia storm, 7 debris flow phenomena were reported (Rio Antermont, Rio Canzoccoli, rio di Mezzavalle, Rio di Penia, Rio Doleda, Rio Piazina), affecting approximately 86000 m^2 of territory, with over 80000 m^2 outside the riverbed. Around 90 event reports were catalogued (some referring to occurrences of the same phenomenon in different parts of the watercourse).

Over the centuries, frequent flooding events have struck Trentino, highlighting the extreme fragility of the territory. Notably, the most significant floods occurred in 1882 and 1966 and are remembered for their devastating effects on the territory and the severe consequences suffered by the population. At the beginning of September 1882, a period of intense rainfall accompanied by warm winds, which caused the rapid melting of early snowfall, particularly affected the central-eastern Alpine region, causing a devastating flood in Trentino as well. The event highlighted the severe state of land instability, exacerbated by excessive exploitation of forests, and highlighted the need for more systematic and specialised river management interventions than had previously been implemented. Similar atmospheric conditions to those of 1882 occurred in early November 1966 too, and on that occasion, rivers and streams also overflowed, dragging numerous debris downstream and causing extensive damages, which would have been even greater without the river management measures implemented up to that point.

In the case of the Vaia storm, the precipitation exceeded that recorded in 1882 and 1966. The event showed high return periods of precipitation across the entire provincial territory. Considering a precipitation duration of 48 hours, the median return period reached, exceeded at 50% of the stations, was 115 years, with 47 stations recording a return period of over 200 years. The main issues were concentrated in slope areas and some valley floor fans. In the valley floors, although significant water levels have been reached, comparable in some cases to those of November 1966, no major criticalities were noted. It should be highlighted, however, that during the event, reservoir basins management played a crucial role in reducing peak flows in the main river network and in containing valley floor water within the banks.

After Vaia, no major precipitation events with widespread impacts were recorded in the pilot area. However, there were a few episodes of particularly intense and localised rainfall that caused significant impacts. One example of this is the intense downpour that affected a small area of the Val di Fassa on the late afternoon and evening of August 5, 2022. An amateur station located in Monzon recorded 123 mm of rain between 5:15 PM and 7:45 PM. The heavy precipitation caused a rapid swelling of the streams, local flooding, and landslides, with numerous damages observed in the municipalities of San Giovanni di Fassa - Sèn Jan, Mazzin, and Campitello di Fassa although the effects on the territory were mitigated by protective works that effectively intercepted the solid material mobilised during the flood.

Currently, although some investigations have been carried out about tendencies for precipitation events that typically trigger them, there are no studies explicitly demonstrating and quantifying either positive or negative trends for flood and torrential phenomena in Trentino.

The rise in temperatures and changes in precipitation patterns—including likely increases in extreme precipitation events over short periods and earlier melting of snow cover—could exacerbate flood risks in the future, particularly in more exposed and vulnerable areas, and depending on land management practices. Studies in the Alpine region emphasise the growing significance of rain-on-snow events due to rising temperatures and higher snowline elevations. These factors could lead to a higher frequency of flood events in Alpine basins. Additionally, flash floods caused by convective precipitation, which impact smaller areas over shorter timescales, could result in significant damage due to collateral effects such as debris flows.

Moreover, the retreat of glaciers and the melting of permafrost are also contributing to the degradation of slope stability and increased sediment availability in high-altitude areas. Changes in forest ecosystems—specifically in vegetation distribution and composition due to climate change—could further lead to cascading effects that negatively impact slope stability, soil erosion, and the likelihood of landslides, debris flows, and floods.

Wind-induced forest collapses

Wind damage was the most notable impact of the Vaia storm: the Vaia storm affected approximately 20,000 hectares of forested land, with a forest resource of 4 million cubic metres of uprooted or broken trees during the storm. The areas impacted either completely or significantly (more than 50% damage) account for a substantial portion of the total damaged areas, totaling nearly 12,800 hectares.

One of the most significant consequences of forest falls is the loss of the forest's protective function, which can lead to an increased risk of avalanches, landslides, flooding events, soil erosion and debris flows. Forest collapses also impact tourism (for example, by disrupting trails and altering the landscape) and biodiversity.

Although there is no statistical analysis exploring the events observed in the past (due to the lack of data and to the short time series), in the future wind damage to forests is likely to increase even if there is no increase expected for wind storm events. This will be due to general warming, which shortens the duration of frozen ground conditions, thereby reducing the ability of plants to anchor themselves to the soil from late autumn to early spring. Additionally, soil saturation in late autumn, which is expected to increase due to higher precipitation during that season, may weaken tree root anchorage, making forests more vulnerable (particularly spruce forests, which have a shallower root system).

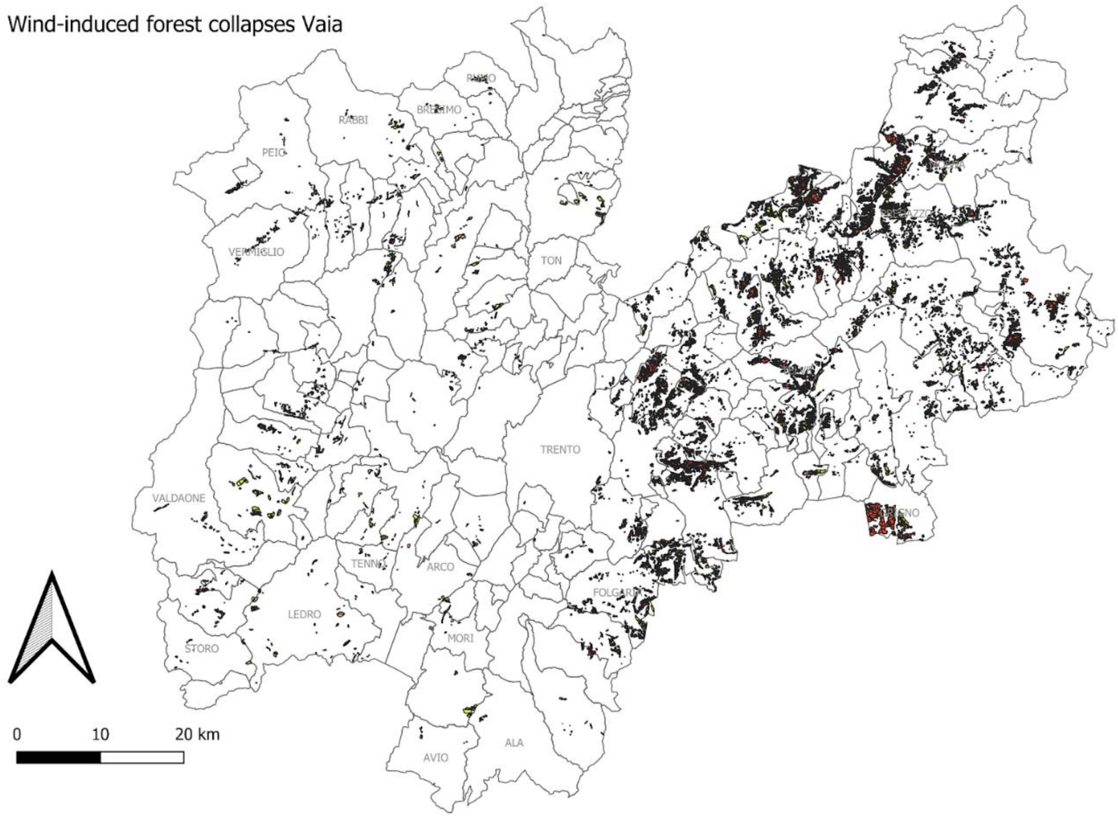

Fig.4 Map of forest damage caused by the Vaia storm in 2018 with the various damage classes.

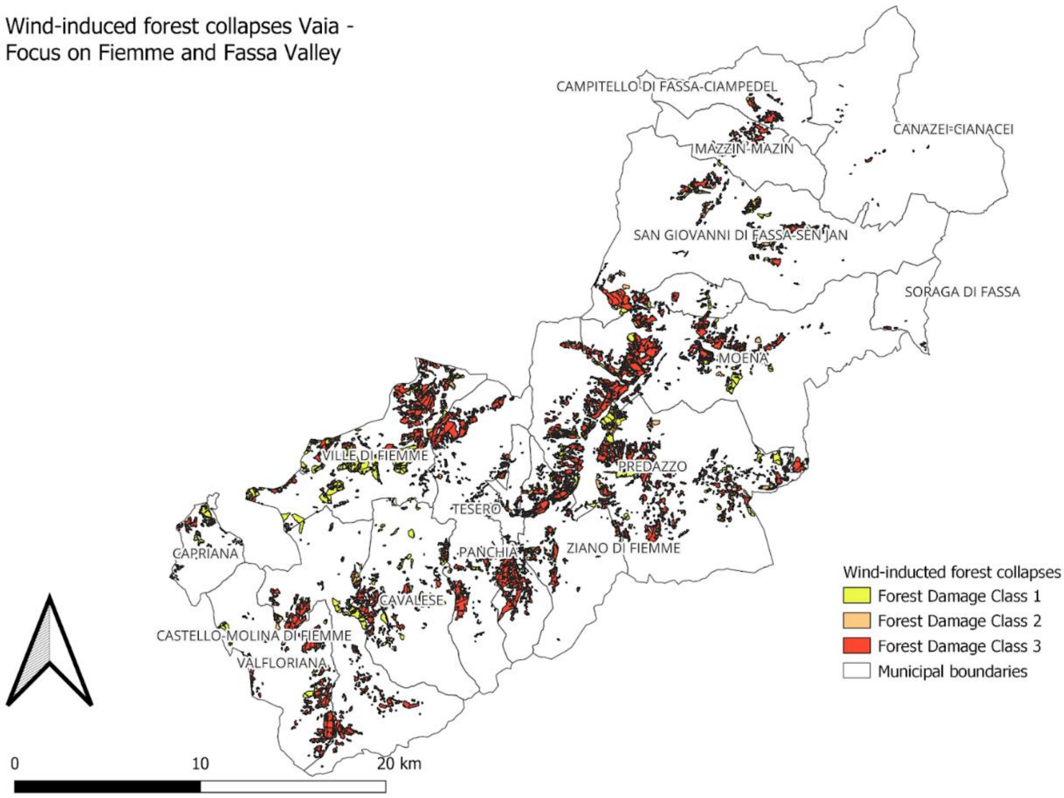

Fig.5 Map of forest damage caused by the Vaia storm in 2018 with the various damage classes with the focus on the Fiemme and Fassa Valleys.

Bark beetle

A cascading hazard triggered by the Vaia storm, which ended up causing more damage to the forests in the pilot area than the storm itself, is the bark beetle.

The bark beetle is a small beetle naturally present in the spruce forests of the Alpine arc. The spread of this parasitic insect, which mainly affects spruce trees, has been caused by multiple factors. The first was the large amount of decaying material on the ground due to the windfalls caused by the extreme winds during Vaia. This was compounded by favourable conditions resulting from other extreme weather events in the following years. These events include a significant increase in temperatures and severe drought in the summer of 2022, which further weakened the spruce forests.

The presence of large quantities of damaged trees allowed bark beetle populations to transition from an endemic to an epidemic presence, expected to last for several years. Anticipating such a proliferation, which regularly occurs after extensive forest damage from wind or snowfalls, the Province of Trento, immediately after the Vaia storm, activated an extensive monitoring system for the insect populations, in collaboration with the Fondazione Mach.

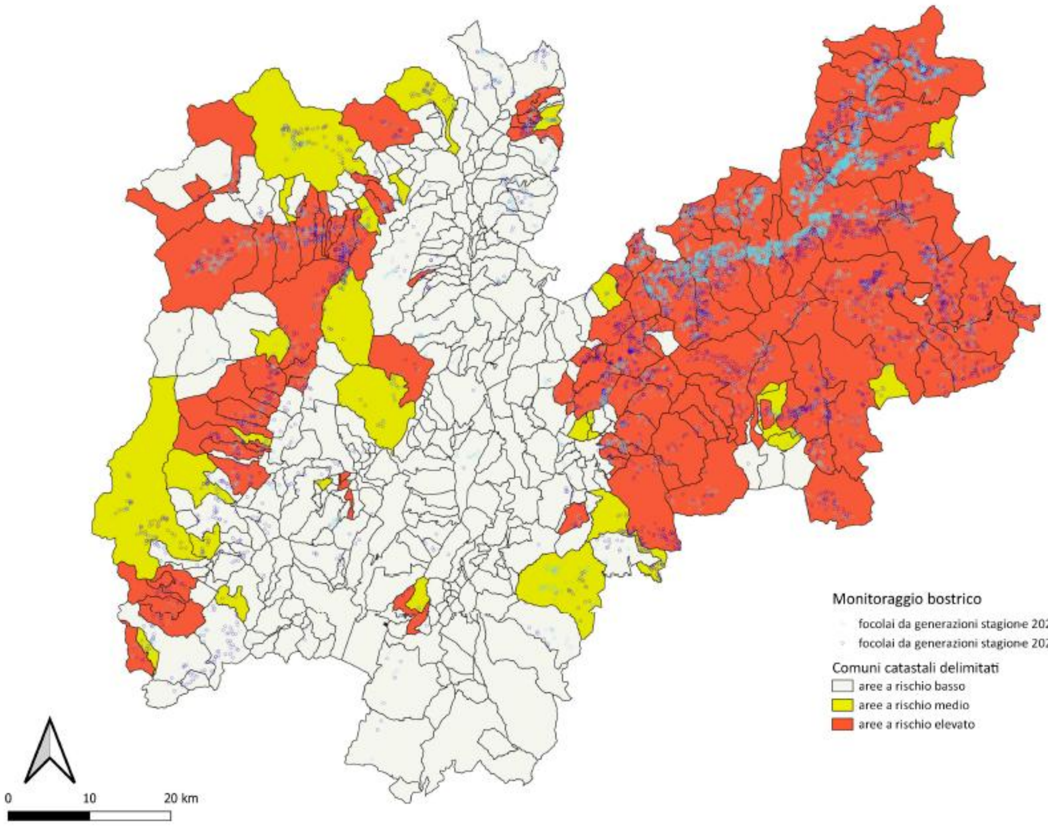

Fig.6 Map of the bark beetle infestation status. The points indicate the outbreaks detected in 2022 and 2023, while the coloured areas correspond to the infestation status in 2024 (absent in white, moderate in yellow, and severe in red).

As of August 2023, the damage attributable to the bark beetle from 2019 to 2022 amounts to approximately 2.6 million cubic metres of timber, about half the damage caused by Vaia, estimated at around 4 million cubic metres. In terms of area, over 13,000 hectares of forests, predominantly in the eastern sector, have been affected by infestations, with significant forest cover loss, especially in certain watersheds.

The rising bark beetle infestations pose one of the most immediate and evident threats to Trentino's forests. However, predicting their progression is challenging due to the lack of comprehensive studies.

The rise in temperatures under various global warming scenarios could also lead to the proliferation of other pathogenic organisms, such as fungi and insects, which no longer remain in the larval stage due to the elevated temperatures observed even in winter. An example of this is the pine processionary caterpillar, a moth with strong urticating and allergenic properties, which increasingly poses a threat to Trentino's forests and parks.

Avalanches

The assessment of the impact of climate change on avalanche risk is complicated by the challenges of monitoring both the snowpack and avalanche activity. The evolution of avalanche phenomena in a warmer climate remains largely unknown and understudied.

On a physical process level, avalanche activity is influenced by rising temperatures and snow accumulation, which have undergone significant changes in recent decades in the Alps.

The snowfall regime in the Alps and Trentino between 1971 and 2019 has shown high interannual variability and a general trend towards reduced snow cover and shorter snow duration on the ground, particularly below 2000 metres above sea level, while no significant change has been observed at higher elevations. Studies conducted in the Alpine region indicate an average decrease in avalanche activity, though with significant interannual variability. This decrease is expected to be more pronounced in the spring and at lower altitudes (primarily due to reduced snowfall), while an increase in avalanches is anticipated in the winter at higher altitudes due to warmer temperatures.

Overall, a future increase in wet and moist snow avalanches is expected, while dry snow avalanches are likely to decrease.

Forest fires

Wildfires are destructive phenomena that often cause irreparable damage to forest ecosystems and pose a threat to human safety. Therefore, they must be carefully considered even in regions like Trentino, where they are relatively infrequent and have shown a general downward trend over time in both the number of events and their extent. Over the past two decades, data from the PAT Forestry Service show a fluctuating annual trend in the number of wildfires, largely explainable by precipitation patterns: 2002 saw the highest peak with 100 fires, while 2014 recorded a minimum of 5 fires.

The frequency of wildfires in Trentino and the Alps is higher during months with low precipitation and when there is an accumulation of dry matter in the underbrush, particularly in the winter-spring season. However, in years characterised by particularly hot and dry summers, climatic conditions can also favour the occurrence of fires in the summer season. For example, in 2013, 82% of wildfires in Trentino occurred between June and August, ignited by both human activities and natural events (such as lightning).

It is important to note that, although natural factors like drought can influence the likelihood of fire development, their ignition is often directly or indirectly caused by human actions, mostly unintentionally, due to careless behaviour or insufficient precautionary measures during agricultural operations or other activities. From 2001 to 2021, fires caused by humans, whether intentional or accidental, accounted for about 62% of cases in Trentino. During the same period, fires caused by natural events made up 18% of the total, while for the remaining 20%, the causes could not be determined with certainty.

Despite current trends towards a decrease in wildfires, it cannot be ruled out that the projected future increases in temperatures, heatwaves, and prolonged drought episodes could potentially elevate the risk of wildfires even in Trentino.

Heat waves and effects of the increasing temperatures

Increasing extreme higher temperatures and especially longer and more intense heatwaves are among the climatic risks that could have a significant impact in the future, both in terms of morbidity, mortality and economic losses, their effects being particularly amplified in larger and densely populated urban areas. Indeed, widespread warming, with significant positive trends in maximum-related mean and daytime temperature extremes, has been observed in the area. In Trentino, the duration of heatwaves is also increasing rapidly and noticeably, with about 20 more days per year on average in 1991-2020 compared to 1961-1990, and peaks of up to 35 additional days. The number of summer days (Tmax > 25°C) and tropical nights (Tmin > 20°C) per year is also diffusely increasing in the area. In Trentino-Alto Adige, between 1981 and 2018, heatwaves have shown widespread increasing trends, leading to a growing exposure of the population to extreme heat. In the same time interval the entire region has experienced an increased risk of heatwaves (~12% higher), much more pronounced (~45% higher) in larger cities. The hazard intensity is without a doubt the main driver that determines the risk level for heatwaves (although some variations in exposure and vulnerability of the population may occur too in the medium-long term, due to external phenomena like ageing population and migration to the larger cities).

Apart from their negative effects on human wellbeing and health, especially for vulnerable and exposed groups (children, elderlies, outdoor workers in agriculture, building industry and others), increasing extreme temperatures and prolonged heat waves in Trentino could also impact negatively the wellbeing of farmed animals and their production (e.g. milk, fish, honey, …), increase the energy demand for cooling of residential and commercial buildings, intensify summer tourist flows (causing overcrowding) and promote the probability of forest fires and associated damages to roads and infrastructures.

Droughts

In the Alps, clear changes in the seasonality of drought are observed, which could become more persistent in the future due to altered seasonal precipitation patterns, reduced snow cover, and increased evapotranspiration due to higher temperatures. These changes have significant effects on natural systems and socio-economic sectors. The concurrent increase in water demand from sectors like agriculture and hydropower production may exacerbate conflicts between different uses, especially in the summer season.

Throughout the Italian Alpine region, since the 1990s, there has been a notable snow drought, particularly in the last decade (2013-2023). In Trentino, the maximum duration of periods characterised by absence of rain has increased significantly, by about 2.5-3.5 days in the thirty-year period 1991-2020 compared to 1961-1990 (approximately a 10% increase). The combination of reduced snowmelt contributions, prolonged absence of liquid precipitation, high temperatures, and increased water demand has recently led to severe drought and water scarcity events across northern Italy, including the Adige River basin, in early spring and late summer 2022, and across southern and central Italy since the beginning of 2024. The 2022 situation resulted in trans-regional conflicts between different water uses, especially between hydropower companies managing upstream reservoirs in the Alps (e.g. in Trentino) and farmers in the downstream plains (e.g. in Veneto and Emilia Romagna).

More intense and frequent drought events in the future could also potentially amplify the risk of forest fires due to dryer conditions and the risk of proliferation of pests like the spruce bark beetle, resulting in multiple cascading effects like a reduced ecosystem services provision, such as protection against hydrogeological risks.

Additionally, dry and arid soil struggles to retain short-term heavy rains, which are expected to occur more frequently in the area based on results from the study conducted during WP1. This can lead to increased surface runoff, moving larger amounts of debris material, thereby increasing solid transport and flow rates in streams and rivers.

A study by the European Environment Agency estimated that there was a statistically significant and quite substantial reduction in soil moisture content in the area, particularly in southern Trentino, between the summers of 1951 and 2012. The same study highlights that future projections estimate a further moderate reduction in southern Trentino. This persistent decline in soil moisture could also result in lower crop yields and increased irrigation needs for agricultural lands.

The future scenarios developed by the University of Trento in the framework of the "Trentino Clima 2021-2023" work program specifically for the provincial territory highlight that:

- Average temperatures and extreme warm temperatures are expected to increase.
- Average summer precipitation is expected to slightly decrease while consecutive dry-day periods show no significant trends in general.
- Due to lower precipitation and stronger evapotranspiration "hydrological drought" and "agricultural drought" conditions are expected to become more common.

Sources:

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- Provincia Autonoma di Trento (2024): Lo stato del clima in Trentino. A cura di: Provincia Autonoma di Trento, MUSE - Museo delle Scienze di Trento
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III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

For the processes identified in the previous response, we have tried to quantify as accurately as possible the frequency and magnitude with which they have occurred in the past and how we expect these to change in the future. Providing a quantitative answer for some of these aspects is very difficult, partly due to the limitations of the available databases: the time period covered by sufficiently accurate and consistently collected data is not very long, and for less recent events, the available data is incomplete.

Another aspect to consider is the breadth of the analysis required by the case study of our pilot area: the processes that occurred following the Vaia storm and that we expect may happen in the coming years due to climate change are numerous, very broad, and varied. To delve into this analysis at the highest level of detail for all these aspects would have required a much larger scope of work than what was allowed (temporarily and resource-wise) within this project.

A recent publication (Jacquemart et al. 2024) extensively reviewed the evidence of the impacts of climate change on alpine mass movements from observational records and found that about one third of the relevant studies detected a measurable impact on the investigated processes. Despite the fact that no study has been included for the territory of the Province of Trento, we assume that some of the key results of the review may be considered valid for the present analysis and we included them in our answers.

However, in general the literature analysis revealed that quantifying such impacts remains difficult due both to the inherent complexities of the natural system and to the limitations in the available datasets, confounding effects, and existing statistical processing techniques. This is also true for other types of hazards/events, like floods, wind-induced forest collapses, bark beetle pullulations, forest fires, etc.

Floods and torrential phenomena

In the early 2000s, the Province of Trento, as a partner in the European project DIS-ALP (Disaster Information System of ALPine regions), initiated an activity to improve and standardise its methods of documenting flood events shared among the various Alpine regions. The project defined shared methodologies and criteria for field data collection of flood events and their implementation on a GIS-based database. In 2012, the Service for Torrent Control of the Province of Trento began its work to enhance flood event documentation by researching historical sources (e.g., newspaper articles, ecclesiastical archives, and disaster event databases) and cataloguing records of past flood occurrences. The knowledge of historical information is extremely useful for forecasting and preventing future events, and understanding the possible hydrogeological response of the territory to heavy weather events. For this reason the importance of collecting information on historical flood events is also recognized by the European Union: the Floods Directive 2007/60/EC requires flood event reporting as an integral part of the cycle of flood risk prevention in the preliminary assessment phase. Currently, the catalogue of flood events of the Service for the torrent control collects about 4000 events over the past century, describing the effects and damage caused to the territory by flood phenomena, classified as liquid flood, solid transport, debris flow or other. It is important to consider that the classification of events is not always clear and unambiguous. In addition, the information is often derived from direct observation of events that have already occurred. More specifically, these are reports of flood events and, for this reason, tend to be concentrated mainly in urbanised areas, thus representing only a part of the total number of events that have really occurred. The density of these points depends, therefore, on the sensitivity of the observer and the frequentation of the sites. Moreover, the increased use of the territory and the greater availability of data have led, over time, to an increase in the reporting of events, with even events with not very significant damage being recorded although still important for the analysis of the phenomena.

The Floods Directive defines some terms used, by adapting them to the Province of Trent database, in this questionnaire. In particular, an **event**, defined as the occurrence of a meteorological event that has significant effects on the territory and is described in terms of location -as a unit of management- and by some data summary of precipitation. The event expression on the territory is represented by the **phenomenon**, described mainly in terms of location on the territory and the type of origin. While the local effects of the phenomenon are represented by the **mechanisms**, described mainly in terms of the mechanism and dynamics of overflow and damage caused at a given location. Damage classification follows the risk receptors defined by the Flood Directive.

There are nearly 300 total reports of flood events within the pilot area (Fig. 9). On a larger time scale at the provincial level there are three major flood events that affected the whole territory: 1882, 1966 and 2018 (storm Vaia). Evidence of the 1882 and 1966 floods is also numerous in the Fiemme and Fassa Valleys, as shown in Fig. 7. Over the years, numerous local events capable of causing significant erosive phenomena and the downstream transport of abundant debris and driftwood causing - cases in some damage to hydraulic defence works, road infrastructure and private homes - have also been observed.

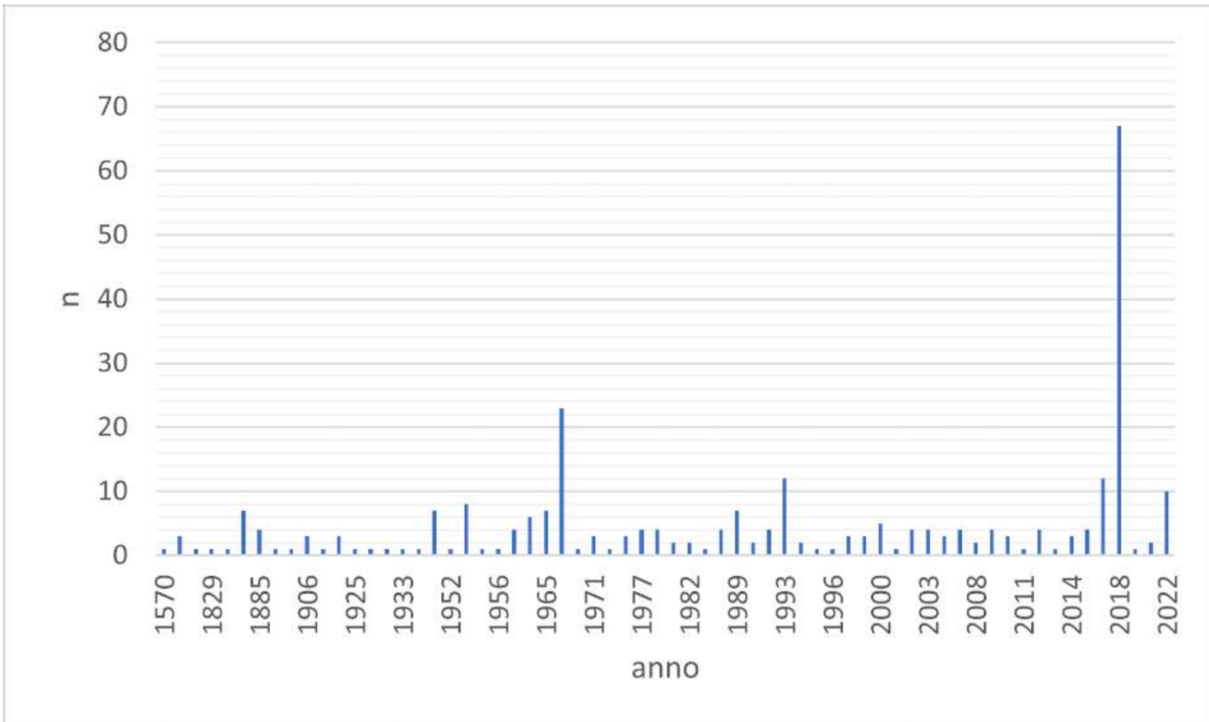

Fig.7 The number of flood events within the pilot area archived in the flood event registry

Liquid floods were the most frequently observed phenomena, although debris flows and liquid floods with solid transport were also numerous. The following Fig. 8 shows the number of flood-affected areas recorded in the catalogue of flood events for the Avisio River Basin distinguished by type of phenomenon. As can be seen, most of the flood-affected areas were due to impulsive debris flows or solid transport phenomena. The low frequency of events recorded as “hyperconcentrated floods” is probably related to the difficulty of identifying a phenomenon that is located between solid transport and debris flow.

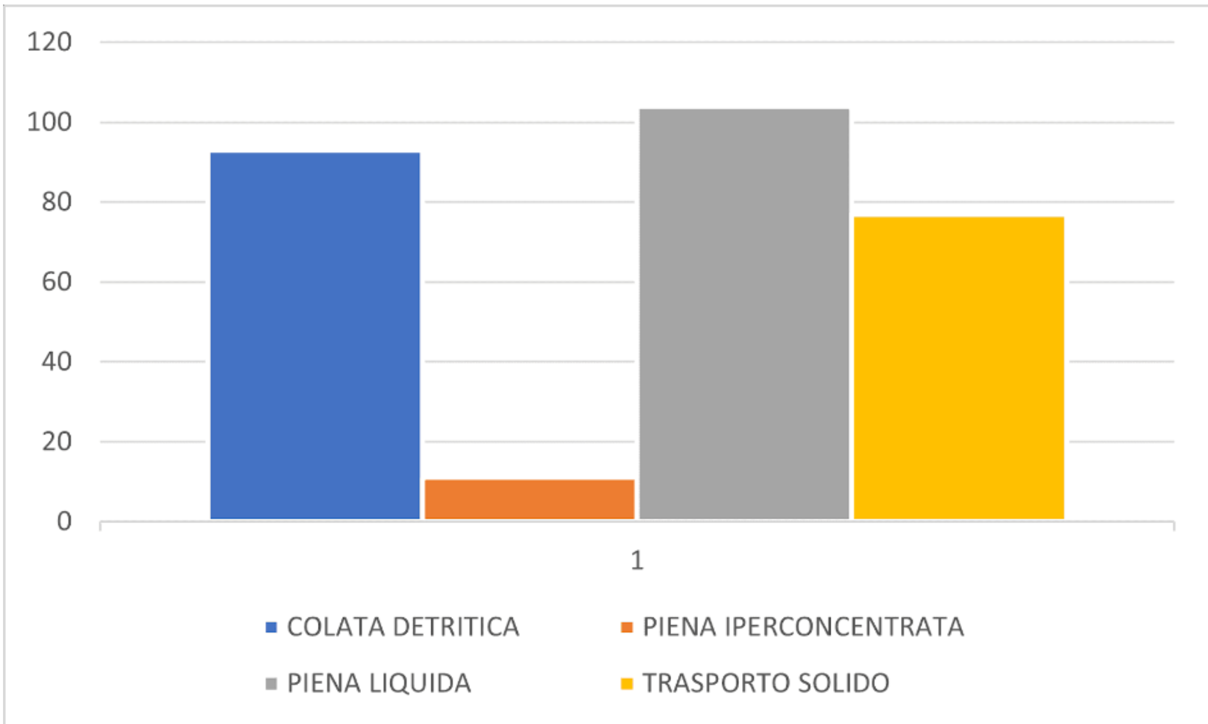

Fig.8 Number of flood-affected areas recorded in the catalogue of flood events for the Avisio River basin by type of phenomena.

During VAIA, heavy rainfall falling on soil already saturated and weakened by the collapse of extensive forested areas caused widespread phenomena of hydrogeological instabilities. Numerous processes of bed erosion, sediment deposition, and logging have been observed. These significantly affected the whole Avisio stream watershed characterised by a limestone substrate, which facilitates an abundant sediment supply, and heavily vegetated slopes.
In accordance with the classification of the Floods Directive, 34 flood phenomena were recorded; these affected 141 different areas or stream sections (mechanisms). In particular, among the affected areas (mechanism), the most frequently observed process was liquid flood with solid transport with 90 occurrences, while 20 were classified as debris flows and 31 as liquid floods (22 occurred in part of the Avisio stream).

Considering the magnitude of the process as the amount of damage caused in the affected areas—while acknowledging that this approach inherently includes the concept of vulnerability—the mechanisms that resulted in the greatest number of high (significant) damages during Vaia were primarily related to liquid flood processes accompanied by solid transport. However, as shown in Fig. 9, the most frequently observed classes of damage were medium and low damage. The severity of the events, in fact, was effectively mitigated by the numerous hydraulic structures located along the watercourses. Thus, damages of low magnitude were mostly observed and often limited to the agricultural and forestry sector along the slopes. In the main river network, liquid flood phenomena mostly occurred, causing a high number of medium damage, but in fact limited to the riverbed and hydraulic works. In practice, analysing the data critically, also considering the flow rates of the main river network, the events with the greatest magnitude were solid transport and debris flow (see Fig. 9).

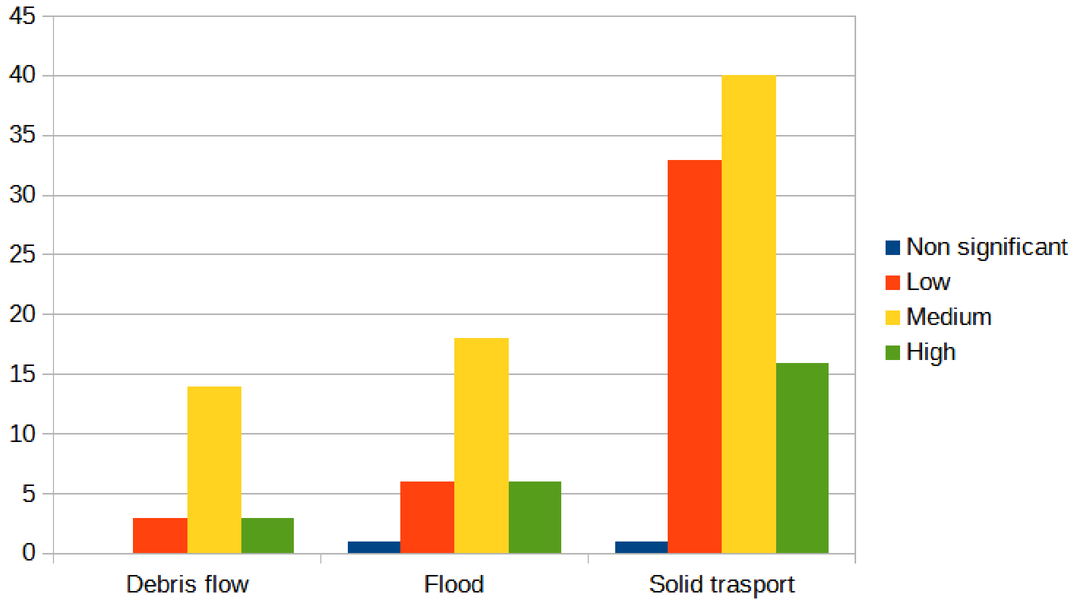

Fig.9 Number of events occurred during Vaia in the study area and recorded in the catalogue of flood events based on the type of event (debris flow, flood, solid transport) and the magnitude expressed as the severity of the damage (insignificant, low, medium, high).

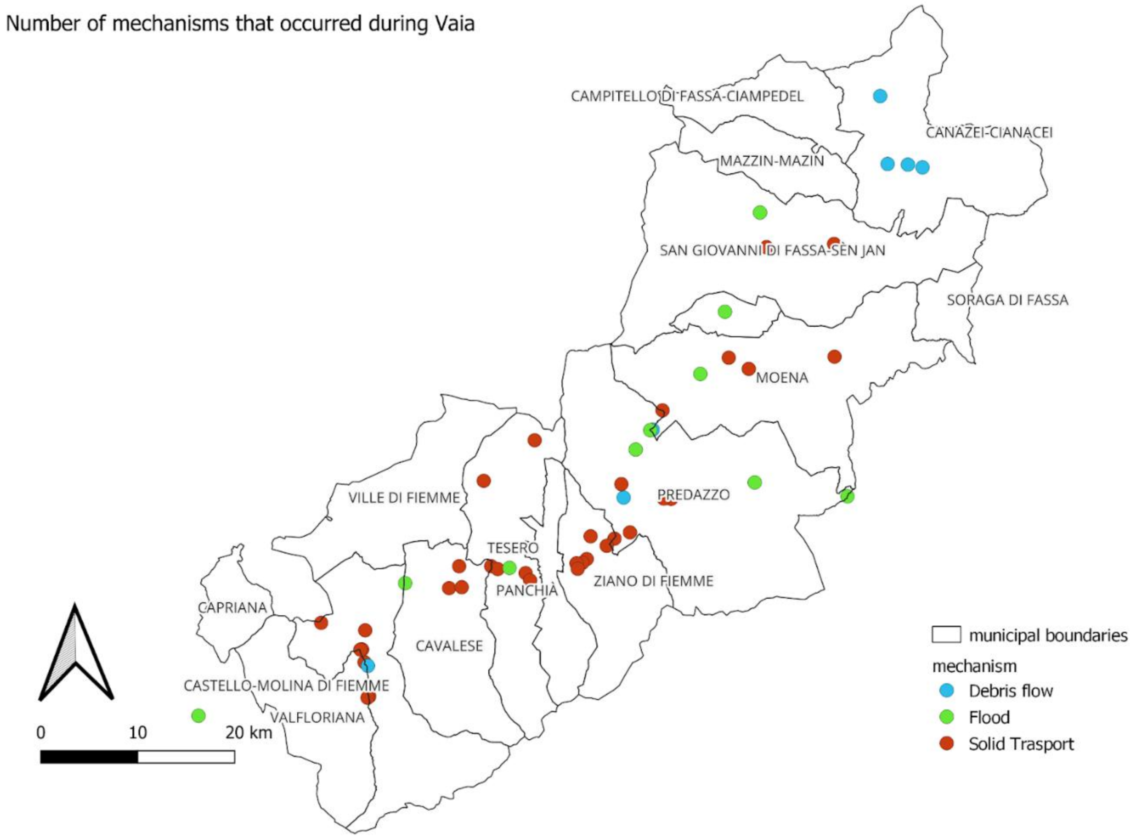

Fig.10 Map of the events that occurred during Vaia.

The analysis of historical data does not show a clear trend of flood events in Trentino. This is also confirmed by a recent study by Schlogl et al. (2021), who analysed a database of data on torrential floods that caused damage (including debris flows) in the Austrian Alps. Considering only debris flows, a similar result is reported by Jacquemart et al. (2024) for the Alps. Although there is a growing trend in precipitation events that trigger such phenomena, there is no evidence that they are increasing. However, there is evidence of increased debris flow activity in high elevation areas above the tree line and in areas where such events have not historically been observed.

Based on the evidence, it appears that some weather events are able to trigger a cycle of instability in watersheds considered stable, making them more susceptible to intense precipitation and, consequently, new flood events in following years. In addition, due to permafrost degradation and glacier melting, we expect new events in areas where historical events have never been reported.

Regardless of the previous consideration, it is reasonable to expect an increase in mass flood phenomena in Trentino, as their occurrence is primarily controlled by meteorological conditions for which an increase in intensity and frequency is expected. Additionally, based on the results of WP1, there is a higher probability that these events will occur during the autumn season in Trentino. Drier summers could lead to the accumulation of a larger amount of sediment within or near the riverbed, resulting in less frequent but higher magnitude mass transport events in the summer season in the future (Stoffel et al., 2014).

Expected future tendency for Trentino in brief:

At present, there is no clear trend emerging from historical observations that indicates an increase in these processes in the recent past (partly due to certain objective limitations of the databases available for analysis, which do not allow for quantitative indications). However, though this is difficult to quantify, it is reasonable to expect a future increase in both the intensity and frequency of flood and mass movement events due to the changing precipitation patterns that generate them. The effect of risk mitigation measures implemented over the years may have masked the observable trends of a climatic nature.

Wind-induced forest collapses

During the Vaia storm, approximately 20,000 hectares of forest were damaged, with an estimated damage of over 4 million cubic metres at the provincial level (Fig. 12), of which more than a quarter occurred in the Val di Fiemme and Val di Fassa, as shown in Fig. 11 and 13. In the latter figure, the distribution of the areas damaged by Vaia, based on the owners of the forest lands, can be seen. About 12,000 hectares were completely felled, while the remaining 8,000 hectares experienced scattered tree falls that reduced forest density.

For data collection of the tree falls, three damage levels were defined: severe (level 3), medium (level 2), and low (level 1). Level 3 corresponds to damage exceeding 70%. This level was determined using a supervised classification of high-resolution satellite images from Pleiades, SuperView, and GeoEye. The other two levels were digitised by forestry staff from forest stations and districts and correspond to damage ranging from 30 to 70% and from 10 to 30%, respectively. Each polygon with a damage level is accompanied by the volume of damage in cubic metres. This data is derived from the average volume per hectare of the forest parcel where the tree falls or its portion occurs. The polygons are divided by forest management plan and by forest district.

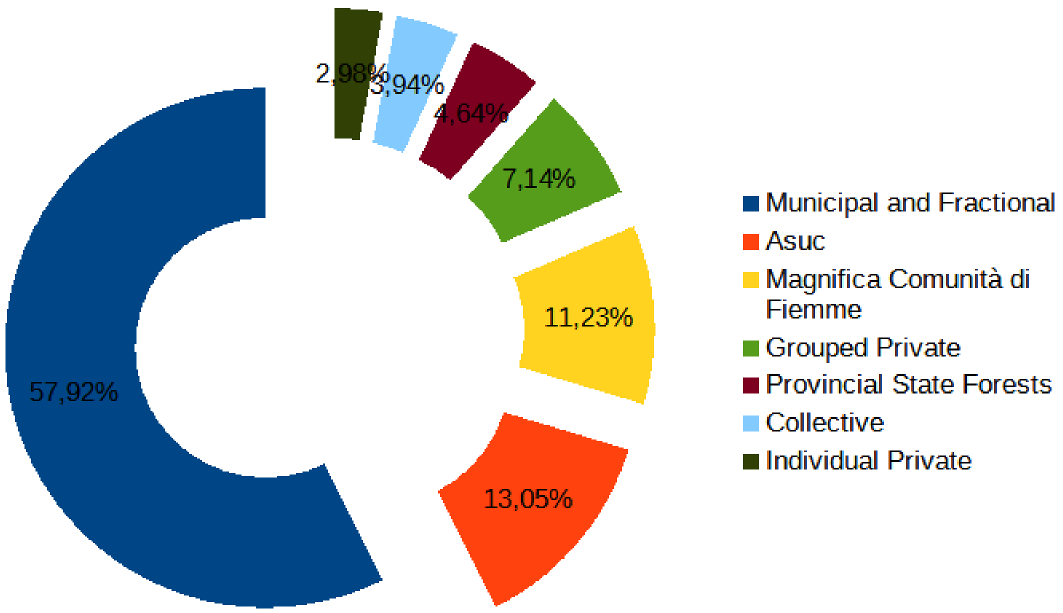

Fig.11 Damage Distribution by Property Type in Trentino Due to the Vaia Storm

Damage	Surface [ha]	Surface [%]	Solid Standing Volume [m^3]	Volume [%]
<30%	4156	21	240200	6
30-50%	2842	15	320200	8
50-90%	4917	24	986222	24
>90%	7885	40	2552100	62
TOTALE	**19800**	**100**	**4098722**	**100**

Fig 12. - Assessment of the extent of crashes divided by damage classes.

UDF	Solid Standing Volume m^3
Borgo Valsugana	652531
Cavalese	1323779
Cles	34874
Malè	58912

Pergine Valsugana	767013
Primiero	490344
Rovereto	304224
Tione	197215
Trento	73898
PAT property	195932
TOTAL	**4098722**

Fig. 13 - Damage distribution based on the forest district office.

From 1882 to the present, there have been at least seven incidents of damage caused by extraordinary weather events, the most catastrophic of which was undoubtedly the one coinciding with the historic flood of 1966. The cyclone of November 4, 1966, particularly affected the southern part of the forest, causing the loss of over 90,000 cubic metres of timber, equivalent to 27% of the total mass. It took more than a year to recover all the fallen and uprooted timber across more than 70 hectares. For an immediate recovery of the forest vegetation, more than 150,000 seedlings, almost all spruce, were planted between 1968 and 1971.

The results from WP1 show that there is no clear trend towards an increase in the intensity and return period of extreme wind events. Due to the observed trend of increasing intense precipitation episodes, the analysis conducted in WP1 forecasts an increase in events that combine precipitation and wind (as occurred during the Vaia storm). By the end of the century, a halving of the return periods is expected. We can therefore reasonably anticipate that widespread forest collapses caused by such composite events will be more likely in the future and occur more frequently than experienced in the past; a ground saturated by prolonged rainfall can indeed lead to a higher probability of collapses.

<u>Expected future tendency for Trentino in brief:</u>

At present, there are no studies that analyse observed or foreseeable trends for this type of phenomena. The X-RISK-CC analyses do not reveal future increasing trends but predict a substantial stability. However, if we consider compound events involving extreme wind and precipitation, which X-RISK-CC predicts to increase in frequency and intensity due to the contribution of extreme precipitation, it is reasonable to expect an increase in damage to forest assets caused by such compound events.

Bark beetle

In spruce-dominated forests, one of the main secondary effects of large-scale disturbance events such as windthrows, snowbreaks, or prolonged drought is the proliferation of bark beetle populations. Experiences from other European countries, which have already been affected by intense and widespread disturbances, have shown that bark beetle outbreaks following severe disturbances last on average 5-6 years, with the peak infestation occurring in the second and third years, followed by a progressive decline in subsequent years. In fact, the damage caused by the outbreaks is distributed over a longer period of time compared to that caused by the initial windthrow. Monitoring of bark beetle population densities and the resulting damage is carried out through trapping and extensive damage monitoring, respectively.

Immediately after the Vaia storm, in Trentino a monitoring network with traps was immediately activated. In 2019, only 10% of the traps exceeded the alert threshold, mostly in areas not affected by Vaia. However, a significant increase in the population in the areas affected by the storm occurred starting in 2020, with 80% of the traps exceeding the alert threshold. In 2021, there was a slight decline (77% of traps) followed by a resurgence in 2022 (86% of traps), partly due to the particularly widespread drought conditions of that year.

The actual duration of the phenomenon, and thus the overall damage, is heavily influenced not only by the speed of removal of the trees damaged by the initial event (the disturbance), but also by seasonal weather and climatic conditions that are more or less favourable to the insect. The substantial unpredictability of these factors makes it difficult to precisely forecast the duration of the outbreak in the Province of Trento.

In some areas of Trentino, particularly in the pilot area, namely the Valleys of Fiemme and Fassa, the damage caused to the forested areas by the bark beetle has been more severe than that caused by the Vaia storm itself.

Since 2019, mapping of areas affected by bark beetle infestations has begun in Trentino. This mapping is conducted by forest stations throughout the region. Damage, in terms of affected forest area and cubic metres of timber, is recorded for each year in which the infestation occurs. The damage year is conventionally defined as running from June 1 to May 31 of the following year. Consequently, if bark beetle damage is detected before June 1, it is attributed to the previous year; conversely, damage detected after June 1 is attributed to the current year. This is because the first generation of bark beetles typically emerges in the spring, so damage observed before May 31 is considered to be from infestations that occurred the previous year but only became visible later due to the winter dormancy period.

Currently, the Forest Service is conducting a study with FEM using Sentinel data to track how the bark beetle population evolves over the years in the affected areas.

<u>Expected future tendency for Trentino in brief:</u>

It is not easy to predict the trend of future bark beetle outbreaks, as they are triggered by a combination of factors. Rising temperatures and drought periods may contribute to an increase in bark beetle populations.

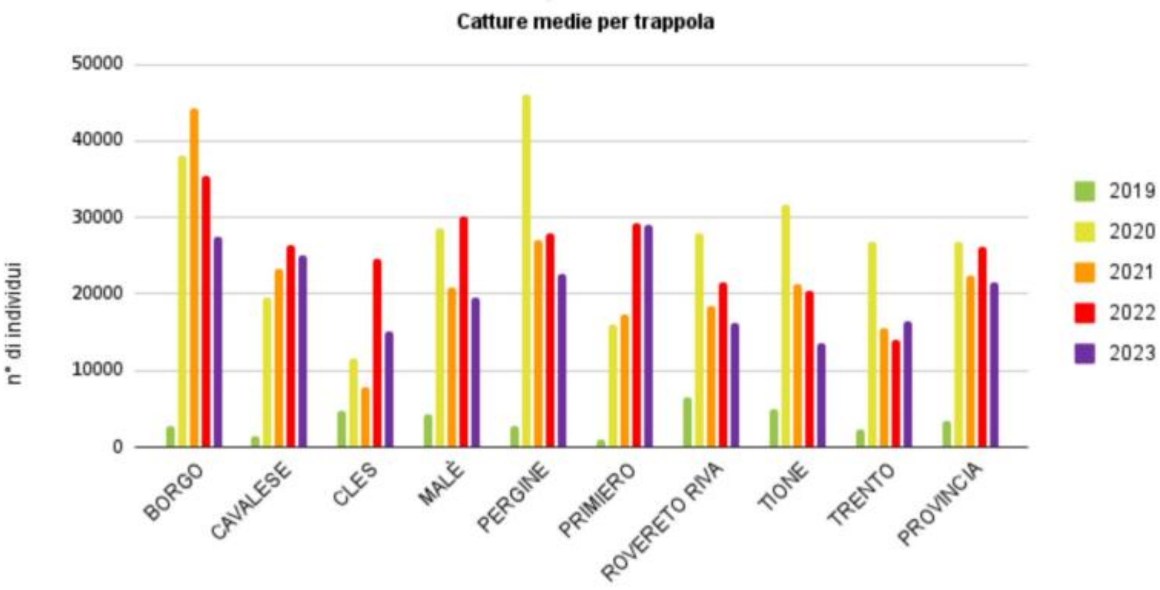

Fig. 14 Variation over time in the average number of catches per individual trap in the different districts/areas, from 2019 to 2023, shows a clear acceleration of the bark beetle outbreak in 2020 and the following years, with some signs of a partial slowdown in 2023.

Avalanches

Trentino monitors avalanche risk through the avalanche inventory, which documents and maps data related to avalanche events recorded from the early 1970s. The inventory is primarily compiled by forestry personnel and, being designed mainly for forest management, it almost exclusively reports avalanches that have affected wooded areas, with damage to vegetation, while documentation of phenomena impacting high mountain areas is almost entirely absent. The inventory has not been updated since the 1990s, although there are recent plans to resume activities and integrate new reports.

Subsequently, for areas of particular avalanche interest, an inventory of avalanches has been carried out through the development of the Probable Avalanche Localization Map (CLPV). Both documents consist of a cartographic section, showing the location of various avalanche sites, and sheets with detailed descriptions of the various phenomena. The CLPV has been created for about 40% of the provincial territory and is drafted following a methodology now internationally recognized, which overlays two separate sources of information while preserving, even graphically, the distinction between the different analyses performed. The data obtained through direct field investigation, bibliographic study, archival research, and interviews with direct witnesses of avalanche events (field survey) is complemented by general morphological studies, traditionally performed through aerophotogrammetry (photo interpretation). The CLPV is prepared for analytical and study purposes, which do not explore aspects such as return periods of avalanche events and do not assess the specific characteristics of the recorded events. This document is simply a summary of the facts known at the time of its publication and does not contain any predictions regarding the potential future limits that avalanches may reach.

Based on general considerations identified for the Alpine arc in the study by Jacquemart et al. (2024), it is observed that at lower to mid-elevations, fewer and less intense avalanches are expected in the future due to scarcer snow conditions. It is also anticipated that the number of wet avalanches may increase at the expense of powder snow avalanches. Trends for ice avalanches are spatially very variable with no clear direction, meaning that despite the fact that ice temperatures are measurably increasing, ice avalanche activity has not been impacted to date.

<u>Expected future tendency for Trentino in brief:</u>

There are no local studies currently available that can tell us how avalanche activity is expected to change in the near future in Trentino. However, it can reasonably be said that a decrease in snowfall at lower elevations, and consequently, a decrease in avalanche probability at those elevations are expected, as recent literature also confirms for the Alpine region.

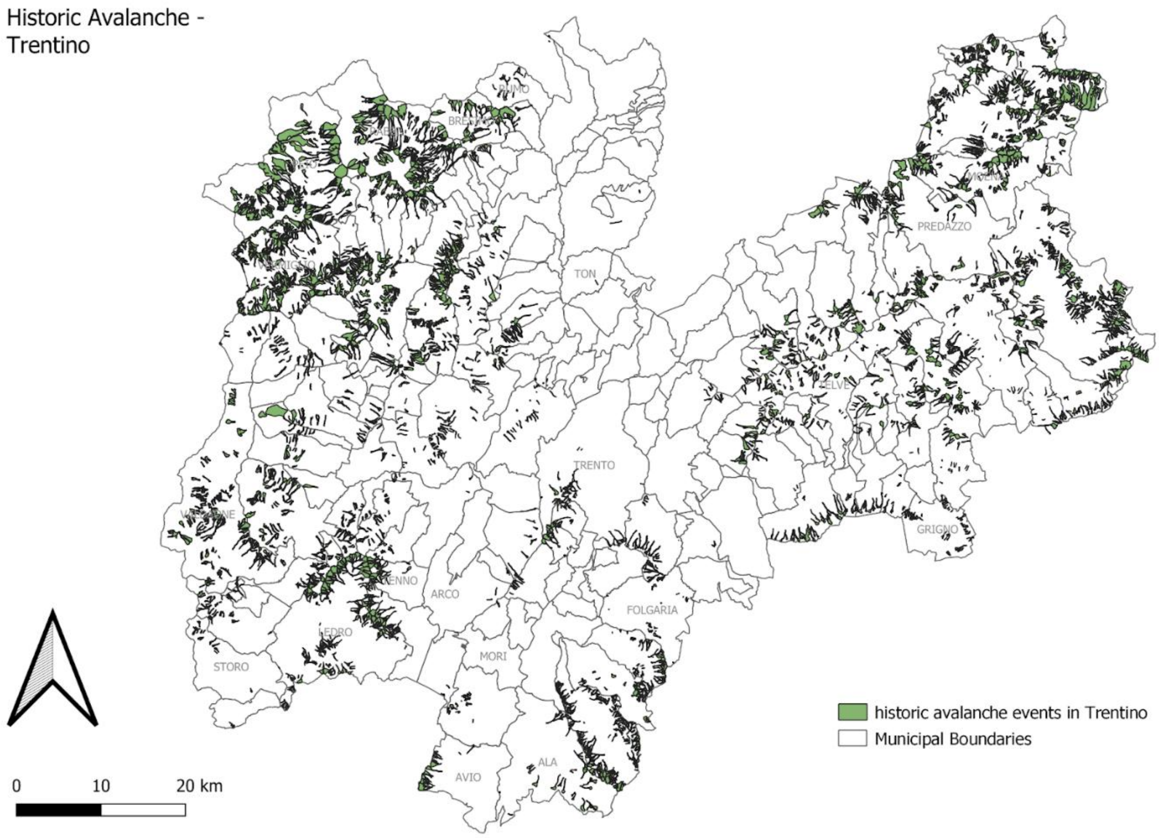

Fig.15 Map of the recorded historic avalanche events in Trentino.

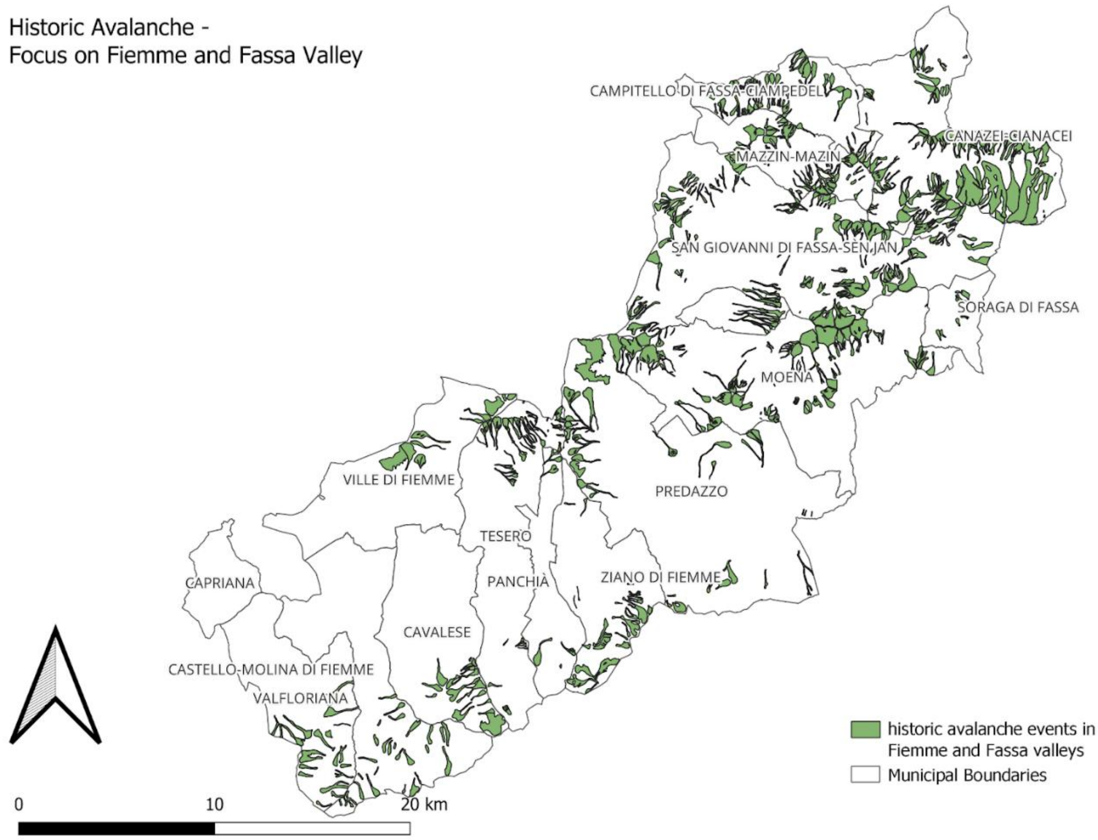

Fig.16 Map of the recorded historic avalanche events with the focus on Fiemme and Fassa valleys.

Forest fires

A consequence of climate change already observed in recent years globally, is the increase in the number of forest fires, their extent, and persistence. This is due to the concurrence of more frequent prolonged drought conditions and relatively high temperatures, which are particularly favourable to both the ignition and spread of fire. These phenomena can significantly contribute to the release into the atmosphere of both pollutants (mainly nitrogen oxides and particulates) and greenhouse gases (carbon dioxide).

Expected drought conditions in summer can change the predisposition of forests in the following ways: increased ignition probability due to lower moisture content and higher flammability of fuels, influenced by weather factors such as high temperatures, heatwaves, prolonged drought periods, and strong winds. Additionally, drier soils and vegetation result from earlier snowpack melting in spring, causing forests to remain drier and more flammable for extended periods. Both factors could lead to an increased probability of wildfires.

After a wildfire has ravaged a watershed, it has various implications. The loss of protective forest and vegetation, coupled with increased hillslope-channel coupling, can lead to debris-laden flows. Additionally, there is enhanced debris flow activity for at least two years.

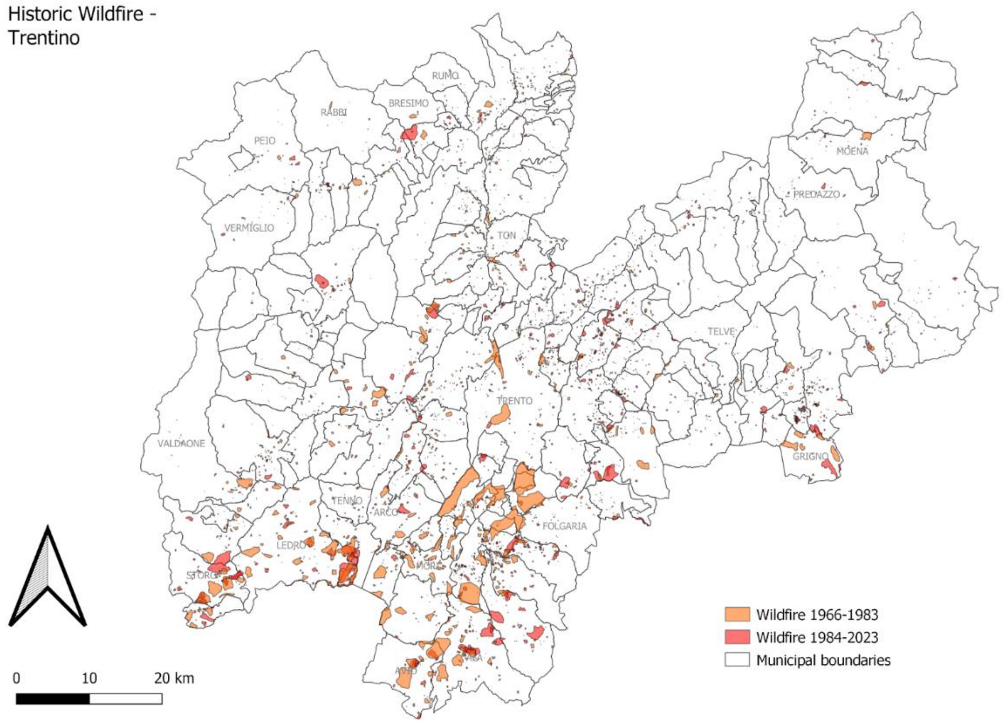

Fig.17 Map of the recorded historic wildfire events in Trentino.

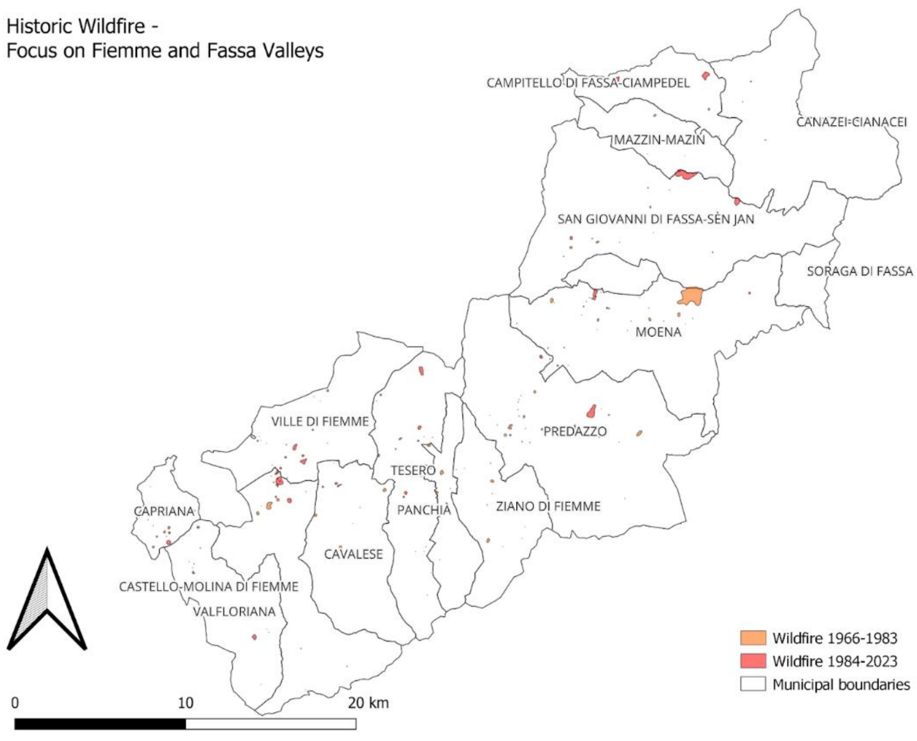

Fig.18 Map of the recorded historic wildfire events with the focus on Fiemme and Fassa valleys.

Expected future tendency for Trentino in brief:

Climate change can affect the frequency of wildfires: higher temperatures and the increasing frequency and severity of summer droughts in the future could indeed promote the ignition and spread of these phenomena, leading to more severe and frequent damage. In Trentino, however, an increase in wildfires has not been observed so far, thanks to the excellent maintenance of the forests.

Heatwaves

In order to analyse the heatwave phenomena, the ETCCDI index "Warm spell duration index" (short name is WSDI) is commonly used for analyses at daily resolution. The index is defined as the annual count of days with at least 6 consecutive days when daily maximum temperature is above the calendar day 90th percentile of maximum temperature centred on a 5-day sliding window during the base period (1961-1990; WSDI is measured in days). In Trentino WSDI is rapidly increasing, by about 20 days more in the period 1991-2020 with respect to 1961-1990, with peaks of about 35 days more detected at some stations. At present, however, there is no comprehensive analysis of such hazards and more investigation is needed, to expand the knowledge on prolonged warmer than average periods.

The future scenarios developed by the University of Trento in the framework of the "Trentino Clima 2021-2023" work program specifically for the provincial territory highlight that as far as temperature extremes are concerned, all climate change indices indicate an increase, with values varying according to the emission scenario (e.g. both summer days and tropical nights are expected to increase).

Expected future tendency for Trentino in brief:

Heatwaves are foreseen in general to increase in the future in frequency and intensity in Trentino, but no precise quantitative analysis is available at the moment.

ANALYSIS OF KEY RISK PATHWAYS

External factors and drivers of non-climatic nature

In addition to climate hazards and exposure and vulnerability factors, climate risks can be influenced (exacerbated or depleted) by external factors of a non-climatic nature. Typical examples are the dynamics affecting the demography of an area or changes in the presence of non-residents in the area (such as tourists). Other examples may concern trends related to new regulatory and normative interventions or to new technologies, as well as environmental or socio-economic trends unrelated to climate change.

As far as the Trentino region and the years to come are concerned, three external factors have been identified as relevant for this analysis.

Increase of tourist flows

Historical data for tourist presences in Trentino show steadily growing numbers, although slower in more recent years, which have recovered quickly after the decline experienced during the COVID phase. Also due to rising temperatures in the countries and areas of origin, a tendency of further increase in presences can be expected in the future, which will clash with a situation of over tourism already evident in some areas of Trentino, including Val di Fassa.

In general, an increase in the overall presence of tourists, that is people who do not know the territory and are therefore more vulnerable than residents to certain risks, can be expected in the future for longer periods than in the past. Limitations to over tourism will be only put in place for specific areas and will probably have no effect on total numbers.

Ageing of the population

The Trentino population has a younger age structure than the Country as a whole. The average age in 2022, up slightly from previous years, is 45.5 compared to the national average of 46.4. However, there are signs of progressive ageing of the population (Fig. 23) and of a reduction in the active population in Trentino as well, although with possible variations for different areas and valleys (source: Ispat). The expected percentage of population above 65 years is expected to grow by about 4% in the next decades to reach around 28% in 2050.

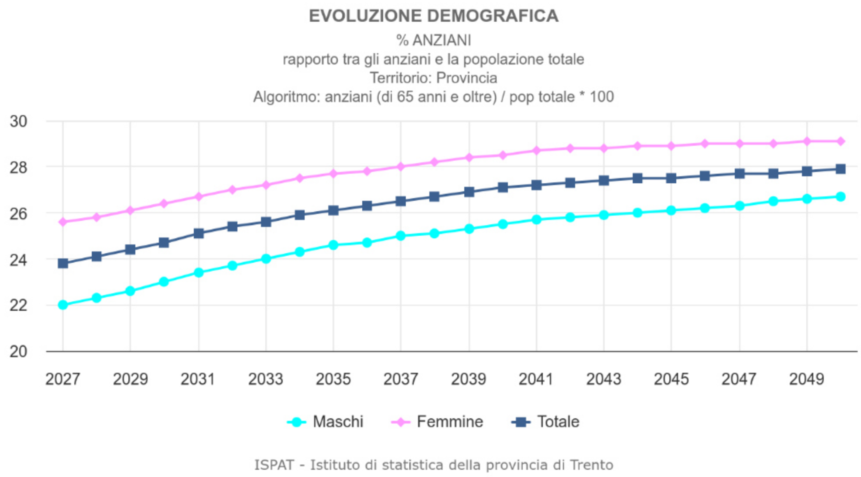

Fig. 23: Forecast of the ratio between elderly people and the total population in Trentino until 2050 (source: Ispat).

Population increase and urbanisation

The population of the Province of Trento has increased by 25% in the last 100 years, with an increase of more than 35% for the Adige Valley, Alto Garda and Ledro, the territory of the Comun General de Fascia and the Rotaliana-Königsberg plain (see Figures 24 and 25 for the study area). Future demographic scenarios elaborated by ISPAT (see Figure XX below) predict that the number of inhabitants in Trentino will grow slightly (about 2.5%, that is about 14.000 inhabitants) by 2050. At the moment, we cannot speculate what the internal redistribution of the population will be in the years to come, in particular in the two valleys under analysis.

As far as the spatial distribution of the population is concerned, the distribution by altitude band indicates that more than half of the population of Trentino (about 51%) lives in the valley bottoms (at altitudes between 0 and 250 m a.s.l.), and that only a 6% of the inhabitants live above 1,000 m a.s.l. If we only consider the overall trend at provincial level, we can speculate that the overall exposure of the resident population in Trentino will tend to remain more or less stable or have a very limited increase in the coming years. However, the fact that a large part of the population lives in the valley bottoms and that there is also a tendency towards greater urbanisation even in the Alpine area (with consequent depopulation of the more rural areas) will probably contribute to increase in relative terms the exposure to those climate risks that preferentially affect areas at lower altitudes and valley bottoms (the most populated 0-250 m a.s.l. altitude band), such as heat waves and/or river floods.

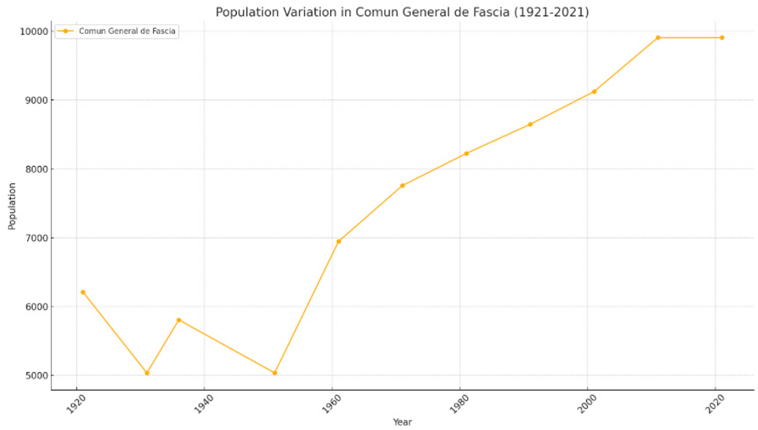

Fig. 24: Historical variation of the population in the Fassa Valley until present (source: Ispat).

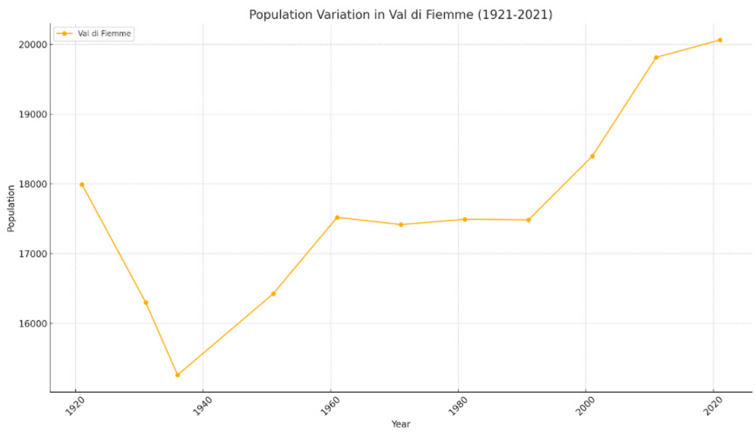

Fig.25: Historical variation of the population in Fiemme Valley until present (source: Ispat).

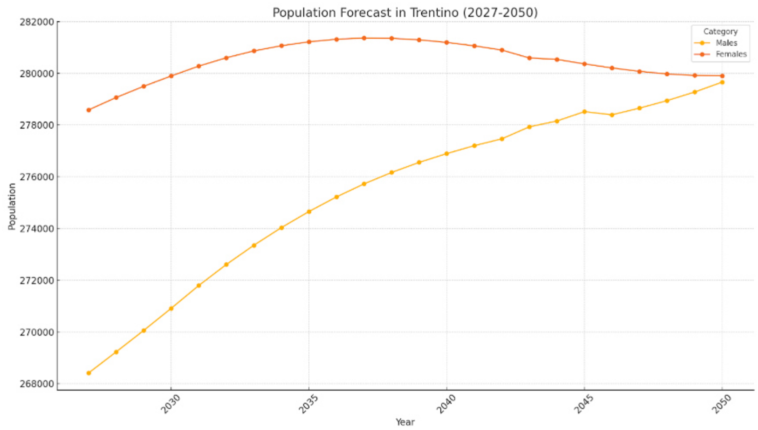

Fig. 26: Forecast of the overall population in Trentino until 2050 (source: Ispat).

ANALYSIS OF KEY RISK PATHWAYS

IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

In the analysis of risk pathways, we started by examining the exposed elements on the territory affected by the Vaia storm, and then expanded our considerations to include all the processes analysed in the previous responses and develop more generally valid considerations, taking into account the climate change scenarios in Trentino outlined in the WP1 analysis and the response to the first question. The areas of analysis in a large pilot case such as the Vaia storm are numerous, but we have tried to address them as comprehensively as possible in order to then proceed to the analysis of vulnerabilities, their potential changes in the future, and finally to possible solutions and adaptation measures.

The impacts of Vaia Storm

DIRECT DAMAGES

- Damage to people: two people died during the event, and three more in the following months due to incidents mainly related to collapses caused by the storm, a decrease compared to the 25 people who died as a result of the 1966 flood.

- Damage to forest heritage: see response 3 for details.

- Damage to road, cycling, pedestrian, forest roads, and trail networks:
The cost for the full restoration of road, cycling, pedestrian and railway networks amounts to 30.6 million euros, of which 93% pertains to road infrastructure (28.4 million euros), nearly 6% to cycling paths (1.8 million euros) and about 1% to railways (350,000 euros). In addition to these amounts, there are costs for the restoration or new construction of avalanche and rockfall barriers, for which an estimated expenditure of over 55 million euros has been projected.

- Damage to private property and vehicles:
According to official estimates, the damage to private movable and immovable property (homes, appurtenances, furniture and equipment, vehicles, urban or adjacent land properties) caused by the Vaia storm is quantified at around 9 million euros, of which 8.5 million euros for primary residences and 172,000 euros for vehicles. The greatest damage was concentrated in the territories of Fiemme, Fassa, Primiero, Valsugana, Val di Sole, Alto Garda and Ledro. The most widespread damage was caused by the wind, including roofs being blown off, trees uprooted and broken and power poles knocked down. Flood damage was mostly localised in Primiero, Fiemme and Val di Sole (Dimaro). As for vehicle damage, equipment and vehicles used by volunteer firefighters during rescue operations were also affected, with damages amounting to 278,000 euros.

- Damage to economic activities:
Damage to productive activities was recorded in the territories of Primiero, Fiemme and Val di Sole and is estimated, based on compensation claims and excluding those that occurred in Dimaro, at 7.6 million euros.

- Damage to agriculture and livestock farming:
For agriculture and livestock farming, the damages amount to just over 7 million euros, primarily concentrated in Valsugana, Primiero and Val di Non.

- Damage to wildlife:
According to information provided by the Forestry and Wildlife Service, it is currently not possible to provide a precise estimate of the damage to wildlife, as vast forested areas remain inaccessible. However, it is worth noting that in places where violent storms have occurred in the past, with tens of thousands of cubic metres of trees downed (as seen in Switzerland, Austria, and Germany), significant and evident damage to wildlife was reported in the aftermath.

INDIRECT DAMAGES

On the timber market: (decrease in timber prices and consequent reduction in income for public administrations owning forested areas);
On the quality of wood biomass, due to potential parasitic attacks on downed trees;
On avalanche and landslide risk, related to the clearing of a large number of forests that serve as protection for the land and the removal of the barrier created by the fallen trees;
On waste management, concerning the disposal of debris and anthropogenic material;
On the safety of workers, residents, and tourists, in relation to the accessibility of trails and hiking paths;
On the tourism sector, with inevitable repercussions on employment.

Floods and torrential phenomena

In the future, changes in the intensity and duration of rainfall, in combination with higher temperatures, will likely lead to an increase in the frequency and magnitude of debris flows increasing the risk related to flood and torrential phenomena.

As floods and torrential events increase, we expect their effects to grow both in frequency and magnitude, along with increased exposure. Therefore, we expect more injuries and fatalities, complete or partial damage of buildings and infrastructure (such as bridges, roads, railways, aqueducts, and power lines) and the more frequent flooding of industrial and commercial activities, as well as private and public structures located in flood-prone areas.

We also expect an increasing number of strategic structure and cultural heritage sites exposed to flooding with both direct effects (such as their damage or destruction) and indirect effects (for example, the acceleration of deterioration of cultural heritage processes caused by increased moisture in historic materials and structures caused by flooding and the loss of availability of rescue and health care facilities).

Ecologically, in the immediate term, torrential phenomena cause siltation of existing aquatic habitat and direct mortality of aquatic species and suffocation of their eggs. In the long term, this causes loss of biodiversity. On the other hand, the deposition of boulders that trap sediment and create complex habitats can also contribute to increasing habitat diversity at the basin scale.

This future outlook necessitates increasing maintenance efforts and the revision of the mitigation strategies, including structural and non structural measures. Additionally, in the long term, socioeconomic impacts are anticipated due to the relocation or reconstruction of structures and the loss of jobs and capital resulting from debris flow hazards. Such a scenario may not be economically sustainable.

Wind-induced forest collapses, bark beetles, forest fires and avalanches

The likelihood of wind-induced forest collapses is expected to increase in the future due to the higher frequency of intense rainfall episodes combined with the overall rise in temperatures. Warming shortens the duration of frozen soil conditions, which normally provides better anchoring for trees from late autumn to early spring. Additionally, soil saturation in late autumn, which is likely to increase due to higher precipitation during that season (as seen in the results from WP1), may weaken tree root systems, making forests more vulnerable—especially spruce formations, which have more superficial root systems.

Forest collapses caused by wind, bark beetle infestations and wildfires are processes for which Trentino lacks a clear trend for the coming decades, but they all share a potential reduction in forest cover, which would impact the protective role of forests. Without protective forest cover, mass movements and avalanches, particularly on steeper slopes, are likely to become more common, and areas previously considered safe may experience increased risk.

Trees left on the ground after windstorms can promote the proliferation of bark beetles, especially under favourable environmental conditions such as high temperatures and droughts, further exacerbating forest vulnerability. All three processes directly impact forests, affecting both natural aspects (such as wildlife and landscape) and economic sectors (notably the timber industry and tourism).

Regarding wildfires, in addition to direct damage to structures, agricultural or forest areas, indirect effects must also be considered, such as service interruptions affecting commercial, industrial and public activities. Disruptions to communication routes or public service infrastructure (such as electricity, water, and telecommunications networks) can hinder the timely response of emergency services and the containment of the fire itself.

Residents and tourists may be affected directly, through property damage, or indirectly, through service interruptions and landscape alterations. Wildfires also have a significant impact on air pollution.

Avalanches, while posing a direct risk to structures and people, generally affect higher altitudes and steeper slopes, meaning overall exposure remains lower.

Heatwaves

Heatwaves have significant effects on the population, with their impacts becoming more pronounced as the intensity and duration of the heatwave increase, especially in larger urban areas and at lower elevations (see the box dedicated to non-climatic external factors).

Heatwaves will also impact the tourism sector, likely leading to an increase in demand for mountain stays during the most intense phases, resulting in higher tourist flows from outside the province. This influx will be accompanied by increased consumption, particularly of water and energy, associated with higher visitor numbers and elevated temperatures (see the box dedicated to non-climatic external factors).

Generally higher temperatures throughout the year and more frequent heatwaves, especially in summer, will lead to a shift in energy demand for heating and cooling private and public buildings across different seasons. In particular, in urban areas of the valley floors at lower altitudes, such as the Adige Valley, high summer temperatures can significantly increase energy demand, putting pressure on infrastructure, such as energy grids, potentially leading to outages and service disruptions.

There will also be peaks in the consumption of drinking water and sanitation, for food, hygiene, and recreational use such as swimming pools.

Droughts

The increase in dry periods will lead to a general decrease in water availability, resulting in heightened conflicts over water use, especially given the overall rising demand, particularly in the summer season. Agriculture will face greater challenges regarding irrigation and systems for protecting against spring frost, while livestock farming will encounter both direct effects, such as water scarcity for animal drinking, and indirect effects, such as forage production issues.

Water scarcity will cause periodic supply problems for both public and private facilities, necessitating improvements to water supply systems as well as the implementation and adjustment of water reuse and recovery systems. Smaller towns located on the slopes of some valleys in Trentino appear more vulnerable to drinking water shortages in summer compared to larger valley centres, which are served by broader and more interconnected water networks fed by multiple springs and sources.

Residents and tourists may be directly affected by interruptions in water supply or indirectly through the inconvenience of water-saving policies. Additionally, the indirect economic impact should be considered, stemming from reduced snow cover in winter and low surface water levels, which will lead to recreational losses and affect the income of other tourist attractions and businesses.

From an infrastructural perspective, dry periods will also have significant impacts on hydroelectric energy production. Forests will suffer direct damage due to increasing mortality rates and reduced growth, as well as heightened vulnerability to forest fires and bark beetle infestations. Wildlife will predominantly face direct impacts from reduced forage and water availability.

The industrial and commercial sectors will be affected in proportion to their needs related to water resources, both in terms of raw materials and for use in cooling processes.

Sources:

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5. Morlot M., Russo S., Feyen L. and Formetta G.: Trends in heat and cold wave risks for the Italian Trentino-Alto Adige region from 1980 to 2018

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

We aimed to identify the qualitative factors governing the vulnerability of the exposed elements outlined in the previous response, as well as to recognize some more general vulnerabilities (not associated with a specific hazard), leveraging the work carried out during the first project workshop.

During the workshop held in Predazzo on December 14, 2023, the working groups focused on determining strengths and vulnerabilities in the different phases of emergency management for the Vaia storm case study. The stakeholders who participated in the workshop were involved in various aspects of emergency management and were either part of local communities or represented the Civil Protection or other provincial agencies involved in the response efforts. The identified vulnerabilities largely coincide with the pre-impact vulnerability factors defined in the first project phase in the Impact Chain.

For the Vaia case study, the main sources of vulnerability are the lack of risk management practices for handling multiple hazards and the inability to cope with events that exceed the existing mitigation measures.

Other important vulnerabilities have turned out in the forest planning, which is not resilient against windthrown, and in the preparedness and education of the population.

Other relevant aspects of vulnerability can be grouped under physical vulnerability, which considers the specific characteristics of the exposed assets, such as how buildings, roads, and infrastructure are constructed, their age, their level of maintenance, and the potential damage they may incur. This, in turn, depends on the type, intensity, and duration of the hazard.

Social vulnerability mainly depends on people, including their age, physical condition, risk perception and preparedness, education level, and the quality of communication with risk managers during the emergency phase. Additionally, population growth can increase residential density in risk-prone areas, thereby raising overall vulnerability. A potential increase in tourists in the pilot area may also heighten vulnerability, as they lack an in-depth knowledge of the territory and potential hazards.

In conclusion, at a general level, it was not possible to define a unique vulnerability value at the provincial level. The vulnerability depends on many factors, mainly related to physical and social aspects. It is very complex to evaluate each exposed asset subjected to a hazard and define a single vulnerability value. Consequently, regarding flood and torrent hazards, the maximum value of vulnerability is assumed. For other types of exposed assets, no unique value has been defined at the provincial level, but once the general risk map comes into force, we will refer to it. This map will assess, among other things, the vulnerability of exposed assets.

Although a quantitative approach to vulnerability assessment is not possible for now, the qualitative discussion regarding vulnerability factors is extremely useful in identifying the most appropriate adaptation responses aimed at reducing the overall vulnerability of the system. We will discuss in the following chapters the possible vulnerabilities of exposed assets in relation to the hazards we have addressed in this study.

Floods and torrential phenomena

In the future, increased rainfall intensity and frequency and land use change will result in increased risk in Trentino due to more frequent and severe flood and torrential events and increased exposure.

Understanding land vulnerability to flooding and how this may change in the future is very challenging and one of the biggest obstacles in risk assessment, but it is crucial for enhancing the adaptive capacity and resilience of communities. Vulnerability is influenced by several factors such as the socio-economic conditions of the community, urban authority policies and capacities, and the condition of infrastructure and human settlements. Vulnerability can significantly vary depending on the characteristics of the calamitous event (for example, in the case of floods, even with the same water depth, vulnerability depends on the spatial and temporal distribution of water velocity) and the structural characteristics of the exposed elements. A structure can be more vulnerable to floods if, for example, there are basements or openings on the upstream side (which is more exposed). Therefore, a quantitative assessment requires a set of information that is currently unavailable for the provincial territory. Consequently, in the flood risk assessment, a maximum vulnerability is assumed for all exposed elements, as indicated in the PGUAP (Public Water Use Plan, D.P.R. February 15, 2006) of the Province.

Other elements of vulnerability to floods are represented by drainage and runoff systems, which are sometimes undersized compared to the intensity of rainfall, the high degree of impermeabilization of urban surfaces, and the location of transportation routes in most Alpine valleys, which are situated in the valley floors near main rivers and streams.

Wind-induced forest collapses, bark beetles, forest fires and avalanches

The vulnerability of Trentino's forests highlighted during the Vaia storm is largely due to the presence of monoculture stands of spruce trees of similar age. The strong winds that followed the intense rainfall caused significant impacts, largely attributable to this weakness.

Additionally, the vulnerability of Trentino's forests is influenced by simultaneous or cascading exposure to different processes. An example is the drought that affected Trentino in 2022 and 2023, which increased the vulnerability of forests to bark beetle attacks.

The loss of protective forests also raises the risk to anthropogenic elements on exposed slopes and the underlying land, as it creates a cascading effect that increases hydro-geological hazard in areas that previously had a lower level of risk.

Heatwaves

As mentioned in the box dedicated to non-climatic external factors, the gradual ageing of the population at both the national and Trentino levels will likely lead to increased vulnerability to heatwaves. Other vulnerable groups include very young children, individuals with disabilities, and those with pre-existing health conditions, although no upward trend is expected for these groups.

The impact of heatwaves will be more pronounced due to the growing population moving to urban areas compared to rural ones, alongside the presence of urban heat islands that exacerbate the effects of these events.

More frequent heatwaves will also lead to changes in energy demand for cooling buildings, particularly in urban areas at lower altitudes. In Trentino, many old and historic buildings lack air conditioning systems and have insufficient thermal insulation, failing to provide optimal living conditions for the more vulnerable populations inside.

Heatwaves significantly impact outdoor workers and those exposed to high temperatures, as well as tourists and residents engaged in outdoor and sporting activities.

Droughts

The impacts of climate change on future water availability heighten the urgent need for improvements in the efficiency of Trentino's water supply system. This system faces several challenges, such as the high number of water supply networks and the significant fragmentation of the networks and associated management, leading to a lack of mutual support during critical situations (i.e., the inability to compensate between different water supply systems). Additionally, 51% of the water supply systems show reduced efficiency, necessitating investments for modernization, while the nearly 2,000 sources of supply incur high maintenance and management costs.

Agriculture in Trentino is the third sector in terms of water usage rights, following hydroelectric and fish farming, with a total of 592.3 million cubic metres per year. The prudent use of water resources, promoted in recent years by the provincial administration through specific investments in irrigation systems, has resulted in significantly lower actual consumption. Currently, over 80% of the irrigated agricultural area (about 20,000 hectares) uses drip irrigation systems, which allow for substantial resource savings. The remaining 20% of agricultural land, associated with water-intensive crops or located in areas where drip irrigation systems are difficult to implement, is still irrigated using so-called spray or sprinkler systems but is expected to transition to more efficient methods in the coming years. These water conservation measures aim to reduce the vulnerability of agricultural crops.

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

In the following chapter, the risk management measures will be described according to the four risk management phases i.e., prevention, preparedness, response and recovery, which do not depend on the hazard type, exposure and vulnerability.

Prevention measures

Prevention measures can be either structural or non-structural.

Structural prevention in the pilot area includes works such as weirs, embankments, valley bottoms, and snow retention structures built to reduce the risk of flooding and landslides and to manage avalanche risk. These structural elements are essential for protecting populated areas and critical infrastructure. A project is currently underway in the province of Trento to map the existing prevention structures in the territory.

Within structural prevention, there is also the construction of new infrastructures using innovative materials and technologies that enhance resilience to extreme events. For example, in Veneto, a traffic light system is being implemented to close roads prone to landslides, debris flows, or avalanches. Another solution could be to establish buffer zones around roads, as mandated by regulations (art. 26 D.P.R. 495/1992). The regulation states that the distance from the road boundary, outside populated areas, for planting trees alongside the road, must not be less than the maximum height achievable for each type of tree species at the completion of its growth cycle, and in any case, not less than 6 metres.

Fra le varie soluzioni vi possono essere progetti di rinaturalizzazione delle rive dei fiumi e dei pendii instabili per migliorare la capacità di assorbimento delle acque e ridurre il rischio di frane. In Trentino è stato realizzato il progetto Life+ T.E.N. “Trentino Ecological Network”. Il progetto si propone di realizzare sul territorio provinciale una Rete ecologica polivalente. Un’azione specifica all’interno del Progetto è la definizione di linee guida provinciali per la gestione dei boschi umidi e della vegetazione lungo i corsi d’acqua. Questa esigenza nasce dalla constatazione del generale cattivo stato di conservazione delle formazioni riparie in Trentino. Un buono stato ecologico è il requisito necessario per rendere i corsi d'acqua capaci di svolgere un ampio ed irrinunciabile ventaglio di servizi ecosistemici e mitigazione del rischio idrogeologico.

The non-structural prevention is done mainly in the planning. In fact, one of the main instruments for the non-structural prevention is the **Hazard Synthesis Map** which analyses the most relevant hazards (mass movements, hydraulic hazards, avalanches, litho-geomorphological characteristics, wildfires and seismic hazard) on provincial level, producing hazard maps for each hazard reported. The Hazard Synthesis Map (CSP), based on the classification of hazard generated by hydrogeological, seismic, and wildfire risks, identifies areas with different levels of penalties that can be divided into two groups: ordinary (high, medium, and low) and other types (residual from avalanches, areas requiring further investigation, negligible, etc.). In areas with penalties, land use is regulated within the implementation rules of the Provincial Urban Plan (PUP).

Forest management, such as maintenance and the planting of new trees, is an important mitigation measure to prevent slope destabilisation and reduce the risk of landslides, mudslides and avalanches.

Preparedness measures

The Provincial Alert System (SAP) of the Autonomous Province of Trento is an essential tool in the field of civil protection, designed to manage hydrogeological, hydraulic, seismic, and forest fire risks. Its primary purpose is to effectively coordinate the monitoring, forecasting, and intervention activities of all involved entities and structures, optimising response times to prevent or mitigate the impact of adverse events on the territory.

The SAP is divided into three operational phases:

- Forecasting: Daily meteorological forecasts are conducted.
- Evaluation: This phase analyses the potential consequences of the predicted events.
- Alerting: During this phase, alerts are issued, and emergency plans are activated if critical conditions arise.

The main use of the SAP is to ensure a timely and coordinated alert system, guaranteeing the safety of the territory and its population.

In the case of weather alerts, protocols are in place and tools are available to provide real-time meteorological forecasting (nowcasting). Nowcasting allows for short-term predictions (up to 30 minutes to 1 hour) of the current weather situation, providing authorities with timely information, enabling evacuations, and other emergency measures. In the future, enhancements to early warning systems are planned, utilising more advanced technologies to improve the accuracy and timeliness of alerts.

Civil protection plans include a thorough assessment of the territory to determine how to evacuate and safeguard exposed assets. It would be beneficial to update these plans to account for the compounded and cascading effects of extreme events driven by climate change. Additionally, it is very important that civil protection plans are well-known and understood both by municipal administrations and by the general public.

Response phase

The **Civil Protection Plan**, designed during the prevention phase, is the instrument that permits to deal with the emergencies and to protect people, goods and services present in an area affected by disasters, that may derive from one or more residual risks. Every municipality in the Province of Trento has a tailored civil protection plan with clear and direct instruction to organise the knowledge, the resources and procedures used to deal with the various critical situations that potentially arise on the municipal territory.
On the territory, there are rapid response teams such as firefighters, employees and volunteers from civil protection, and medical personnel. These groups are trained to respond quickly to emergency events.

The Civil Protection Department of the Autonomous Province of Trento is responsible for forecasting floods in watercourses and, when necessary, activating the Flood Service. In the event of floods, the Operations Room can be activated and remains open 24 hours a day until the flood event concludes. The responsibilities of the Operations Room range from forecasting the phenomenon to informing the relevant Civil Protection structures and agencies about the ongoing and expected event, as well as coordinating the activities of the Flood Service.

One possible area for improvement that emerged during the workshop in Predazzo is the communication between the various structures responsible for managing emergencies and the population. While there is a high level of coordination and communication among the operational structures involved, the public can easily fall victim to misinformation because the communication channels during emergencies are not clear or well known.

During the workshop held in Predazzo, the need to educate the public on managing emergency situations was highlighted. There is a necessity to organise training and informational days to raise awareness about the Civil Protection plans within the communities.

Recovery phase

At this stage, financial support is generally provided to facilitate rapid reconstruction. From the workshop, it emerged that after the Vaia emergency, resources arrived quickly, but their management could be improved. While urgent measures were addressed promptly, less attention was paid to the long-term impact of the Vaia storm, particularly regarding the increase in bark beetle populations and its repercussions on the timber sector. It is suggested to plan reconstruction and restoration with a medium-term perspective, taking these impacts into account. It is highly important to conduct debriefing with the various stakeholders who were involved during the different phases of the emergency. This will allow for learning from both the strengths and the areas for improvement in the event management and the roles of the different actors involved.

Floods and torrential phenomena

Predicting the location of flood-prone areas using flood hazard maps, and urban flood risk mapping can mitigate the effects of flooding in urban areas and can be used for city planning. In Trentino, hazard maps have been used to identify and classify natural risks in the territory. They have guided urban planning activities and the implementation of public and private interventions. It is very important to keep hazard maps up-to-date based on recent events. In particular, the layout of activities and infrastructures is thought in function of their vulnerability in relation to the flood hazard and any intervention in hazard-prone areas is subject to prior verification of compatibility with respect to the anticipated hazard in order to design and construct adapted/resilient structures. Compatibility can also be achieved through the adoption of appropriate structural or management mitigation measures. The aim is for flood-adapted/resilient buildings to be designed and constructed using temporary or permanent obstruction systems. An important point to work on, also from a cultural perspective, is that a policy based solely on protective measures is not sufficient to make a territory resilient to flooding.

Urban drainage can be improved by promoting nature-based solutions so as to reduce the sealing of urban soils. Efforts should be made to design sewer systems that improve the flow of stormwater towards the sewer collectors and eventually to the urban wastewater treatment plants. A crucial aspect will be to maintain the sewer systems to reduce leaks and improve the inflow coefficient to the sewers. Over the years, environmental monitoring and inspections of landfill coverage have intensified to monitor the production and concentration of leachate contaminants.

Wind-induced forest collapses, bark beetles, forest fires and avalanches

To reduce the vulnerability of the forests in the pilot area and make them more resilient, practices should be promoted that encourage the development of mixed-age forests. Improved forest and land management practices could help make our forests less susceptible to windthrow in the future. These good management practices are also very effective in reducing the presence of bark beetles in the forests of Val di Fiemme and Val di Fassa.

In the pilot area, wildfire management is carried out through land monitoring, along with extensive training and information dissemination to the population. Additionally, generally favourable climatic conditions reduce the risk of wildfires.

Good forest management practices can also positively influence the protection of the territory and exposed assets against avalanches. In areas affected by the Vaia storm, avalanche barriers have been constructed to protect the assets located below the impacted areas. Immediately after the event, a study was conducted in the affected areas that considered the slope conducive to avalanche initiation, elevation, and exposure. Consequently, the Hazard Summary Map was updated with new areas that may pose a risk requiring further investigation regarding avalanche danger.

One tool for reducing risk for hikers and ski mountaineers is the avalanche bulletin. This institutional document provides a concise description of snow cover, snowpack conditions, and avalanche danger in a specific territory, using a scale consisting of five levels, known as "danger levels." It is based on an assessment that takes into account various parameters, including snowpack status, weather conditions, and forecasts.

As part of the X-Risk-CC project, the Province of Trento has commissioned the development of a checklist aimed at stakeholders who need to make decisions in areas affected by Vaia that may present avalanche hazards requiring further assessment, as outlined in the Hazard Summary Map.

Heatwaves

Some solutions to reduce heatwaves impact include climate-proof buildings with proper insulation and cooling technologies. This technology prepares homes for future climate impacts and curbs their contributions to the climate crisis.

Other solutions are Nature-based Solutions (NbS), which are defined by the IUCN as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." Nbs could be green and/or blue solutions, involving both vegetation and water. The municipality of Trento is currently involved in a European project dealing with Nbs implementation, i.e. the renaturalization of a reach of the Fersina river.

Additional solutions could include urban climate shelters: i.e. public buildings equipped with air conditioning that are open to the population, providing better conditions for the most vulnerable groups during heatwaves.

An improvement solution may also involve changing habits during the summer months, which are most affected by heatwaves. For example, implementing different working hours with municipal ordinances regulating working times and prohibiting certain activities during peak heat hours. Heat bulletins for most vulnerable categories could also be of use.

Droughts

One of the solutions to pursue is to diversify energy sources and make agriculture and irrigation systems smarter to reduce waste associated with inefficient irrigation methods, such as surface and sprinkler systems. Decreasing water waste can also involve cultivating less water-intensive varieties.

As mentioned in previous discussions, it will be essential to improve aqueduct systems to reduce inefficiencies and losses due to the ageing of the networks. It is estimated that the Italian aqueduct system currently has real losses of around 30-40%. At the provincial level, significant efforts have been made in recent years to reduce losses in the Trentino system, which now stands at approximately 20%.

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

Whenever multiple hazardous events impact the same region within a reasonably short timeframe, the potential damages or losses resulting from their effects can combine and amplify. We have reflected on how the exposure and vulnerability of the affected elements change when two different hazards, as analysed in previous questions, occur simultaneously or in succession.

This indeed happened with Storm Vaia, where the combination of heavy rainfall and strong winds caused a series of cascading impacts, such as tree falls and soil erosion. The interaction between extensive forest collapses and the subsequent prolonged drought led to an increase in bark beetle proliferation. Ultimately, the bark beetle caused the same degree of damage to the forest as the storm itself, particularly affecting the protective function of the forest and increasing the vulnerability of the territory to landslides, erosion, and avalanches.

In the context of WP1, the future trend was analysed only for compound extreme events, identified when both precipitation and wind speed exceed the corresponding 97th percentile. The study showed that compound extreme events of precipitation and wind occur more frequently in autumn, with the lowest frequency observed in spring throughout Trentino. Compound events of heavy precipitation and wind are expected to increase across all analysed Global Warming scenarios, largely due to the anticipated rise in the frequency of intense precipitation events. In the worst-case scenario (GW4), these compound events are projected to occur with a frequency over 30% higher than the period from 1991 to 2020.

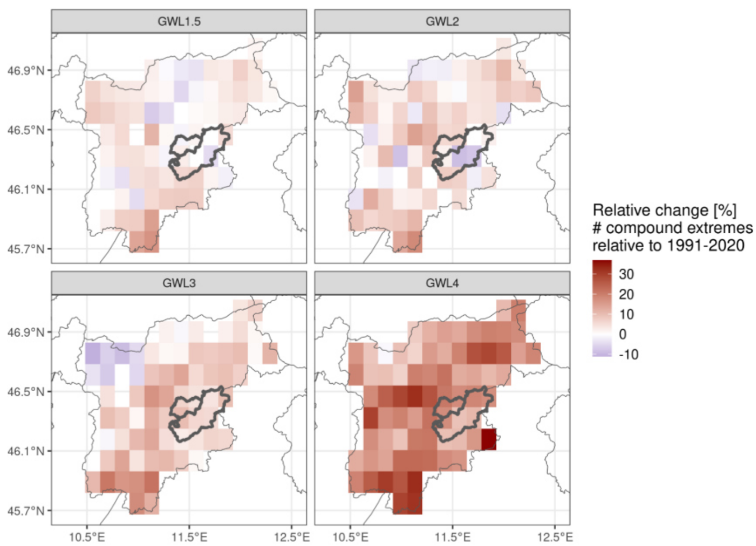


Fig. 27 Relative change in frequency of compound events of precipitation and wind speed exceed the corresponding 97th percentile in different Global Warming scenarios.

AFTER ➡ BEFORE ⬇	Precipitations	Wind	Bark beetle	Avalanches	Heatwaves	Droughts
Precipitations	-	Tree falls, loss of protective forest	Rainy periods can inhibit proliferation	Tree falls, loss of protective forest	-	-

Wind	Instability on slopes left without trees	-	Greater damage to the forest	Greater damage to the forest	-	-
Bark beetle	Rainy periods can inhibit proliferation	Greater damage to the forest	-	Greater damage to the forest	Further proliferation	Further proliferation
Avalanches	Instability on exposed slopes	Unstable trees	-	-	-	-
Heatwaves	-	-	-	-	-	-
Droughts	After a dry period, the ground does not absorb, resulting in greater impact.		Further proliferation	-	-	-

<u>Focus points for the considered compound and cascading hazards:</u>

Heavy Precipitations: Periods of intense rainfall can have contrasting effects: they promote hydrogeological instability (landslides and floods) and influence bark beetle proliferation. If they occur after dry spells, the soil will be less capable of absorbing water, worsening the damage.

Strong Winds: Strong winds can cause tree falls, worsening instability on slopes without protective vegetation. Winds following periods of stress for trees (e.g., drought or diseases) or after heavy rainfall cause more severe damage.

Bark Beetle: Bark beetle proliferation is influenced by climatic conditions, with rainy periods potentially inhibiting its development. However, following droughts or heat, proliferation can accelerate. Damage to trees makes them vulnerable to wind and avalanches.

Avalanches: The loss of protective forests, caused by tree falls or bark beetles, exposes slopes to avalanches and landslides, especially after intense rainfall or snow on unstable ground.

Heatwaves: Heatwaves may exacerbate drought effects, increasing the vulnerability of soil and forests.

Droughts: Drought increases vulnerability to bark beetles, promoting their reproduction. If intense rainfall follows drought, the soil does not absorb adequately, worsening erosion and instability effects.

7. Arly River Catchment, France

RISK QUESTIONNAIRE

Arly River Catchment

October 2024

(MULTI-) HAZARD ANALYSIS

I. Which are relevant weather extremes and how do you expect them to change in the future?

The pilot area of the Arly basin, located in the northern French Alps (Figure 1), located astride the departments of Savoie and Haute-Savoie, is well known to the French scientific, technical and operational risk management community for its high exposure to the natural mountain hazards (landslides, torrential flooding, avalanches) that frequently affect this area.

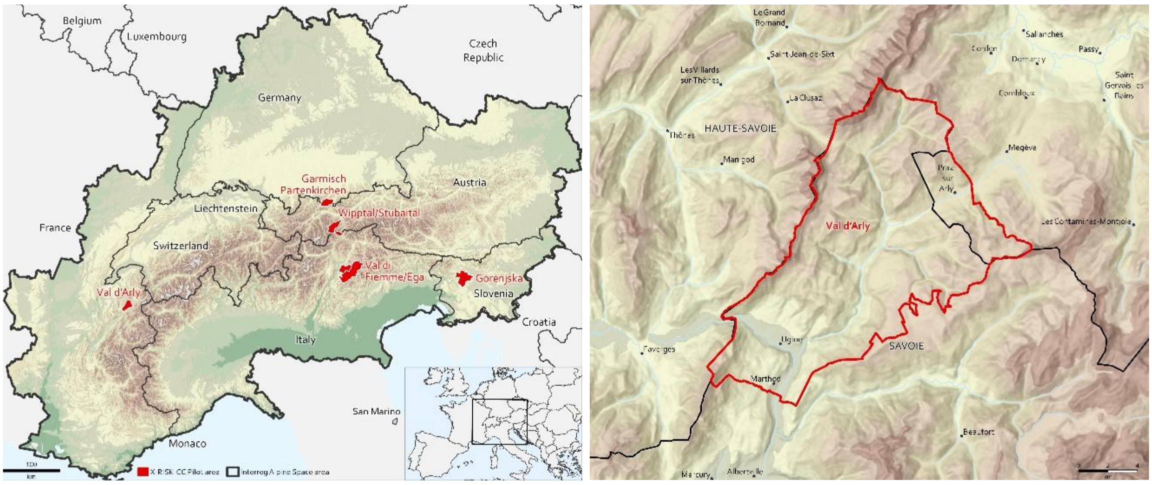


Figure 1 - X-RISK-CC pilot areas (left) and the pilot area of the Eleanor storm – Val d'Arly (right).

In the French Alps, the warming trend observed between 1900 and 2023 is +2.45°C (Figure 2), greater in the Northern French Alps (+2.7°C) than in the Southern French Alps (+2.2°C) (OBSCAN, 2024).

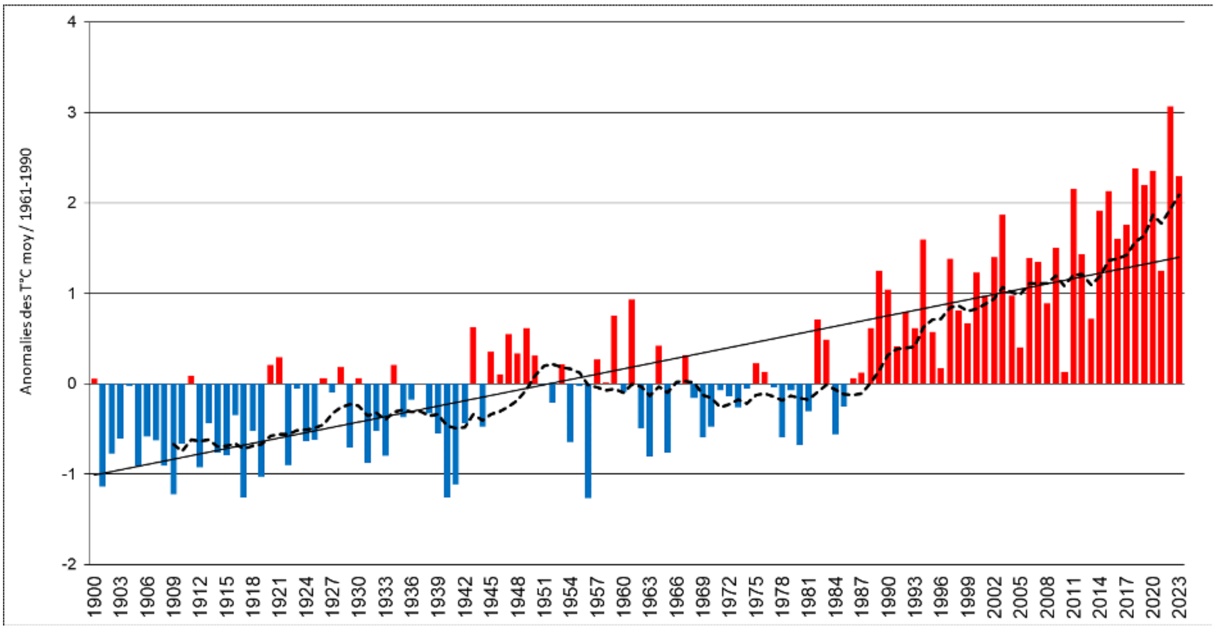


Figure 2 - Differences in mean annual temperatures (in °C) between 1900 and 2023 compared with the 1961-1990 normal in the French Alps. Solid line: linear trend. Dotted line: ten-year average. Source: HISTALP data (www.zamg.ac.at/histalp), and homogenised series from the Météo-France measuring stations at Bourg-Saint-Maurice (73) and Embrun (05), processed by AGATE. In OBSCAN (2024).

Under the influence of this accelerated warming, the Arly basin is subject to rapid changes in the various components of the mountain environment, particularly with regard to the development of extreme events.

a) Past/present weather extremes

Relevant weather extremes in the area of Val d'Arly are extreme 1- to 5-day precipitation and heavy winds, associated with larger storms, causing avalanches, rockfalls, landslides, flooding and other damage in the region, particularly when co-occurring. Temperature variations during these events play a major role in the occurrence of compound and cascading phenomena, such as episodes of rapid melting of the snowpack and rain-on-snow events (Figure 3), which favour the formation of torrential floods and the triggering of landslides in Alpine regions (Beniston et al., XXXX).

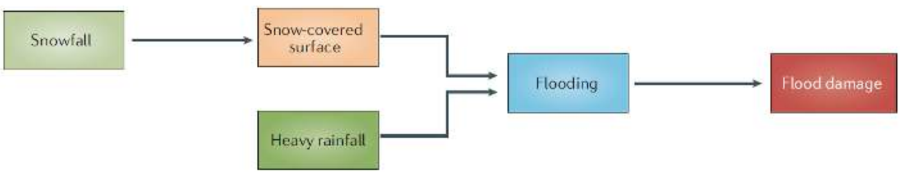


Figure 3 - Rain-on-snow processes. In Zscheischler et al. (2020).

Winter storm Eleanor in 2018 is an example of such meteorological event (Vautard et al., 2019; Stoffel and Corona, 2018: Figure 4).

A January of extremes: In January 2018, measured air temperatures nat low elevations in large parts of France, Switzerland, Bavaria and Austria exceeded long-term means by 4–5 °C (Fig. 1a). The exceptionally warm temperatures in the lowlands were due to the Jetstream sitting farther to the south than usual in December 2017, thereby transporting warm and humid air masses to the Alps and generating strong winter storms. Within the Alps, and especially at higher elevations, temperatures also exceeded long-term average values by 2–3 °C, although the influence of the Jetstream was less marked. The mild air masses also carried excessive humidity to the Alps that led to more than twice the usual precipitation over many regions, especially the Northern French and Western Swiss Alps (Fig. 1a). At lower elevations, this precipitation delivered multiple rain-on-snow episodes that induced flooding in smaller catchments and critical discharge levels in montane rivers north of the Alpine divide. In addition, water-saturated soils abetted the release of shallow landslides and debris flows in valleys where, historically, landslides and debris flows have been exceptionally rare. Furthermore, the winter storms led to snow accumulations exceeding five metres at high elevations (Fig. 1b). These immense snow burdens pushed avalanche risk to extreme levels, threatening villages and communication routes, and leaving tourists stranded in mountain resorts. Several popular ski destinations — including Chamonix, Saas Fee, Val d'Isère and Zermatt — shut their ski runs and put helicopter shuttles in place to evacuate tourists from resorts during the major snowfall episodes.

An analogue for future winters: The conditions during January 2018 may be anomalous in today's climate, but that is projected to change. When compared to localized climate model scenarios for those stations with the longest historical records in Switzerland, the temperatures measured in January 2018 are projected to become commonplace at higher elevations by the end of the century (Fig. 1b). Climate warming in the European Alps will probably also be accompanied by changes in the seasonality of precipitation, with increased occurrences of extreme precipitation in the colder part of the year.

Despite projections that rain-on-snow events and related floods are likely to increase by 2100 by almost 50% with temperatures 2–4 °C warmer than today (Beniston and Stoffel, 2016), the events of January 2018 have demonstrated that communities throughout the European Alps are not yet ready to cope with increased winter landsliding and flooding. There is a clear need to better understand winter mass movements and flooding at lower elevations under warmer climates to improve residents' resilience to climate warming in the European Alps.

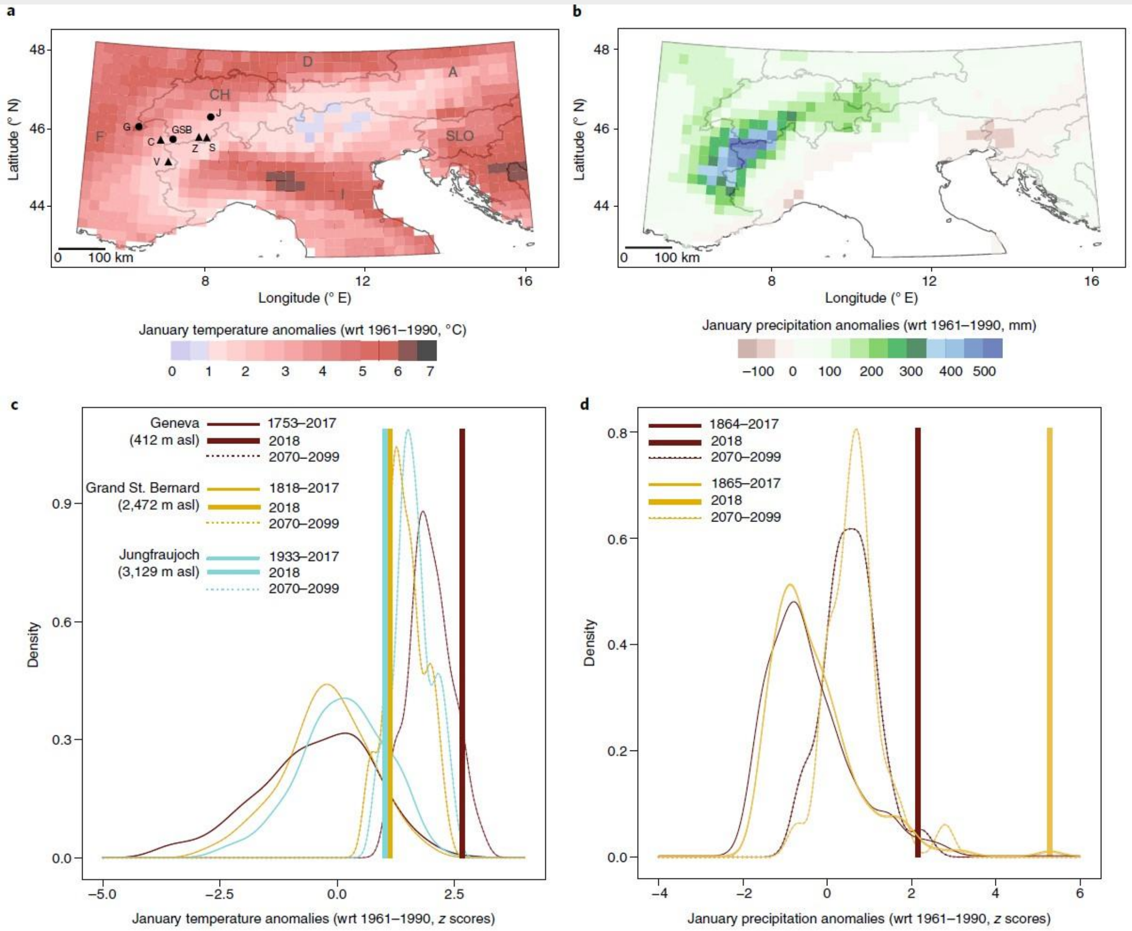


Fig. 1 | Temperature and precipitation anomalies measured across the European Alps in January 2018. a, Temperature anomalies (0.25 × 0.25 °C) obtained from the daily, high-resolution E-OBS dataset. **b**, Precipitation anomalies from the E-OBS dataset as compared to 1961-1990 values. **c**,**d**, Temperature anomalies (**c**) and precipitation anomalies (**d**) for January 2018 as compared to the distribution of previous January anomalies measured at the meteorological stations of Geneva, Grand St. Bernard and Jungfraujoch, and future January anomalies projected by climate models to the end of the twenty-first century. A, Austria; CH, Switzerland; D, Germany; F, France; I, Italy; SLO, Slovenia; C, Chamonix; G, Geneva; GSB, Grand St. Bernard; J, Jungfraujoch; S, Saas Fee; V, Val d'Isère; Z, Zermatt; wrt, with respect to; asl, above sea level.

Figure 4 - Temperature and precipitation anomalies measured in the European Alps in January 2018. In Stoffel and Corona (2018).

In the Arly basin, Eleanor storm locally brought over 130 mm of rain over two days (a rare event for winter in this area with an estimated return period of 30 years) in combination with strong winds reaching 115 km/h. Due to the brevity of the data, the evaluation of return periods for extreme winds is not possible with a high degree of confidence.

Variable/index	Measured value (station)	Return period
1-day precipitation	75 mm (La Clusaz) *100 mm/24h from hourly data (Cohenoz)	~ 5 years (annual ~ 14 years (winter)
2-day precipitation	**132 mm** (La Clusaz)	~ 20 years (annual) **~ 30 years (winter)**
3-day precipitation	138 mm (Hauteluce, La Clusaz)	~ 5–8 years (annual) ~ 6–9 years (winter)
Maximum daily wind speed (10 min averages)	70 km/h (Col des Saisies)	short data record
Maximum wind gust (instantaneous)	**115 km/h** (Col des Saisies, Mont Arbois) *120 km/h from hourly data (La Giettaz)	short data record

Table 1 - Maximum observed precipitation and wind speed during storm Eleanor at weather stations in the Val d'Arly pilot area.

This precipitation was followed by an unusual thaw on 2-3 January 2018, which raised the rain/snow limit above 2000 m and led to the formation of a thick layer of wet snow (Evin et al., 2021), as well as rain-on-snow events in the mountains, triggering numerous snow avalanches, landslides, mudflows and torrential floods (Evin et al., 2021). The La Giettaz station, at an altitude of 1812 meters, and the Val d'Arly station (Cohennoz), at an altitude of 713 meters, recorded meteorological data attesting to the exceptional nature of the event. For the month of January 2018, the La Giettaz station (1812 m) recorded winds of over 120 km/h on January 3, temperatures fluctuating between -7°C +3°C, and rainfall intensity of up to 10 mm/h on January 3 (Figure 5). The Val d'Arly station (713 m) recorded almost exclusively positive temperatures over the month of January, and a rainfall intensity of up to 8 mm/h on January 4, during storm Eleanor (Figure 6).

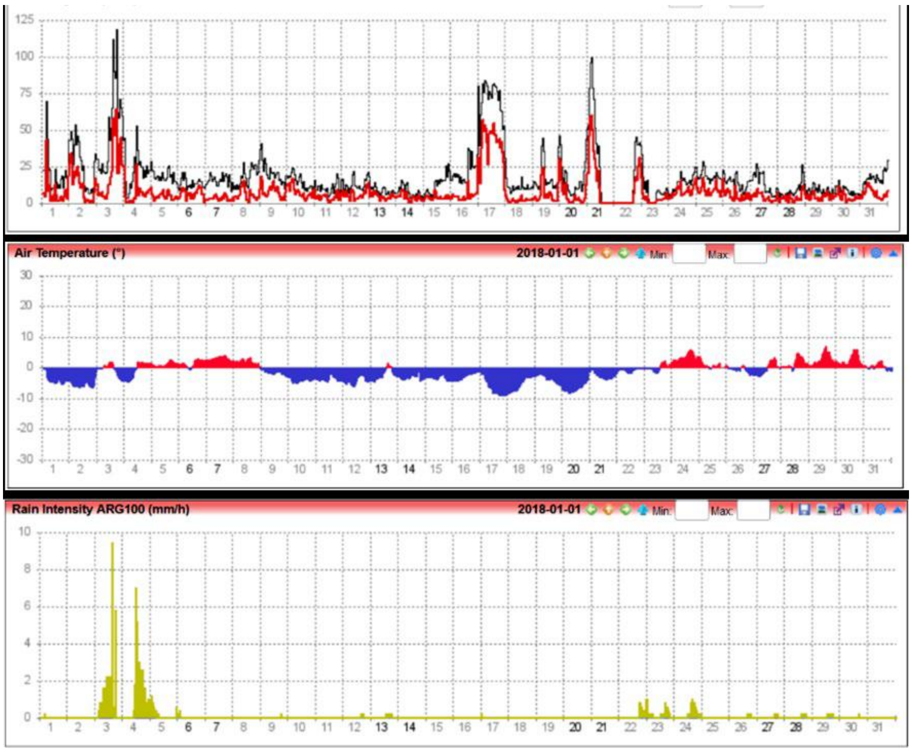


Figure 5 - Wind (A) (average per hour in red and maximum per hour in black), temperature (B) and precipitation (C) data for January 2018 at la Giettaz ISAW station.

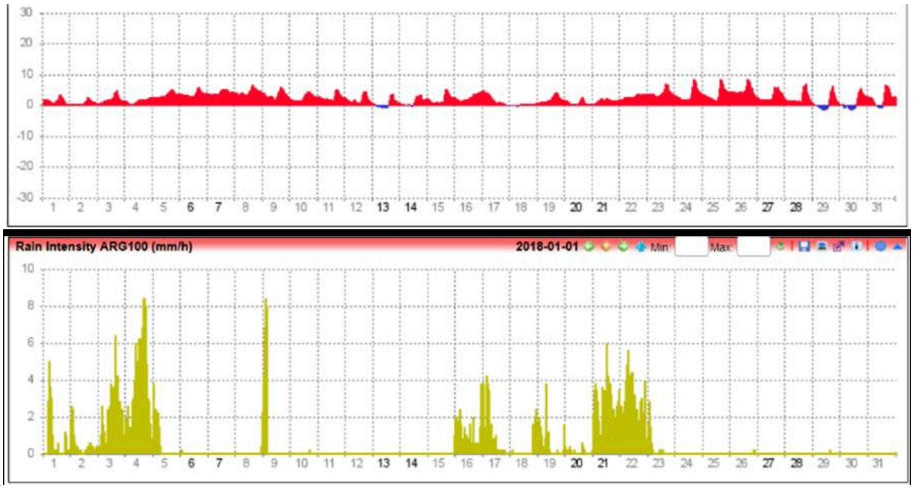


Figure 6 - Temperature (A) and precipitation (B) data for January 2018 at the Val d'Arly ISAW station.

Figure 7 shows the evolution of seasonal precipitation for the Isère catchment over the period 1950–2017 (Blanc et al., 2022). The increasing spring precipitation is the only significant trend in the Isère River catchment. However, by considering separately precipitation driven by Atlantic and Mediterranean circulations, we observe an increase in spring precipitation under Atlantic circulations and a decrease in winter precipitation under Mediterranean circulations. These trends are explained by an increasing contribution of Atlantic circulations to spring precipitation and a decreasing contribution of Mediterranean circulations to winter precipitation.

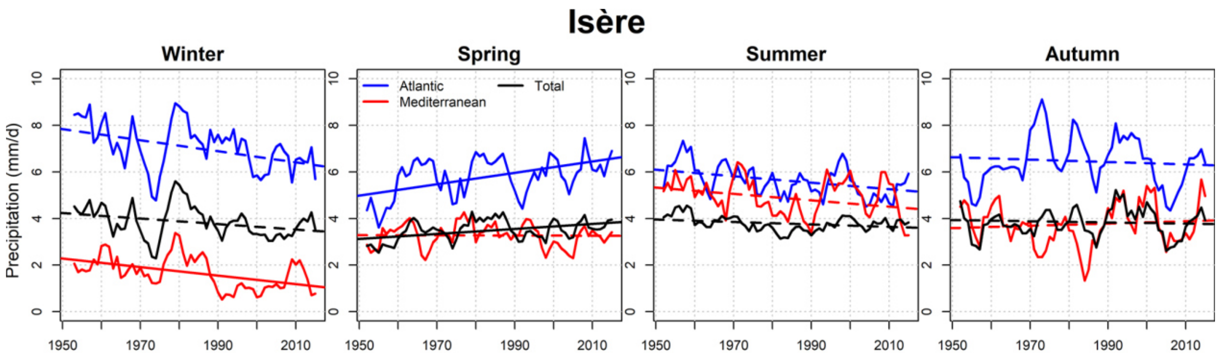


Figure 7 - Evolution of seasonal precipitation (mmd⁻¹) for the Isère River catchment over the period 1950–2017 (black lines). For Atlantic and Mediterranean circulations, the seasonal precipitation is normalized by the number of days associated with the given influence. A running average of 5 years is applied to allow a clearer visualization. Non-significant trends are represented by dotted lines. The trend is considered as significant if the p value of the Student test is lower than 5 %. *In* Blanc et al. (2022).

Trends in mean daily seasonal maxima of precipitation in the Isère River catchment (encompassing the Arly basin) was obtained using a non-stationary GEV (generalized extreme value) model, able to consider an evolution in both the mean value and the variability in the maxima (Blanc et al., 2022). Results show a significant decrease in winter extreme precipitation, a slight decrease in autumn and a moderate increase in spring extreme precipitation in the Isère River catchment (Figure 8). The magnitudes of the trends are quite small and are more pronounced for larger return levels (Blanchet et al., 2021).

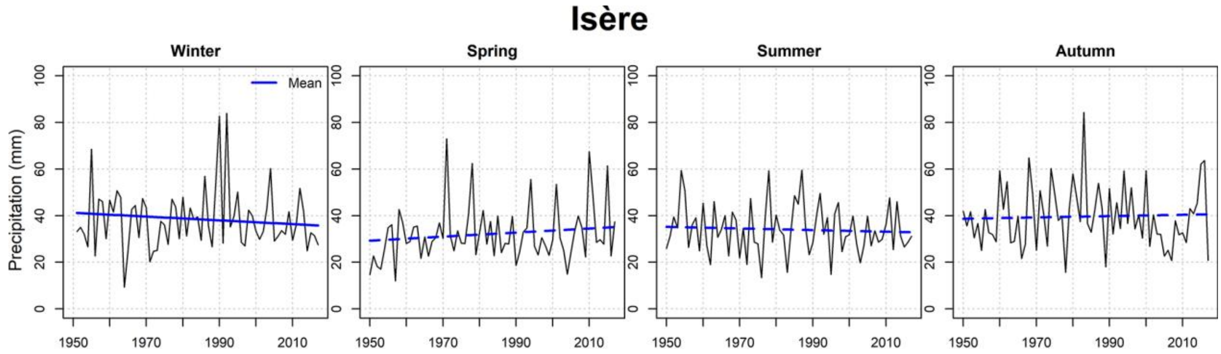


Figure 8 - Seasonal maxima of daily precipitation for the Isère River catchment (bottom) over the period 1950–2017. The blue lines represent the evolution of the mean seasonal maximum obtained with the best non-stationary GEV model, following the methodology of Blanchet et al. (2021a). Non-significant trends are represented by dotted lines. The trend is considered as significant if the non-stationary model is significantly better than the stationary model according to the likelihood ratio test (*p* value < 5 %). *In* Blanc et al. (2022).

At the scale of the Arly basin, trends in extreme precipitation and wind observations from 1990 to 2022 analysed in the X-RISK-CC project show partly similar seasonal differences. The intensity of extreme 1-day precipitation is increasing in spring and decreasing in autumn, while no significant changes in winter or on an annual basis are observed (Figure 9). There is no trend in intensity of 2- to 5-day precipitation or in frequency of extreme precipitation.

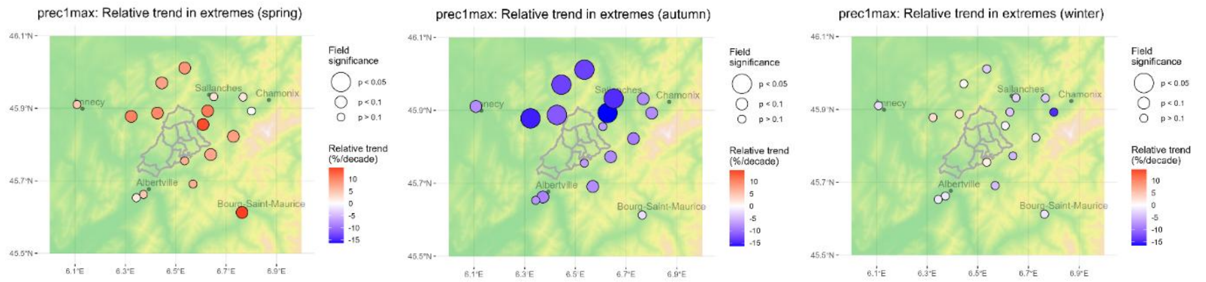


Figure 9 - Tendance relative des précipitations maximales sur un jour pour l'hiver (en haut à gauche), le printemps (en haut à droite) et l'été (en bas) au cours de la période 1990-2022, y compris la signification sur le terrain pour tenir compte de la dépendance spatiale entre les différentes stations dans la zone d'étude de cas. Extrait du rapport X-RISK-CC Pilot Report Eleanor (2023).

For maximum daily wind speed, the changes in intensity and frequency in the past depend on the location. A significant positive trend in both is observed only for slightly elevated station Col des Saisies for summer. Compound extreme precipitation and wind speed events do not show significant change with time.

b) Potential future weather extremes

In the future, the annual and seasonal precipitation amounts over the wider area of Val d'Arly will be slightly higher (up to 10 %) than in the reference period (1991–2020). The exception is summer, when a general decrease is expected, greater than 20 % in the case of global warming level 4 °C. Annual maximum values of 1- to 5-day precipitation will be higher in the future, ranging from 5 to 10 %, mainly due to winter (up to 10 %), since a decreasing trend with increasing level of global warming is observed for all multi-day extremes in summer (Figure 10). **Extremes will be stronger and more frequent in the future**, as the number of days above the 97th percentile also shows an increase of around 20 % (25 % for 1-day precipitation and 20 % for 2- and 3-day precipitation) on an annual level compared to the reference period. Seasonal increase is the largest in winter, around 40 % in the case of 1-day precipitation and around 30 % in the case of 2 and 3 –day precipitation. The expected increase is the smallest in spring and summer (less than 20 % relative to the reference period).

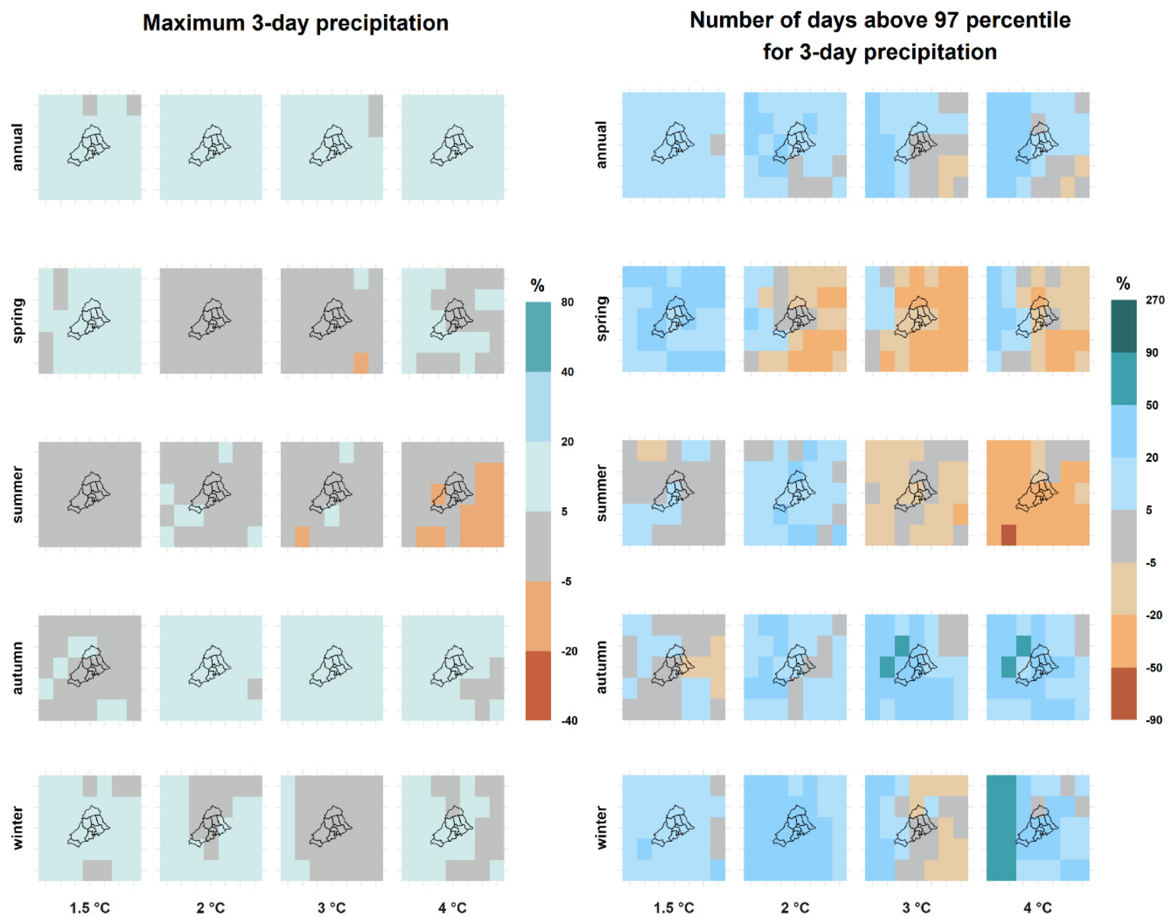


Figure 10 - Relative change in intensity (left) and frequency (right) of 3-day extreme precipitation events for four global warming levels relative to 1991-2020, shown by the median of the model simulation ensemble.

The frequency of days when daily mean wind speed exceeds the 97th percentile of the reference period also shows a slight increase mainly under global warming level 4 °C, about 10 % on an annual level and for winter, however, these changes are accompanied by a large uncertainty. Changes are even smaller for other seasons and global warming levels, some even showing a decrease in the number of such days. The annual and seasonal maxima of daily mean wind speed also show a small increase mainly under global warming level 4 °C, particularly for winter, where the maximum daily mean wind speed is expected to increase by approximately 3 % (0.3 m/s), however, both changes on an annual level and for winter are accompanied by large uncertainties.

II. Which hazard processes can be triggered by current and future weather extremes?

In the mountain regions, river and torrent floods triggered by intense or extreme rainfall events combine high liquid flows with significant solid transport, fed by the many processes affecting the slopes and banks, which are sources of lateral material input: gravity phenomena (landslides, landslides/blockfalls, avalanches), bank erosion, etc. This solid transport is likely to profoundly modify the morphology of river and torrent beds, leading to overflows and embankments. This solid transport is likely to profoundly modify the morphology of river and torrent beds, leading to overflows and siltation. During extreme weather events, the region is affected by these different processes at the same time. To establish an overall view of the area's exposure to these risks, it is therefore necessary to consider all the phenomena triggered during each intense meteorological event.

The Arly catchment is a mountainous area with altitudes ranging from 340 m to 2,686 m, covering an area of 645 km². It is divided into 3 sub-basins, with almost 300km of watercourses: (1) the Arly, which drains the Val d'Arly and the Albertville basin (267km²), (2) the Doron de Beaufort, which drains the Beaufortain (275km²) and (3) the Chaise, which drains part of the Pays de Faverges (104km²).

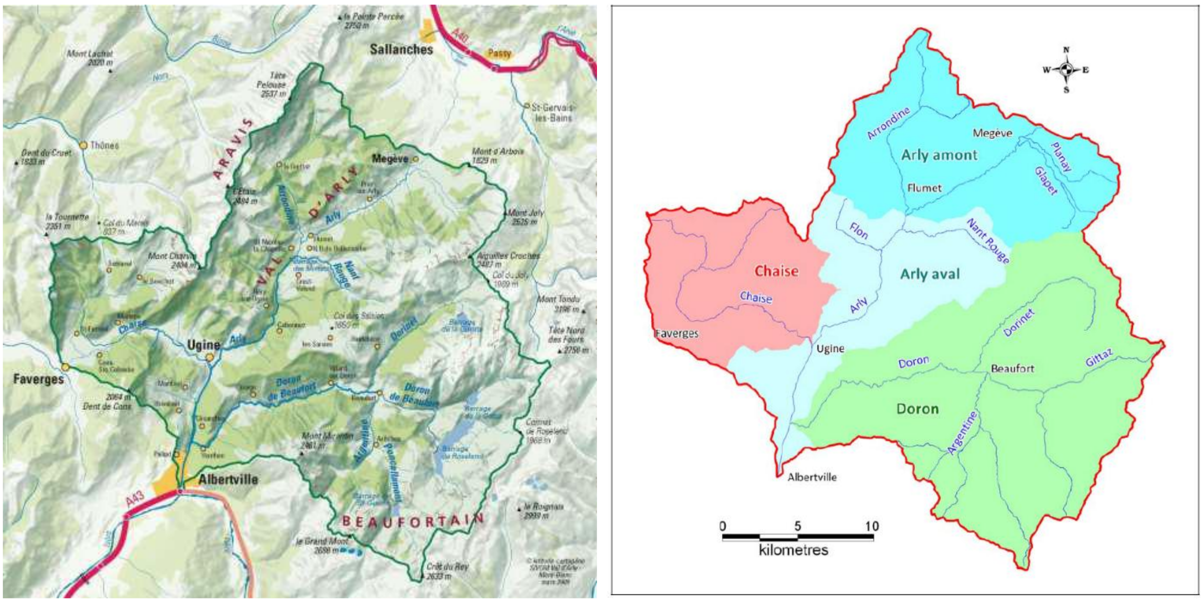


Figure 11 - The Arly catchment area. Source: SMBVA.

Upstream of the village of Flumet, the Arly valley is a wide, U-shaped valley typical of glacial valleys. From this village to Ugine, the morphology of the valley changes completely. The slopes become steep. The width of the valley diminishes sharply, becoming a narrow canyon. The river's trajectory becomes sinuous. From Cohennoz onwards, the valley widens, but the steep slopes persist until the Arly joins the La Chaise at Ugine (Figure 11). In the 15 kilometers between Praz sur Arly and Ugine, the river Arly drops from an altitude of 1,000 meters to 400 meters, a difference in altitude of 600 meters.

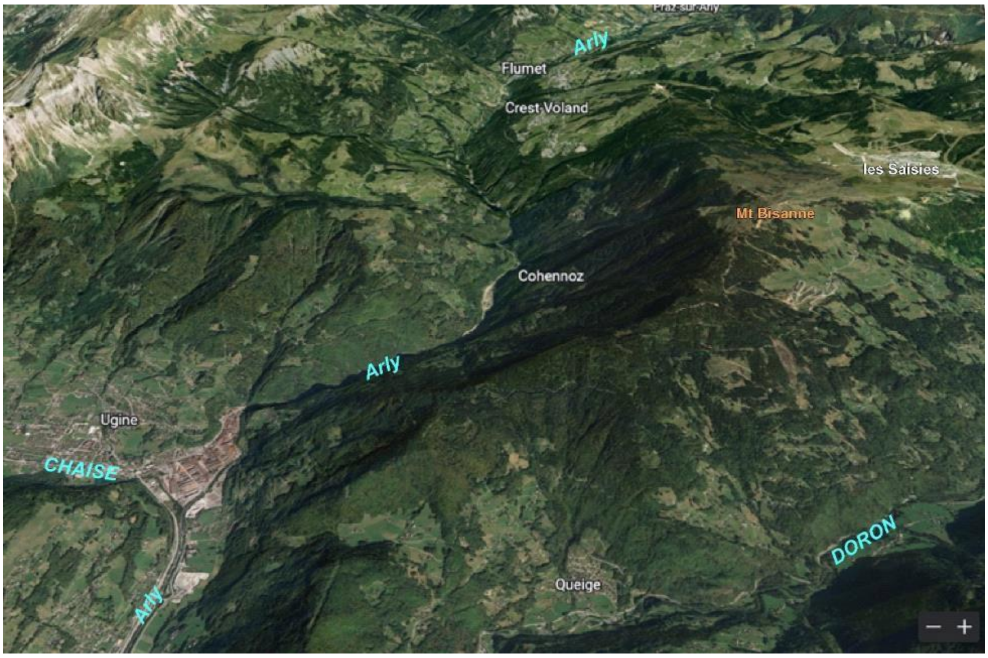


Figure 12 - Aerial view of the study area from the south (GoogleEarth). In BRGM (2024).

The relief to the west of the Arly river is characterized by a succession of ridges ranging from 1,500 to 2,100 meters, cut by perpendicular valleys that feed the Arly river. To the east, the relief is simpler, with a plateau (plateau des Saisie) incised by a river flowing northwards and joining the Arly north of Crest-Voland. Small rivers incise the eastern slopes, forming gullies known as “nants”. To the south, a narrow ridge rises from Mont Bisanne at 1941 meters, linked to a large glacial valley and the Doron river further south.

The region is exposed to numerous natural hazards (Figure 13), which are taken into account in risk prevention plans (see section VI below).

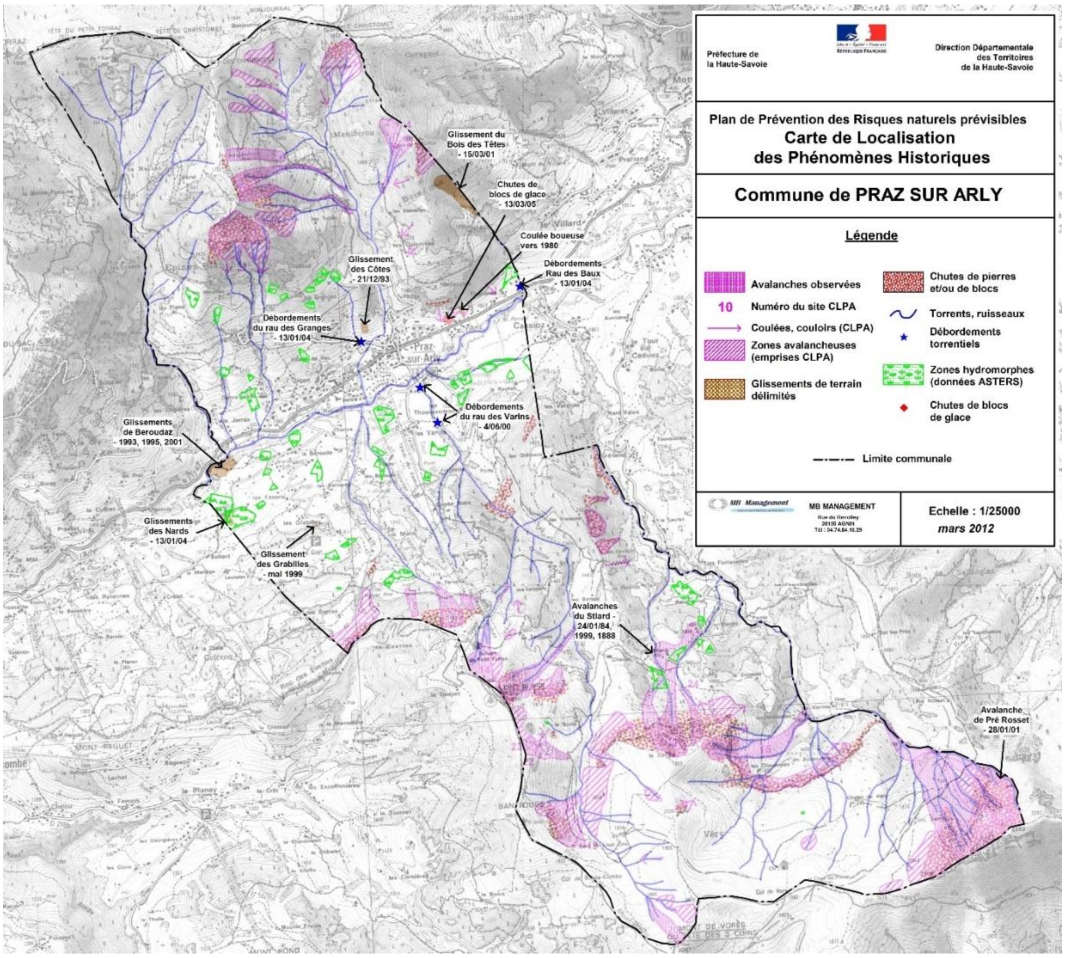


Figure 13 - Map showing the location of historical phenomena in the commune of Praz-sur-Arly (Haute-Savoie) as established on May 2012. Source : DDT74.

a) Past/present hazard processes due to weather extremes

Single hazards triggered by extreme weather events in the Arly basin are landslides, rockfalls, floods, debris flows and snow avalanches. These phenomena can occur in combination or in cascade, simultaneously or successively.

For example, during the floods and landslides in the Arly Gorges at the beginning of May 2015, materials from the slopes, estimated at 400,000 m3 in total, were then carried down the Arly, invading factories and ZACs downstream. The events of the winter of 2017-2018, and in particular the passage of storm Eleanor, produced important floodings and contributed to the reactivation of landslides (Montgobert, Bersend, etc.) and to the high mobility of the torrential beds. The repeated events of November-December 2023 once again caused numerous compound and cascading hydrological, gravitational and torrential phenomena in the Arly catchment.

The Syndicat Mixte du Bassin Versant de l'Arly (SMBVA), in charge of flood and torrential flood risk management, has noted the occurrence of extreme phenomena in the region, the intensity and/or frequency of which is tending to increase in the context of climate change, as well as the concomitance of several phenomena (e.g. landslides-torrential floods).

Landslides

The Arly catchment area is frequently affected by various types of landslides (landslides, rockfalls, mudflows), generally triggered by heavy rainfall and often accentuated by snowmelt and/or rain-on-snow events, which also cause torrential flooding. These phenomena have been studied in the MIROIR project (BRGM, 2024).

The entire eastern part of the Arly gorges is particularly prone to landslides (Figure 14), due to the presence metamorphic micaschists of the Satinée Series, composed of very brittle rocks that have been altered by the presence of water (Desrues et al., 2022).

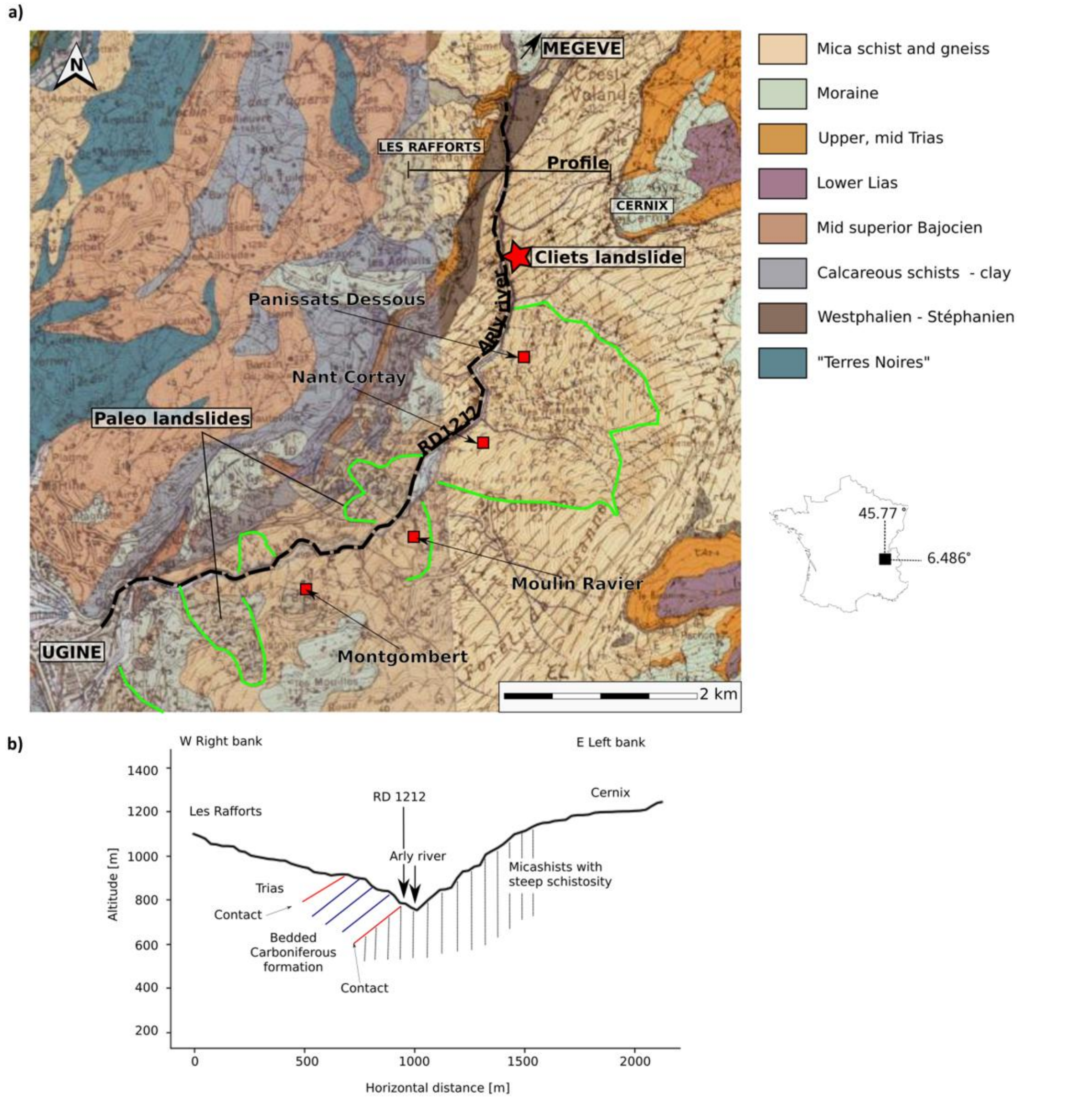


Figure 14 - Geological context of the Arly valley with (a) the localization of the Cliets rock-slide and its geological context simplified and (b) a geological cross-section of the upper Arly gorges. *In* Desrues et al. (2022).

It is the incision of the Arly at the foot of the slope that generates instability (BRGM, 2023). An analysis of the morphology of the valley from Megève to Ugine shows that the Arly is not at equilibrium and that it has strongly incised the relief created by the last glaciations. The V-shaped lower Arly valley (Figure 15) reflects the recent capture towards Ugine of the upper V-shaped glacial Arly valley which flowed in the opposite direction, and the altimetric shifts have favoured a marked incision of the Arly at the level of the Gorges de l'Arly with sustained undercutting of the banks at the foot of the slope, which maintains a high level of instability on the valley slopes. At present, the river is still not in equilibrium. Compared with the usual flows in the valleys in the sector, there is a 600 metre difference in level over the 12 kilometres between Flumet and Ugine. This morphological anomaly in this sector of the Arly valley is the main factor behind the incision and landslides.

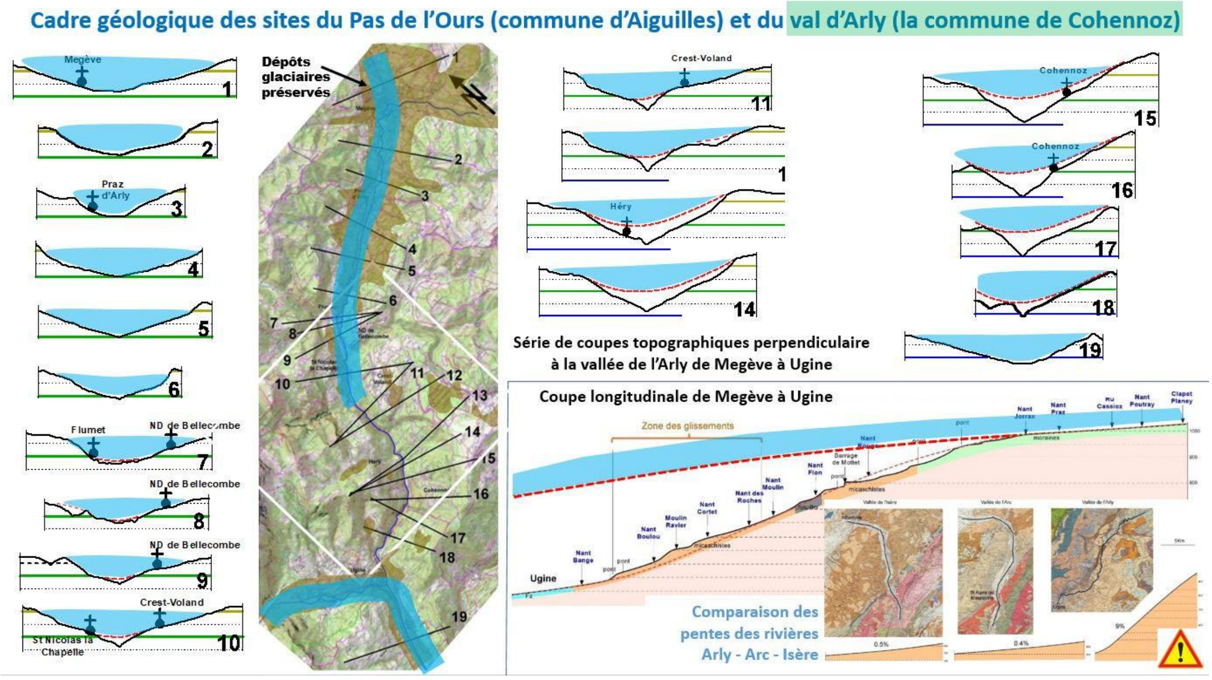


Figure 15 - Portion of the Arly valley in a V-shape at Les Gorges and otherwise in a glacial U-shape upstream and downstream, testifying to the late capture of the Arly. ***In*** **BRGM (2024a)**

The most active landslide in recent decades has been the Moulin Ravier landslide, an event of which that took place in 1955 is reported to have involved around 17 million m^3 of material (Desrues et al., 2022). In the last decade, several events generally affecting the RD1212 road have been recorded in the Arly gorges, such as the Dessous de Panissats landslides in 2014 and 2016, the regular landslides at the Nant Cortay site (≤ 10000 m^3) and the Montgombert landslide in 2016 and 2018 (Desrues et al., 2022). To the east of the Montgombert sector, since 2019 the Champs Claret sector has also shown signs of instability at the level of the RD71 (Figure 16).

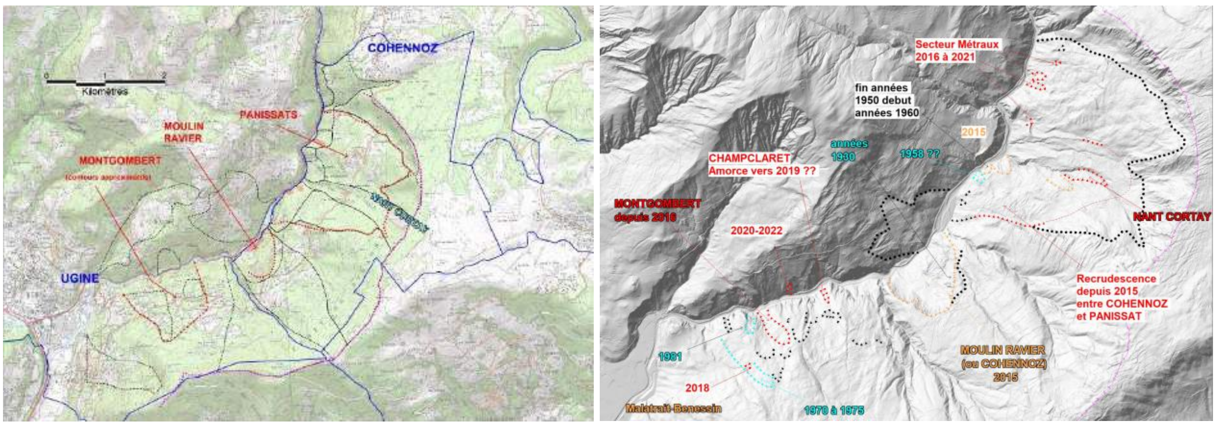


Figure 16 - Active landslides in the Arly gorges (left). Historical landslide activity from 1930 to 2022 (right). In Equilbey (2023)

Analysis of lidars acquired between 2013 and 2022 has enabled us to define the most active sectors at present and to quantify movements on the left bank of the Val d'Arly along the RD1212, between the towns of Ugine and Saint Nicolas la Chapelle (ADRGT, 2023). This analysis enables 4 major movement sectors to be robustly identified, characterised by displacements of more than 10 m in 2 years (Figure 17): (A) the Montgombert and Champ Claret landslides, where displacements may reach at least 8 m between 2013 and 2022); (B) the Moulin Ravier movement, where displacements are at least 9.5 m; (C) the Seuil movement, where displacements reach at least 10 m; and (D) the Panissats movement, where displacements reach 9 m. The extent of some of these movements appears to be decreasing as far as the RD71 (Champ Claret Est, Le Seuil).

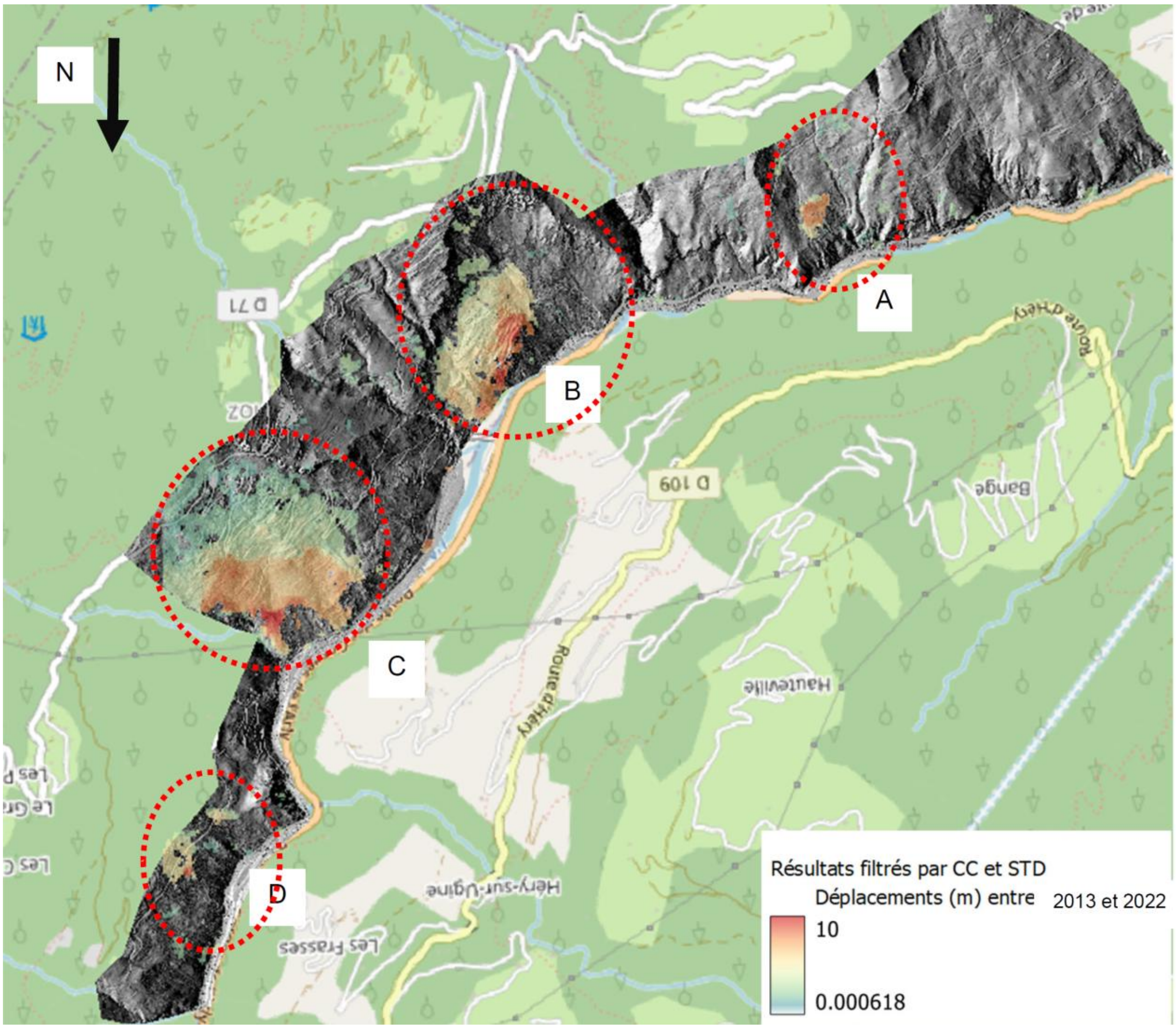


Figure 17 - Result of the correlation of the 2013 and 2022 DSMs with STD and CC filtering. MIROIR project (ADRGT, 2023).

This TSM analysis of the 2013 and 2022 LIDARs highlighted the following issues: (1) Movements on the left bank of the Arly gorges only impact the RD1212 when it passes along the left bank of the Arly, i.e. in line with the Montgombert landslide; (2) The RD1212 could be impacted by movements in Champ Claret Est, Moulin Ravier, du Seuil and Panissat if these cause an ice jam on the Arly; (3) The movement in Champ Claret Est is regressing upstream, and signs of movement are already visible on the RD71. This road could be more significantly affected in the coming years. It will be important to keep an eye on the signs of movement on this road.

The Montgombert landslide, which was already unstable in the past (1970s and 1980s), has been particularly active since spring 2016 and has been heavily monitored since then (Carrier et al., 2024). The most active part of the landslide is about 100 m width and 200 m long, and its depth is evaluated to 15 to 30 m. The piezometric level at the top of the active part of the landslide is 18 to 16 m below the topographic surface in spring and 30 to 31 m at the end of the summer. The surface displacements show that movements are more important in the lower part of the landslide and can reach 25 m within a year. The landslide is water sensitive and is particularly active in the spring following heavy rains and/or fast snow melting. The particularly rainy winter 2017–2018 generated a sudden reactivation of the landslide. Open fractures up to 2 m wide and 10 m long have been produced, 7000 m^3 of rock debris have reached the road, and several hundreds of thousands cubic meters of material have moved from 50 cm to 15 m at the surface of the landslide and stayed in equilibrium on the slope (Figure 18).

Figure 18 - Montgobert landslide, cutting the RD1212 after storm Eleanor in January 2018 (©Département de la Savoie).

The Bersend landslide, situated in the municipality of Beaufort-sur-Doron, is another huge landslide, moving a volume of 4 million m^3. Its reactivation in autumn 2015 has profoundly altered the flow patterns in the area, with the formation of new talwegs and deep erosion of the main flow channel of the Bersend torrent (Figure 19). As a result, each time there is a significant rainfall event, the run-off moves the materials until around ten debris flows are formed each year. These debris flows reach the open check dam built in 2013 upstream of the confluence with the Doron. Since 2016, the average annual volume of debris flows has been more than 10,000 m³. Since 2017, this inflow of material has caused a great deal of damage, destroying the departmental road and filling in all the meadows and the live bed of the Doron. This damage requires regular restoration work and cleaning of the 20,000 m³ capacity check dam.

Figure 19 - The Iles-de-Joux landslide and depositional area of the Bersend torrent at Beaufort-sur-Doron (SMBVA, 2023a).

Smaller landslides occur every year during episodes of intense precipitation, often interacting with the melting and/or leaching of snow cover. For example, the winter flood event of 23-24 December 2022, which was relatively short (36 hours) but was accentuated by a strong thaw that melted the snowpack at higher altitudes, resulted in a significant cumulative rainfall of almost 90 mm to 100 mm over the catchment area (SMBVA, 2023). The snowpack initially acted as a sponge, retaining the accumulated water, before releasing it until it had completely melted below 2200 m altitude, thereby increasing the input to the watercourses. Against this backdrop of unfrozen, soaking wet ground, this precipitation generated numerous landslides, particularly at the head of the catchment area (upstream Arly, Beaufortain, Chaise upstream-Serraval). In many cases, these landslides interact with watercourses (Figure 20), as in the case of the Argentine, Bersend, Arrondine and Arly rivers upstream of Flumet.

Figure 20 - Debris flow from the Bersend on 23/12/2022. *In* SMBVA (2023)

Rockfalls

Rockfalls and rockslides also occur frequently in the Arly gorges, as shown by historical archives (Figure 21).

Figure 21 - Rockfalls in 1892 (1000 m^3) and 1898 (4000 m^3) on the Arly gorges road (RD1212) at Moulin Ravier (RTM73). *In* ACTHYS-Diffusion (2022).

Over the 1948–1996 period, a total of 153 rockfalls of between 1 and over 10,000 m^3 (overhanging micaceous shales) were recorded in the Arly gorges: 111 in the upper gorges; 19 rockfalls of over 1 m^3 in the middle gorges and 23 rockfalls in the lower gorges (Figure 22; Dussauge et al., 2002). Data gathered over the 1954–1976 period show a good agreement between the observed volume distributions and a fit by a power-law distribution for volumes larger than 20 m^3. The main mechanism for rock falls is toppling, in the micaschists as well as in the Carboniferous formation. Since most of the rock falls have their origin above the man-made cut, mainly in the Carboniferous formation, the influence of the road cut on the triggering of events is assumed to be weak.

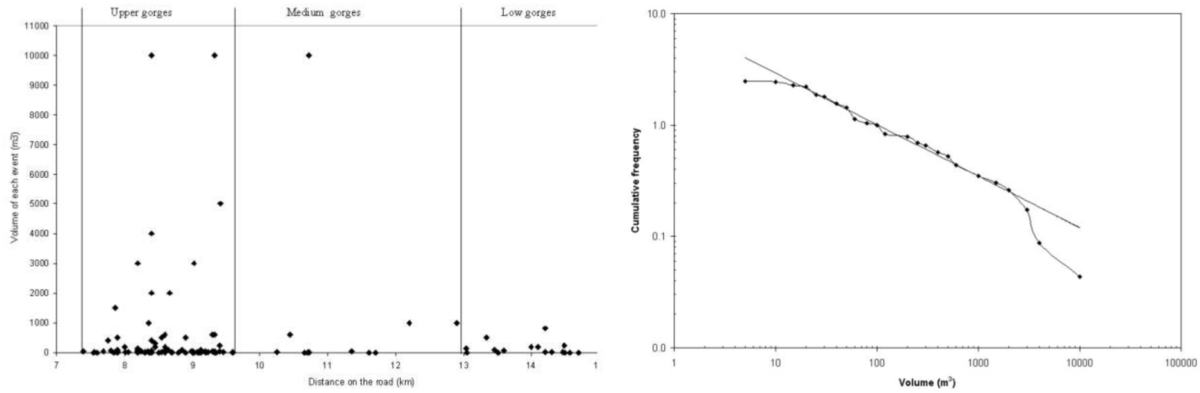


Figure 22 – Right: Spatial distribution of the rock falls along the road 212 in the Arly gorges in the 1948–1996 period. Data from Jeannin (2001). Left: Cumulative frequency distribution for the rock fall volumes from the upper Arly gorges (59 events recorded over 2.2 km between 1954 and 1976). The straight line represents the power-law fit, with the equation f = 8.5 V −0.45 over the 20–3000 m³ volume range. In Dussauge et al. (2002).

At the Cliets tunnel, rockfalls were documented in December 1996 (1500 m^3), October 2003 (3000 m^3), January 2014 (9000 m^3) and February 2019 (10000 m^3) (Desrues et al., 2022).

Figure 23 - The Cliets rockfall along the RD1212.

Figure 24 – Cliets rockfall on the RD1212 on 11th February 2019. Sources: Journal du BTP, in CRC 2022 (left), radiomontblanc.fr (right).

After this rockfall, the road stayed closed during two and-a-half years (France Bleu Pays de Savoie, 2021).

Floods

Hydrographic and hydrologic features of the Arly basin

The Arly basin is typical of Alpine basins, with the majority of its surface area located in 'mid-mountain' areas at altitudes ranging from 500 to 2,500 m. Over a distance of almost 300km, the streams and rivers in the Arly basin can be classified into three main hydromorphological types, from upstream to downstream:

- **Torrents and small streams** at the head of the catchment area;
- **Torrential rivers**, which receive torrential water from various tributaries. These rivers are the Arrondine, the Dorinet and the upstream parts of the Arly, the Chaise and the Doron;
- **Main rivers**, which flow through the alluvial plains at the bottom of the valley in the downstream part of the catchment area: the Arly, the Chaise and the Doron.

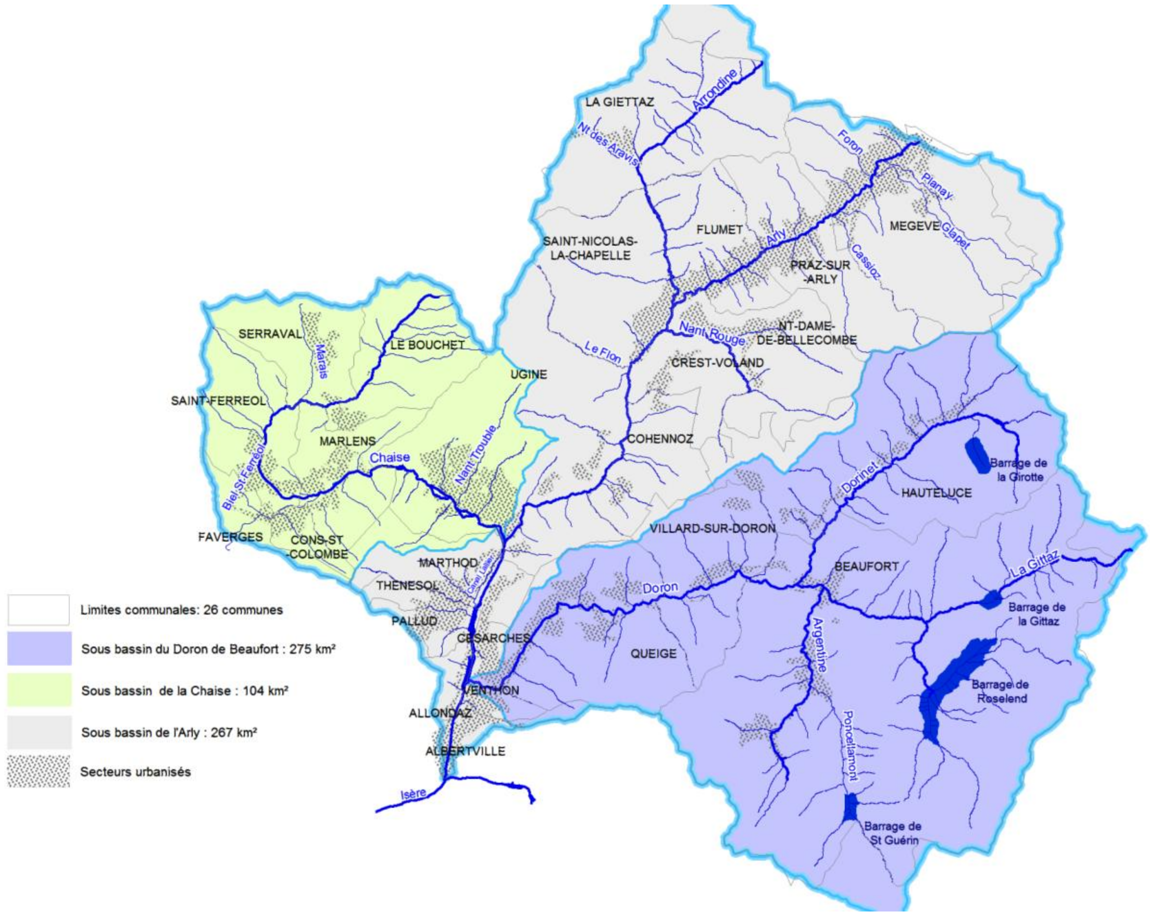


Figure 25 - Hydrographic network of the Arly catchment area. In SMBVA (2012).

The following table shows the main characteristics of the hydrographic network.

	Sous bassin de l'Arly	Sous bassin du Doron de Beaufort	Sous bassin de la Chaise
Surface	267 km²	275 km²	104 km²
Cours d'eau	Arly	Doron	Chaise
Principaux affluents	Planay, Glapet, Cassioz, Nant Rouge, Arrondine, Flon, canal Lallier	Torrent de la Gittaz, Argentine, Dorinet	Ruisseau des Marais, biel de St Ferréol-Faverges, Nant Trouble, Nant Pugin
Principaux lacs	Lac de Javen, Plan d'eau de Flumet,	Lac de retenue de la Girotte, lac de retenue de la Gittaz, lac de retenue de Roselend, lac de retenue de St Guérin	Plan d'eau de Marlens

Table 2 - Characteristics of the hydrographic network in the catchment area (SMBVA, 2012).

Like the whole of the north-eastern quarter of Savoie, the Arly basin is subject to oceanic disturbances from the west, the succession of which results in significant rainfall or snowfall. These phenomena lead to long floods that can last for several days. On a more occasional basis, heavy thunderstorms and/or heavy snowmelt linked to warm air masses from the south or from the east, generate sudden, heavy and often exceptional flooding. The most intense events result in significant solid transport, major morphological variations in the riverbed and sometimes damage near key areas (SMBVA, 2012).

In the Arly basin, the hydrometric regime is predominantly rain-fed: the alternation of winter low-water and spring high-water, typical of the upstream Isère and Arc basins, is less marked on this river, which can be explained by the watershed's average altitude and consequently low snow cover, and by its geographical position under the more marked influence of the westerly flow (DDT73, 2008).

Bassin	Surface (km^2)	T= 2 ans (m^3/s)	T= 5 ans (m^3/s)	T = 10 ans (m^3/s)	T= 30 ans (m^3/s)	T= 50 ans (m^3/s)	T= 100 ans (m^3/s)
Arly à l'amont d'Albertville	647	220	325	385	505	560	660

Table 3 - Maximum flows for different return periods T. Source: DDT73 (2008).

An analysis of historical floods (SMBVA, 2012) shows that the residents of the catchment area have always had to contend with flooding from the Arly and its tributaries. The first records of flooding on the Arly date back to 1594, when the entire plain between Ugine and Conflans was inundated. Between 1700 and 1900, the Arly and, more generally, the Chaise and Doron rivers burst their banks 45 times. These numerous floods were often destructive: destroying bridges, tearing up tracks, roads and houses, digging up the riverbed to a height of 2 m, etc., and led to numerous measures being taken to make the surrounding area safer (mainly diking).

Over the past fifty years, the major events recorded in the Arly basin were those that occurred in September 1968, February 1990, on 13 January 2004, on 1 May 2015, on 4 January 2018, and on 14 November 2023 followed closely by the flood of 11 December 2023 (see hereafter Section III).

Floods and debris flows

The Arly basin is exposed to the risk of torrential flooding, which generally occurs after violent hydro-meteorological events, as was the case in May 2015, January 2018 and late 2023.

With regard to the risk of flooding, the solid transport generated by steeply sloping torrents is an aggravating factor, regularly causing difficulties and damage in this area. Some torrential tributaries with significant names (Nant Bruyant, Nant Trouble, Nant Grossi, Nant Traversier) can carry large volumes of material, which is transported during certain flood episodes in the form of debris flows (SMBVA, 2018).

Figure 26 - Cartography of the risk of torrential flooding in the Arlysère territory (Source: BD-RTM, Consultation 2019, Treatment AERE). In Arlysère (2019).

Geomorphology, sediment sources and solid transport

Numerous areas of active erosion, located either at the head of the catchment area or at the heart of the gorges, supply the watercourses. Several sectors have been identified (SMBVA, 2023X): the gorges de l'Arly with the Panissats, Moulin Ravier and Mont Gombert (or Montgobert) landslides, upstream of the Ugine conurbation; the gorges des Esserieux with the Nant Bellet sur la Chaise landslide upstream of the Saint Ferréol conurbation; the Entreroches gorge with the Iles de la Joux/Bersend landslide on the Doron de Beaufort, upstream of the town of Beaufort; the head of the Aiguille Croches basin and the Planay and Glapet gorges, upstream of the town of Megève (SMBVA, 2012).

The Arly is made up of 5 distinct morphological sectors (Figure 27): (1) the tributaries upstream of Megève (Glapet and Planay), (2) the glacial trough from Megève to Flumet (1.5% gradient), (3) the Arrondine, (4) the gorges between Flumet and Ugine (4% gradient), (5) the alluvial plain from Ugine to Albertville. The Chaise is made up of 2 distinct sectors: (1) the alluvial cone from St Ferréol to Marlens, (2) the stretch from Ugine to the Arly. The Doron is made up of 2 distinct sectors: (1) the upstream torrent and its main tributaries at Beaufort, (2) the river between Beaufort and Venthon.

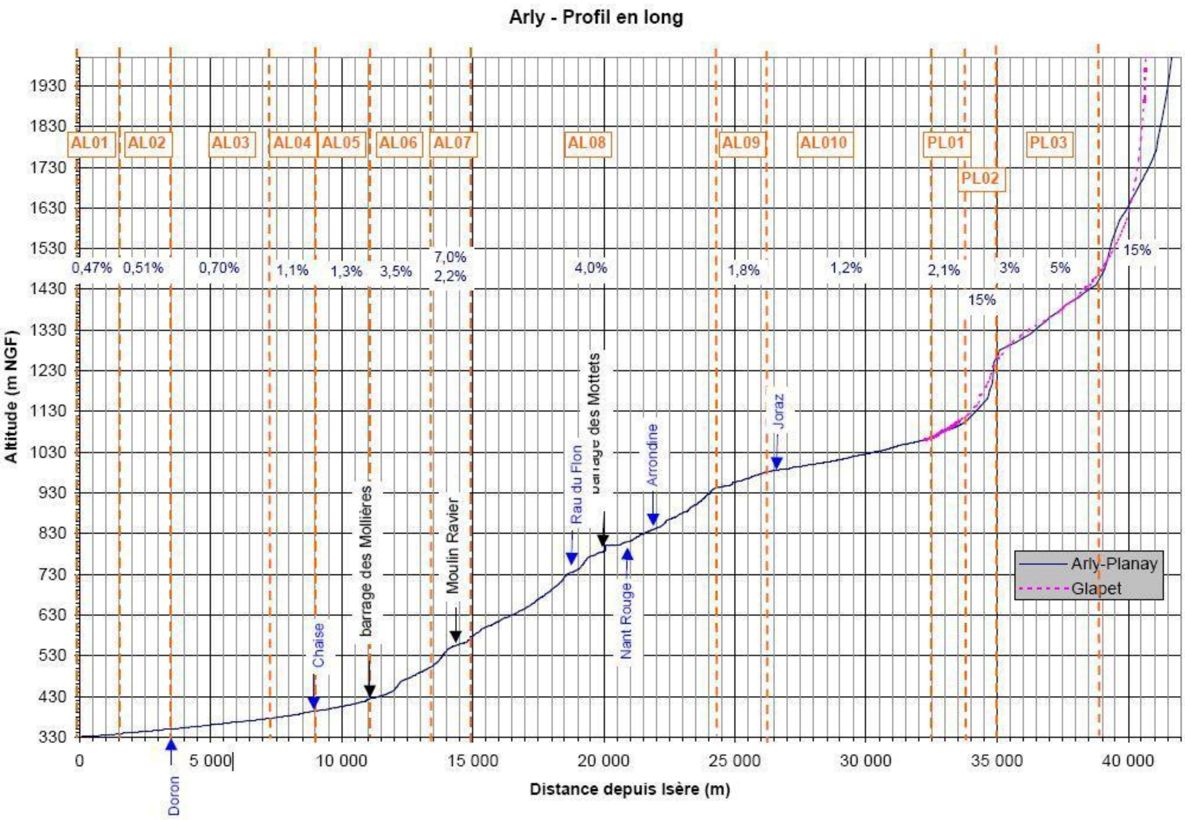


Figure 27 - Longitudinal profile of the Arly. In SMBVA (2012).

Upstream of the catchment area (Megève to Flumet), the Arly flows in a single meandering channel set in a glacial moraine trough. The riverbed has a reduced gradient (5 to 1.2%) compared with upstream tributaries (15%), with highly unstable banks. Only a few tributaries provide material (Le Glapet and the torrent de plaine Joux, Le Planay, the ruisseau du Cassioz and the Jorrax). As a result, the bed load remains limited. The Arly seems to have found an equilibrium longitudinal profile between a few natural or artificial riffles that allow sediment continuity between upstream and downstream, favouring the relative stability of the bed at higher altitudes. In the transition zone upstream of the gorges, the gradient increases and the river bed becomes increasingly incised from the Jorrax onwards. Numerous landslides affect the banks and the bed load is more pronounced.

In the gorges (Flumet to Ugine), the gradient is steeper and the banks are mainly mineral (rock outcrops or protection for the RD1212). Lateral inputs (landslides, rockfalls, tributaries) are potentially significant, albeit irregular. The river flows mainly over alluvial material from the slopes or from upstream. In the gorges, the low level of regular solid contributions to the Arly compared with its theoretical transport capacity generates a sediment deficit, and consequently a general tendency for the riverbed to incise. This phenomenon was exacerbated by the extraction of materials between the 1960s and 1990s and by the operation of the Mottets dam. However, this trend is slow and is counteracted by natural sills created by localised landslides that level out the longitudinal profile.

In its alluvial plain (between Ugine and Albertville), the Arly flows in a bed that is not very free-flowing today, with a regularly decreasing gradient, locally blocked by weirs, numerous anthropogenic constraints having progressively encroached on the river's mobility space (urbanisation, RD1212), with artificial banks along most of its length. Lateral inputs are virtually non-existent (disconnection of the right bank tributaries, Ruisseau du Creux and St Maurice, which are equipped with deposition beaches). The uneven bed load is limited by the vegetation on the banks and by past quarrying, which has now been stopped (Glaires sector at Thénésol).

Relatively balanced sediment transport. The transport capacity is in line with the available solid load, particularly in stretches where the Arly still has sufficient space to divide (Glaires-Albertville crossing). On the other hand, in the channelled and confined sectors, such as the Ugine crossing, the theoretical transport capacity of the Arly is much greater than the average sediment flow, due to the almost generalised paving of the bed. The hydraulic constraints at play on this stretch contribute to a strong destabilisation of the banks and at least partial washout of the bed cannot be ruled out during an exceptional flood. Sediment flow is between 5 and 10,000 m^3/year and in floods between 10 to 15,000 m^3 for a ten-year flood and 20 to 30,000 m^3 for a 100-year flood.

In the alluvial plain, the Arly's mobility space has been progressively reduced. From 1730 onwards, successive developments were carried out to protect crops, followed more recently by the construction of the dual carriageway between Albertville and Ugine (1980-2000) and the Albertville embankment road (2008). The dykes that have been built have gradually reduced the mobility space of the Arly (Figure 28). At Les Glaires in Thénésol, the active strip was 350m wide in 1730 and over 100m wide in 1978. Today, the Arly flows along an active strip just under 50m wide in a dyked bed around 60m wide, limited by the embankment of the RD1212 on the right bank and by alluvial terraces that are sometimes perched as a result of the sinking of the bed or fixed by vegetation.

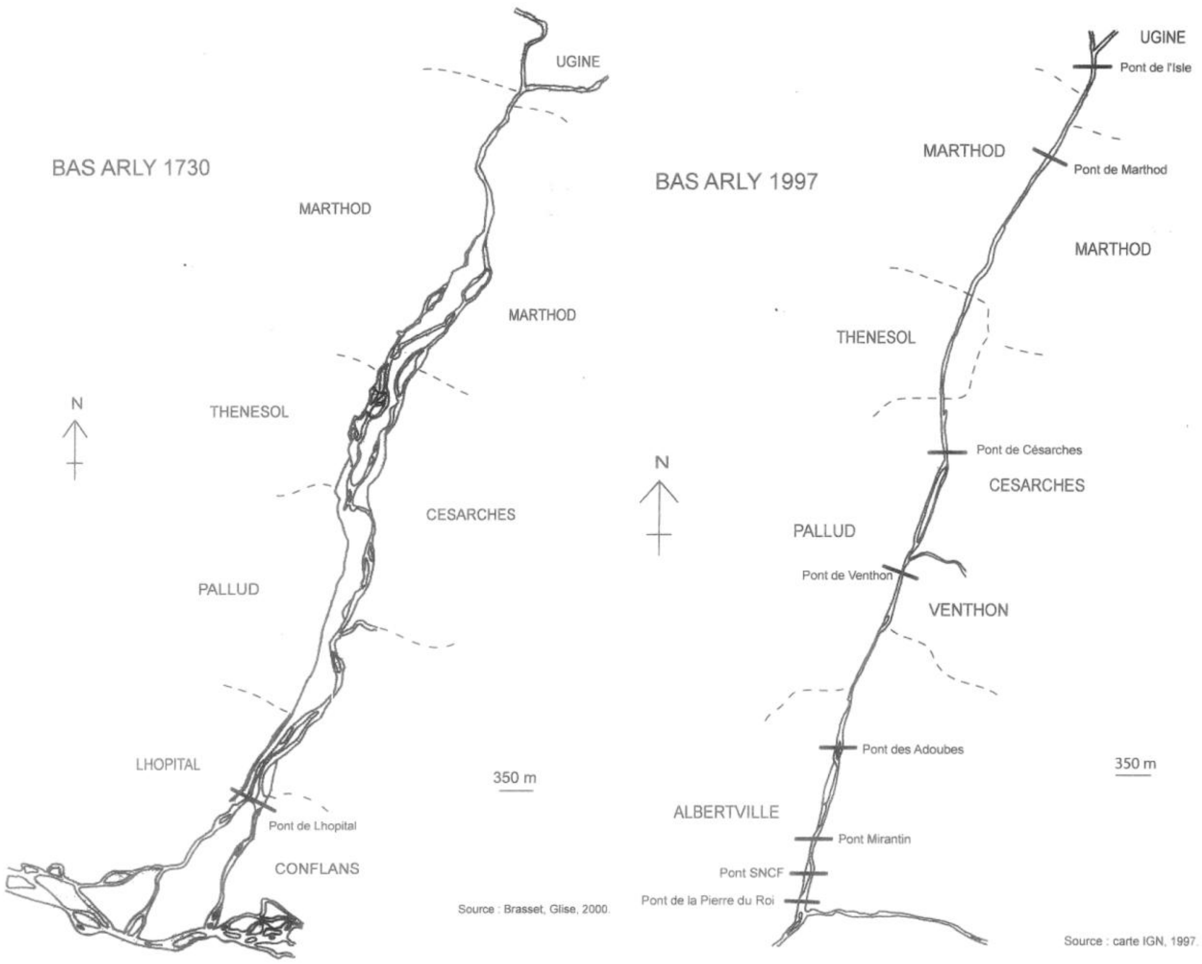


Figure 28 - Comparison of the Bas Arly in 1730 and 1997 (Source: F. Guillon, 2002). ***In*** **SMBVA (2012).**

Snow avalanches

The upper parts of the Arly basin are exposed to the risk of avalanches (Figure 29). The map above shows past avalanche phenomena and reports of avalanches in the mountain ranges, indicating the areas at risk of avalanches. The ongoing avalanche survey highlights areas that are not included on the map because they are not part of the mountain massifs. These areas are located on the south-western edge of the region, in the communes that are part of the PNR des Bauges.

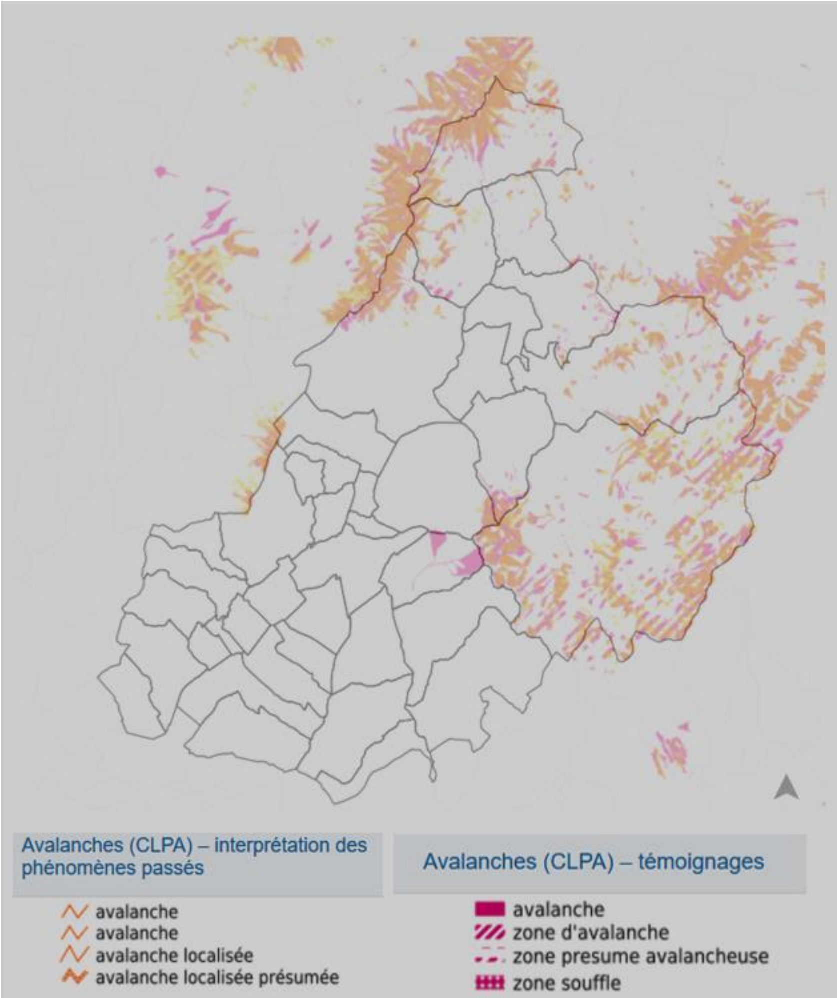


Figure 29 - Avalanche risk map of the Arlysère territory (Source: Géoportail). In Arlysère (2019).

Probable Avalanche Location Maps (CLPA) drawn up in the French Alps identify the main areas at risk.

Dép.	Intercommunity	Commune	Beaufortain	Bornes-Aravis
Savoie (73)	CA Arlysère	Albertville		
		Allondaz		
		Beaufort sur Doron	CLPA	
		Césarches		
		Cohennoz		
		Crest-Voland	CLPA	
		Flumet	CLPA	CLPA
		Hauteluce	CLPA	
		La Giettaz		CLPA
		Marthod		
		Notre Dame de Bellecombe	CLPA	
		Pallud		
		Queige	CLPA	
		Saint Nicolas la Chapelle		
		Thénésol		
		Ugine		CLPA
		Venthon		
		Villard sur Doron	CLPA	
Haute	CC Pays du Mont Blanc	Megève		CLPA

Savoie (74)		Praz-sur-Arly	CLPA	CLPA
	CC Sources du Lac d'Annecy	Faverges-Seythenex		
		Saint Ferréol		CLPA
		Val de Chaise		
	CC Vallées de Thônes	Le Bouchet Mont-Charvin		CLPA
		Serraval		CLPA

Table 4 - Communes affected by the risk of avalanches in the Arly basin according to the Carte de Localisation Probable des Avalanches (CLPA), from IINRAE (IRSTEA, 2016). Compilation: PARN.

In the Bornes massif and the Aravis mountain range, the area studied by the CLPA was 33,417 ha in 2012 and concerned all or part of 15 municipalities, including 8 SMBVA member municipalities in the Arly basin: Le Bouchet Mont Charvin, Flumet, La Giettaz, Megève, Praz-sur-Arly, Saint-Ferréol, Serraval and Ugine (IRSTEA, 2016a).

In the Beaufortain, the surface area studied by the CLPA (IRSTEA, 2016b) was 28,211 ha in 2010. This surface area covers all or part of 12 communes, including 8 communes within the SMBVA: Beaufort, Crest-Voland, Flumet, Hauteluce, Notre-Dame-de-Bellecombe, Queige, Villard-sur-Doron and Praz-sur-Arly. On December 23, 1923, ten people died in the hamlet of Les Lanches in Beaufort during the Beaubois avalanche (Givry and Perfettini, 2004; Figure 30), still the deadliest snow avalanche in the area (La Savoie, 2023).

Figure 30 - On December 23, 1923, the Beaubois avalanche in Beaufort engulfed a barn and two dwellings, killing ten people, before ending its course on the D925. In Savoie (2023).

Major events recorded in the Arly basin

Floods and landslides of September 15, 1940: Remarkable flooding occurred on the tributaries of the Isère on September 15, 1940, following an episode of intense rainfall (in excess of 100mm/24h in the most heavily watered area) across the Northern Alps (Pardé, 1941). This precipitation, which fell on already wet soils, was probably reinforced by snowmelt. In the Arly basin, Maurice Pardé estimated the total rainfall at 118mm, and the river flow was estimated at 500 to 550 m^3/s (this estimate, although subject to caution, seems reasonable given the current knowledge of the Service de Prévision des Crues des Alpes du Nord: Alain Gautheron, personal communication, 2024). The Arly river had not experienced such a major flood for 40 years or more, and landslides occurred in the Arly gorges, as well as major damage to the Doron de Beaufort: "*The damage was very serious, especially in the Doron area: concave banks attacked and landslide slopes produced by this work of undermining; new beds opened up in the meadows; road cut in many places, even washed away right down to its rocky foundations; bridges destroyed, some buildings torn up, nine power transmission pylons knocked down, Queige factory invaded to a depth of 1 m. 90. The Arly River, for its part, put the gorge road to a severe test, causing it to be torn up in many places and completely cut off at four or five points. One of the breaches was 100 meters long. But the road bridges were spared. On the left bank, near the village of Cohennoz, the unstable banks were deeply scoured. This triggered landslides which subsequently became more severe. In the upper reaches, the lesser damage indicates a less furious surge of water.*"

Flood of 15 February 1990: A flood with a return period estimated at 50 years (197 m^3/s in the Arly gorges at Moulin Ravier) is reported in the literature but no information has yet been found about it.

Flood and torrential erosion of January 13, 2004: This flood, considered to be a thirty-year flood, had the particularity of being relatively long since the flow was still sustained 24 hours after the peak. This major flood caused significant changes to the riverbed (SMBVA, 2012): erosion of the embankment over a distance of around one hundred metres at Moulin Ravier, erosion of the embankment of the RD1212 between Ugine and Moulin Ravier, major deposits of material (10,000 m^3; 1.5 to 2 m high) at the entrance to Ugine at the water intake sill of the Ugine steelworks (Mollières bridge) and erosion of the road embankment over a distance of 10 m at the entrance to Ugine. During this flood, inflows from the main tributaries were estimated at 50 m^3/s on the Chaise (ten-year flood) and 100 m^3/s on the Doron de Beaufort (undetermined occurrence).

Flood and torrential erosion on April 30-May 1st, 2015: April 2015 was characterised in the Alps by mild temperatures and several stormy episodes. Between 26 April and 5 May, heavy thunderstorms caused extensive flooding and landslides in Savoie (CCR, 2015). In Savoie (73) and Haute-Savoie (74), a month's rain fell in 24 hours, i.e. around 70 to 90 mm, with peaks of 130 mm locally on 1 May alone. Between 30 April and 2 May, rainfall totals reached 150 to 160 mm, with records of 180 mm at the Hauteluce dam (73) and 190 mm at Thônes (74). The end of the storm disturbance on the morning of May 2 led Météo-France to lift the orange alert in the four départements. However, due to the heavy rainfall, Savoie and Haute-Savoie were placed under a 'Flood' orange vigilance in the afternoon. This remarkable rainfall came at a time when the rivers were already swollen by melting snow, increasing the risk of overflowing. The overflowing rivers flooded the Ugine hydroelectric power station and several houses, particularly in Flumet. In addition, many roads were damaged, like the RD1212 (Figure 31), isolating several communes.

Figure 31 - Flood of May 1, 2015 in the Arly gorges. Source: Département de la Savoie (in Arlysère, 2019).

Figure 32 - Flooding on May 1st, 2015, in the Arly gorges at Moulin-Ravier (upstream of the weir). Source: IRMA

During this flood event, the old Moulin Ravier flow measurement station was destroyed, interrupting the series of measurements in the Arly gorges in May 2015.

Floods and torrential erosion on January 3 and 4, 2018, following the passage of storm Eleanor: Two successive floods on 4-5 and 21-22 January 2018 affected the Arly catchment area, within 15 days of each other, damaging buildings and infrastructure and causing major damage in some communes. The 2 floods were characterised as follows: Above 900m/1200m - depending on the isotherm (constant temperature line) the heavy precipitation, in the form of rain and/or snow, was buffered by the snow cover, then gradually released in part. At medium (< 900m) and low altitudes, the precipitation generated heavy runoff, saturating the drainage capacity of the river system. The combination of heavy precipitation and the thaw that caused the snow cover to melt, on water-saturated soils, led to numerous landslides and road overflows. The towns worst affected in the catchment area were: Le Bouchet-Mont-Charvin, Marlens, Ugine, Marthod and Thénésol. In the Beaufortain region, the towns of Villard-sur-Doron and Queige were heavily affected.

Figure 33 - Arly flood at Ugine downstream the pont de l'Isle on 3-4 January 2018. Source: SMBVA.

The flood of 4-5 January 2018, which occurred every five years in the alluvial plain (345 m3/s), was not an exceptional flood on the Arly, but it was exceptional in the La Chaise catchment (80 m3/s) and was more than every three years (SMBVA, 2019). This flood has a return period of fifty years (maximum instantaneous flow estimated at 84 m3/s by Banque Hydro). The flood of 21-22 January was also strong, with a return period of five to ten years. The basin of the Doron de Beaufort was also affected, on the tributaries of the Doron in the communes of Villard-sur-Doron and Queige. Numerous emergency interventions and post-flood restoration operations were undertaken by the communes (police powers of the mayor) and by Arlysère as part of its GEMAPI remit. In the catchment area, almost 20 sectors have been the subject of emergency work or post-flood restoration, for a total of almost €320,000 (GEMAPI, excluding roads).

Figure 34 (SMBVA, 2018)

The work undertaken was brought to the attention of the partners and included in the compensation file submitted by the competent local authorities (Arlysère, communes) at the beginning of March 2018 (one-stop shop: solidarity fund - State, FREE fund - Savoie Department, regional aid). For the SMBVA's technical team, providing technical support to local authorities for the implementation of restoration work (files/works) required almost 2 months of full-time work.

The occurrence of storm Eleanor on already wet soils and the rapid rise in temperatures that followed triggered at least 30 torrential flood, landslide and mudslide events, causing numerous disorders in the Arly basin between January 2 and 6, 2018 (Figure 35).

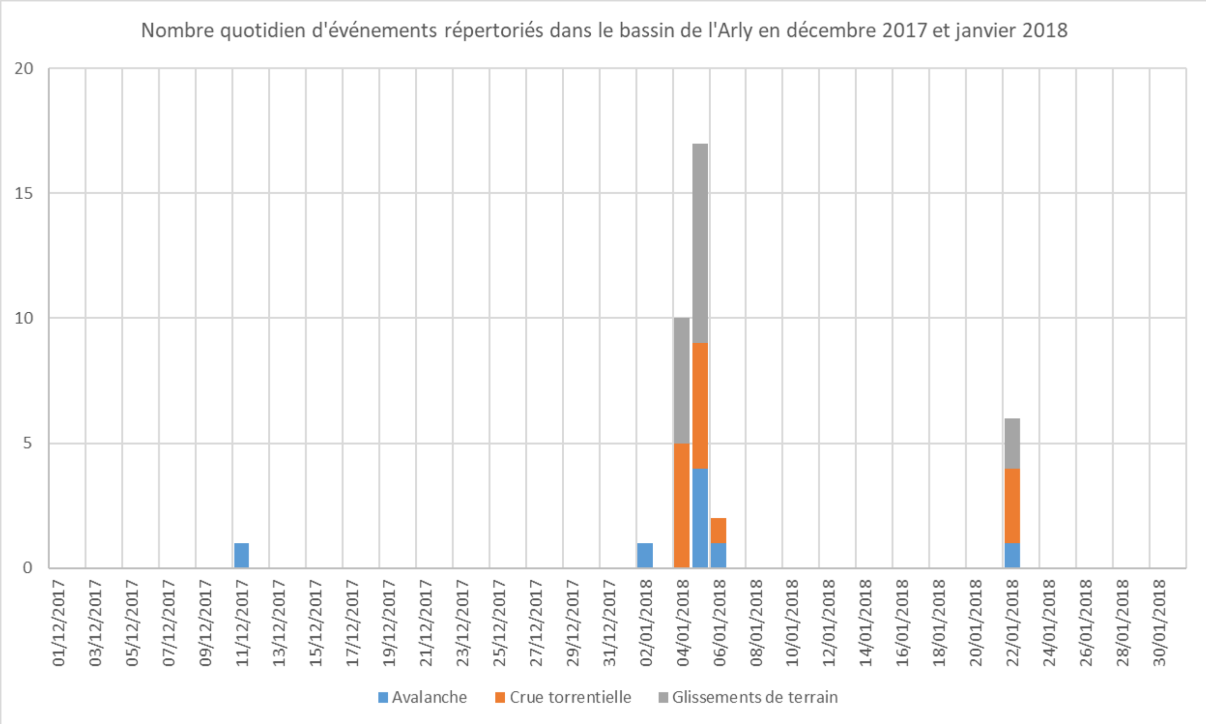


Figure 35 - Daily number of events in the Arly basin in December 2017 and January 2018 listed in the BDRTM. Processing: PARN.

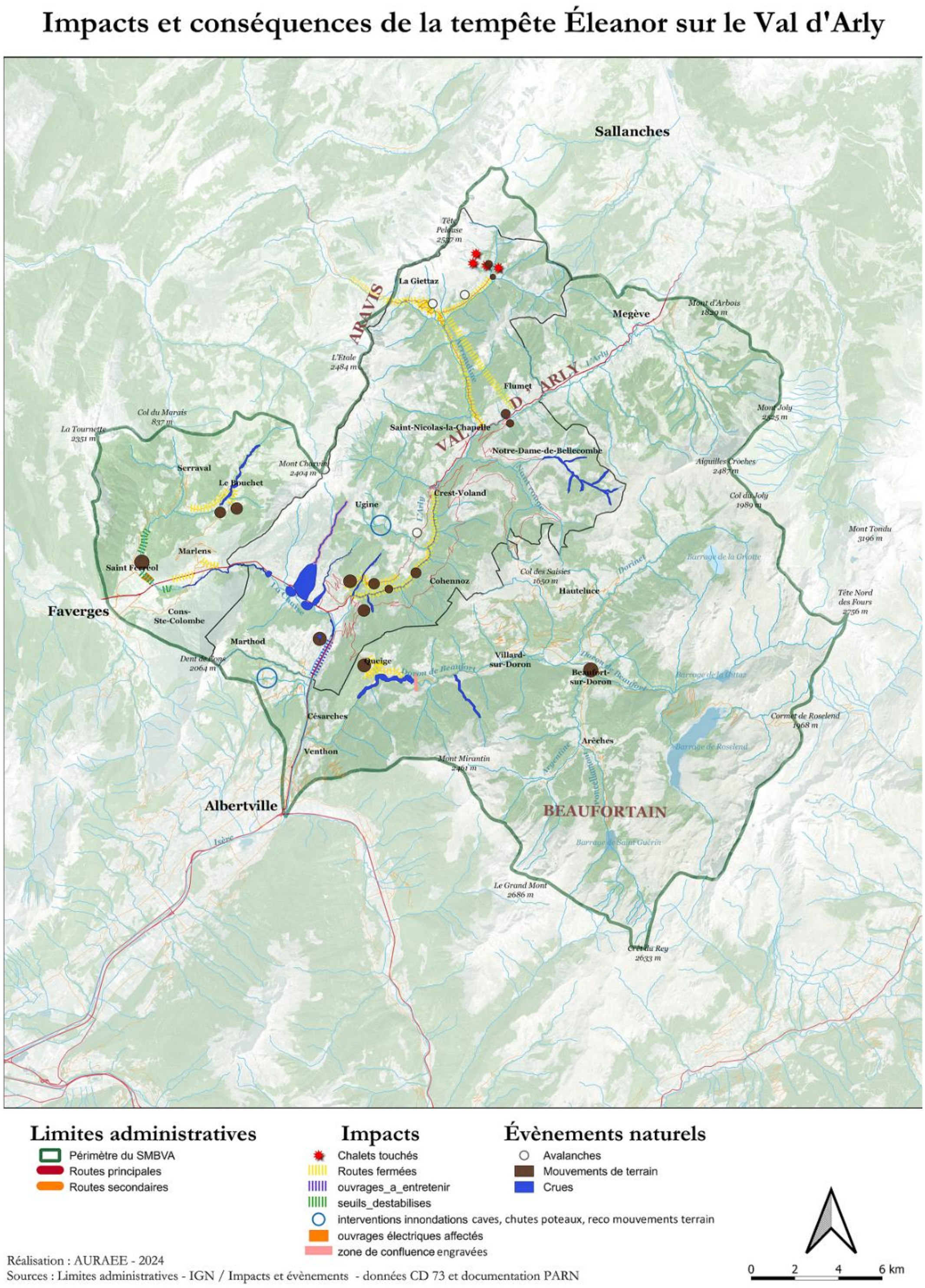


Figure 36 - Impacts of natural events associated with the passage of storm Eleanor in January 2018, as identified by local stakeholders at the X-RISK-CC project workshop in Ugine organised by AURA-EE and PARN on 6 February 2024.

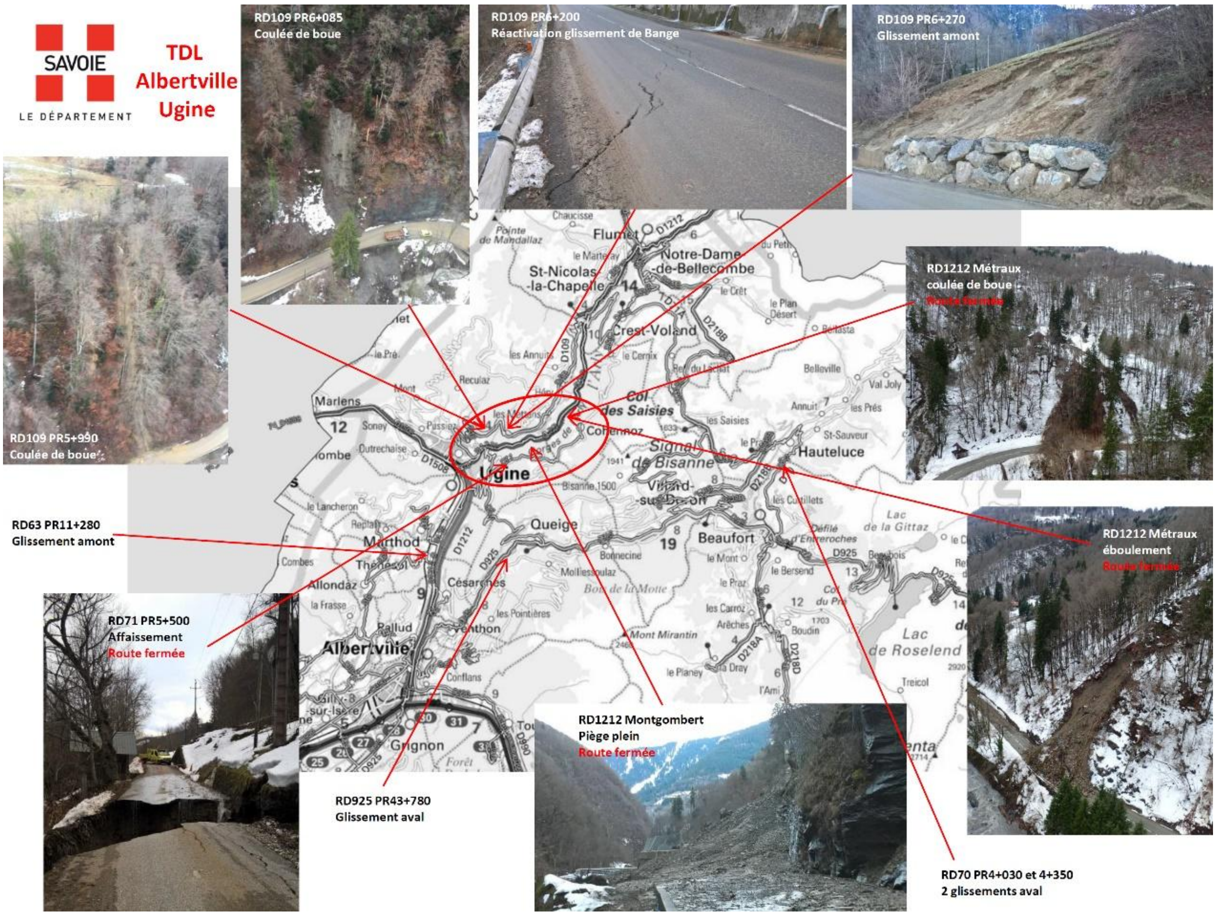


Figure 37 - Examples of hazards that affected the area between Ugine and Albertville following the events of January 2018. Source: Département de Savoie (Lescurier, 2018).

Floods and torrential erosion of late autumn 2023: In November and December 2023, Savoie was hit by a series of rainfall events of remarkable duration and intensity. No less than the equivalent of ten months' precipitation fell in 7 days, exacerbated by the melting snow generated by the “thermal yoyo” phenomenon, a visible effect of climate change (Gaymard, 2023). The rocky massifs also suffered from water saturation of the soil and freeze-thaw periods.

During these episodes, the Arly catchment area experienced **3 successive floods** in less than a month (15/11, 30/11 and 13/12/2023), again as a result of heavy rainfall with a marked thaw at higher altitudes, causing the snowpack to melt. Heavy soil saturation also encouraged run-off and the triggering of landslides throughout the area (SMBVA, 2023). These 3 episodes of flooding, accompanied by bank erosion and landslides, were morphogenic. (Figure 38). The significant mobility of the watercourses caused a widening of the riverbeds through lateral erosion, with damage to roads and networks close to the watercourses, and the mobilisation of stocks of materials, leading to embankment on certain stretches. The concomitance of floods and landslides (saturation of soils and landslides in watercourses and undermining of landslide bases by watercourses) resulted in the triggering of debris flows and torrential floods (Bersend, Nant Pelloux), the rerouting of watercourse beds (Bossonaz, etc.) and the formation of logjams (Chaise au Bouchet-Mont-Charvin).

Figure 38 - Bank erosion on the Arly downstream of Cassioz on 20 November 2023 (top left), etc. Source: SMBVA

Nearly 90 sites have been affected in the catchment area, 40 of which have been the subject of post-flood restoration work by the SMBVA (Figure 39), at a cost of more than €987,000 (SMBVA, 2024).

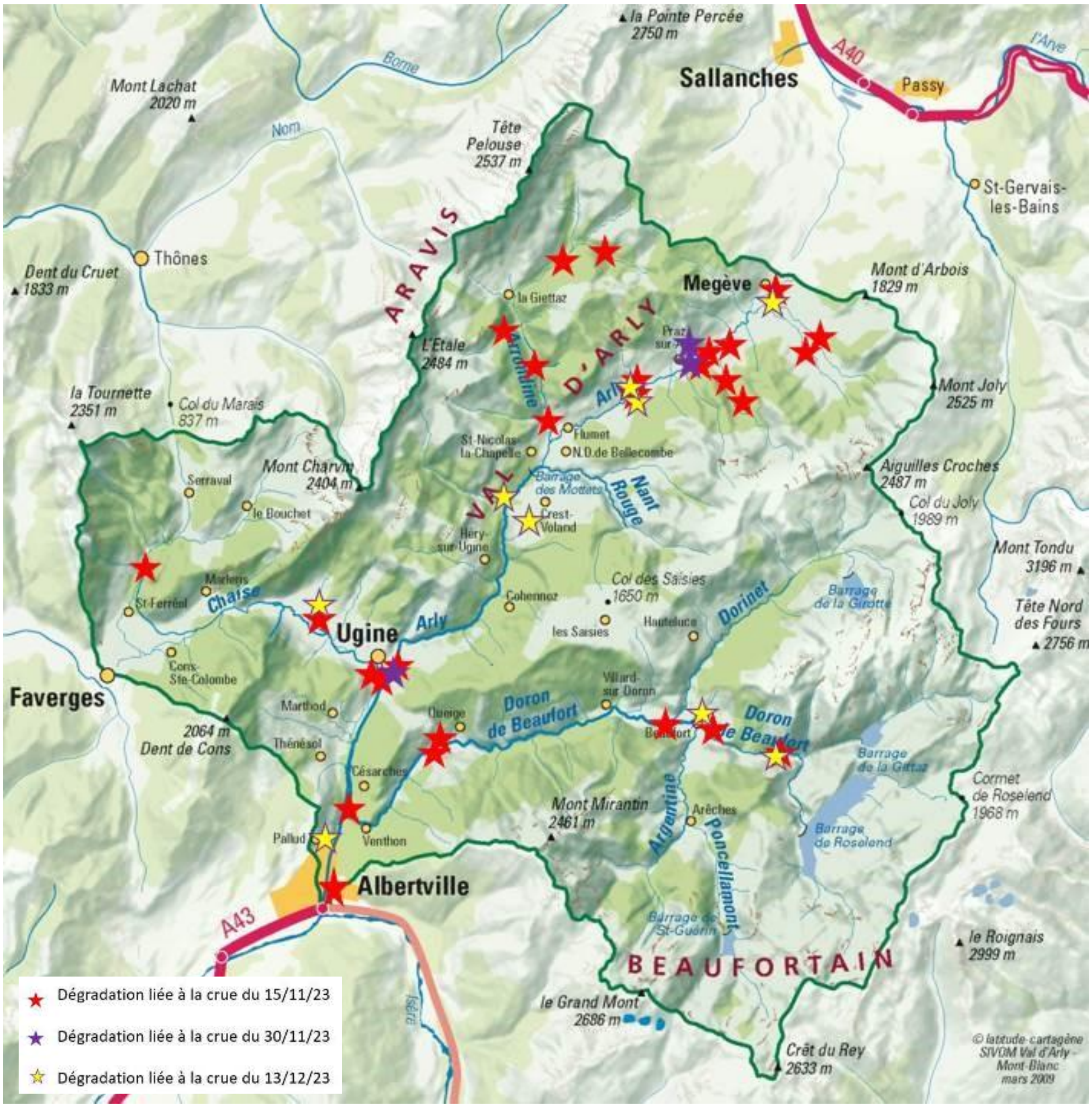


Figure 39 - Impact of the November and December 2023 floods in the Arly basin (SMBVA, 2024).

Thie 3 successive floods of November-December 2023 enabled to measure the positive effects of the prevention work carried out by the local authorities in charge of GEMAPI flood prevention programs (see section VI hereafter). The work to restore the public river domain, undertaken with the financial contribution of the State, prevented a disaster on a completely different scale in the Combe de Savoie, given the unprecedented flows recorded on the Isère at Albertville for almost a century (Gaymard, 2023).

b) Potential future hazard processes due to weather extremes

The mechanisms of climatic control on certain types of natural hazards tiggering conditions highlighted in the Alpine Region call for increased vigilance with regard to the future evolution of phenomena with proven climatic sensitivity, such as landslides, rockfalls, river and torrent flooding, as well as snow avalanches (Einhorn et al., 2015).

Landslides

As temperatures continue to rise, we can expect an increase in the frequency of milder spells likely to cause rapid melting of the snowpack and rain-on-snow events such as those observed in January

2018 during storm Eleanor (Stoffel and Corona, 2018) and again during the repeated flooding events that occurred in the Arly basin in November-December 2023 (SMBVA, 2023).

Floods

In the coming years, the risk of flooding is likely to increase due to global warming. Indeed, global warming is causing an increase in the seasonality of precipitation, leading to intense rainfall events at times when soils have already reached their maximum infiltration capacity. Sewage systems are not designed to cope with such events and risk becoming saturated, while groundwater will no longer be able to absorb the water (Arlysère, 2019).

III. Which processes occur more/less frequently and with high/low magnitude and how do you expect this to change in the future?

Changes in climate, their impact on the Alpine environment and on natural hazards observed in the French Alps in the last decades reveals climatic control mechanisms exercised at different timescales by some weather parameters (temperature and precipitation) on formation conditions for certain types of hazards (Einhorn et al., 2015).

In the Arly basin, changes in the activity of certain natural hazards, such as landslides, rockfalls, floods and debris flows, have already been observed by risk managers and the scientific community.

a) Past/present frequencies and magnitudes

The Val d'Arly is a steep-sided Alpine valley subject to historical slope instability, which can lead to large-scale landslides causing significant direct damage, but also indirect damage due to torrential flow of watercourses, which then impact roads and economic activities. Because of the aggravating factors linked to climate change, it is becoming important to be able to estimate the scale of these phenomena, which occur rarely but with sudden outbursts of very large volumes, in order to gain a better understanding of them and prepare for them, by setting up appropriate preventive monitoring systems if necessary (BRGM, 2024).

The ONF-RTM database (BDRTM) of the French Torrent and Avalanche Control Service (‘Service de Restauration des Terrains en Montagne de l’Office National des Forêts’) records natural mountain events in the 6 departments of the French Alps (BDRTM, 2024). As part of the X-RISK-CC project, PARN has compiled existing data for the 25 communes in the Arly basin (synthesis of data available for the Savoie and Haute-Savoie departments). The inventory of events recorded in the Arly basin comprises 463 events recorded by the RTM services since 1715 (99 avalanches, 210 torrential floods, 96 landslides and 58 rockfalls), with visibly better documentation from the 20th century onwards (Figure 40). Note that only torrential floods are recorded before the 20th century: avalanches and boulder falls are only recorded from 1900 onwards, and landslides mainly from the 1980s onwards.

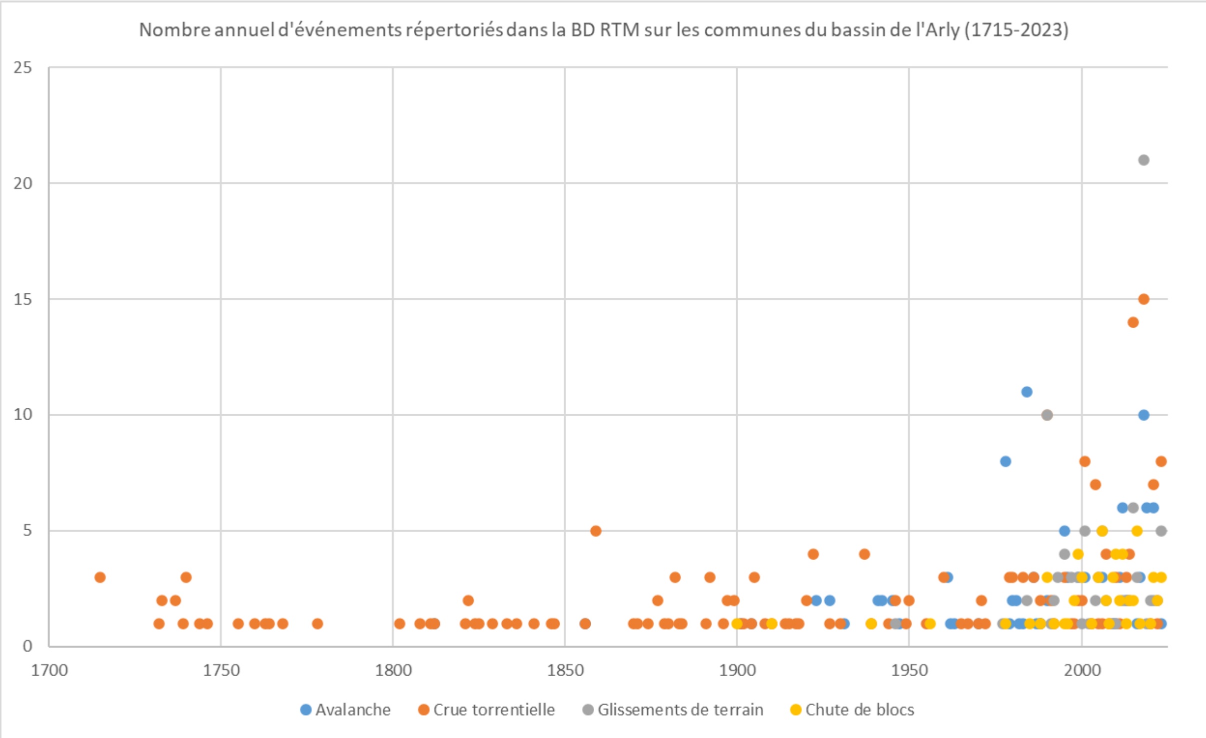


Figure 40 - Annual number of avalanche, torrential flood, landslide and rockfall events in the Arly basin (1715-2023), inventoried in the BDRTM. Source: ONF-RTM; Processing: PARN.

In the 20th century, the BDRTM recorded events more systematically from the late 1970s onwards, and showed an apparent increase in the number of annual events, without it being possible to separate the respective contribution in this increase between the improved quality of the inventory and an objective increase in the activity of floods and inundations, torrential floods and associated gravity phenomena, noted elsewhere in the north of the Alpine Region (Schmocker-Fackel and Naef, 2010; Einhorn et al., 2015; Jomelli et al. 2019). A noticeable increase in the annual number of recorded events is noted from the 1980s onwards (Figure 41). The episodes of 1990, 2015 and 2018 stand out clearly (>20 events/year), as do the episodes of 2021 and 2023 (>15 events/year).

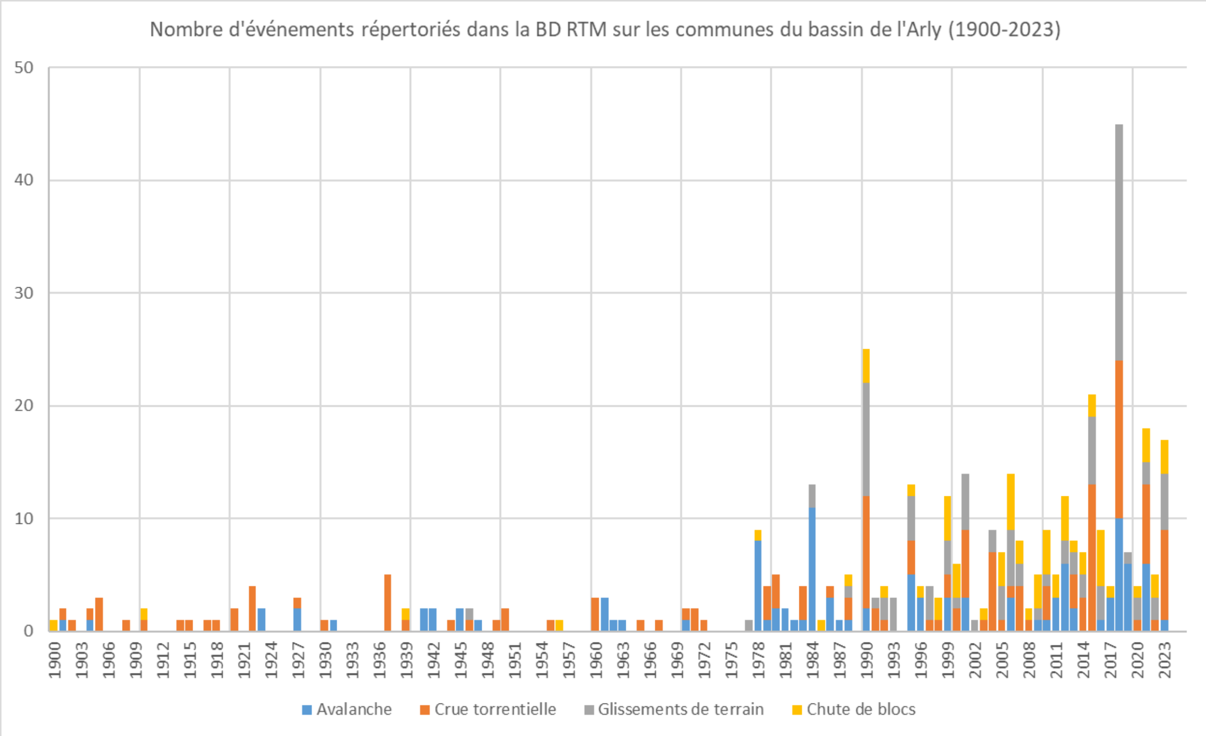


Figure 41 - Annual number of avalanche, torrential flood, landslide and rockfall events in the Arly basin (1900-2023) inventoried in the BDRTM. Source: ONF-RTM; Processing: PARN.

Over the period 1980-2023, the main hydro-gravitational events identified in the literature in the Arly basin are recognisable in the BDRTM inventory (Figure 42), in particular: the main avalanche events (1984, 1995, 2012, 2018 and 2019), torrential events (1990, 2001, 2004, 2015, 2018, 2021 and 2023), landslides (1990, 2015, 2018...) and rockfalls (more of which have been recorded since the 1990s).

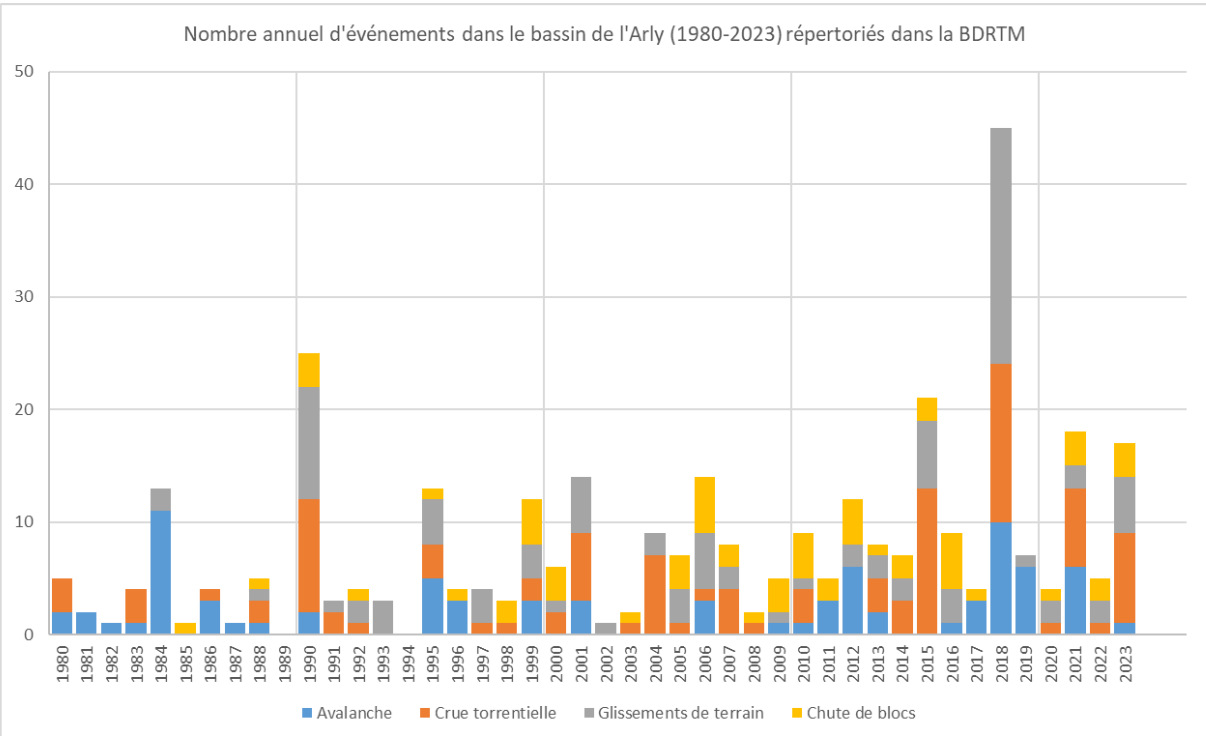


Figure 42 - Annual number of avalanche, torrential flood, landslide and rockfall events in the Arly basin (1980-2023) inventoried in the BDRTM. Source: ONF-RTM; Processing: PARN.

The year 2018 stands out in particular, due to the large number of landslide, torrential flood and avalanche events triggered recorded on January 3 and 4, 2018 following the passage of storm Eleanor (see Section II).

Landslides

Generally speaking, the Savoie département in charge of road management has seen an increase in landslides, mudslides and debris flows over the last ten years or so (Einhorn and Peisser, 2011; CRC, 2022), under the influence of changes in the meteorological factors controlling their triggering (Einhorn et al., 2015).

The RTM database records 100 landslide events in the Arly basin on the period 1946-2023. These gravitational events associated with the torrential floods of 1990 (10 events), 2015 (6 events), 2018 (21 events) and 2023 stand out clearly (Figure 43). These landslides mainly occur between December and May.

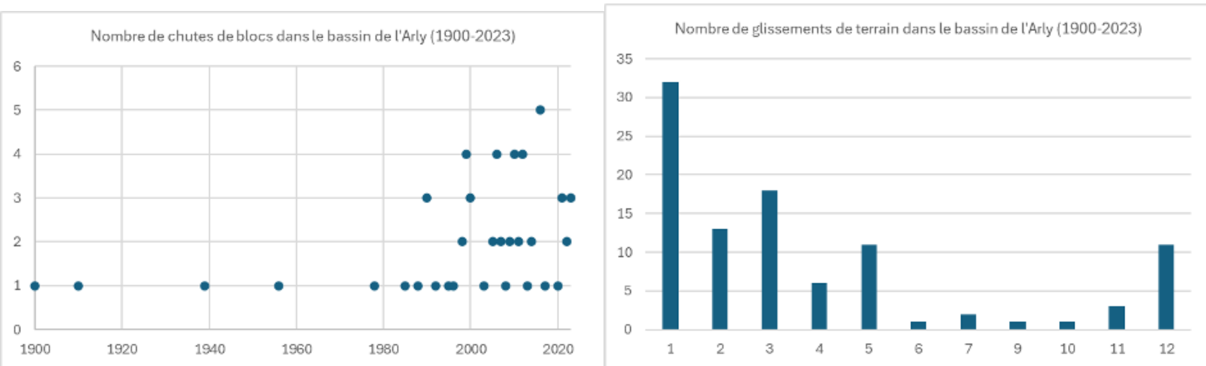


Figure 43 - Annual number of landslides in the Arly basin recorded in the BDRTM (left). Monthly breakdown (right). Source: ONF-RTM; Processing: PARN.

In order to study the ground movement activity in the Arly gorges and the potential sediment yield to the river, a preventive and prospective study of slope instabilities in the Arly gorges has been carried out by BRGM and ADRGT as part of the MIROIR project. The historical study carried out as part of the MIROIR project (Equilbey, 2023) identified 171 events (floods, landslides and boulder falls) between 1721 and 2022, spread over three successive periods: 82 historical events prior to 1926, 46 old events between 1926 and prior to 1956, then 53 more recent events up to April 2022 (Figure 44).

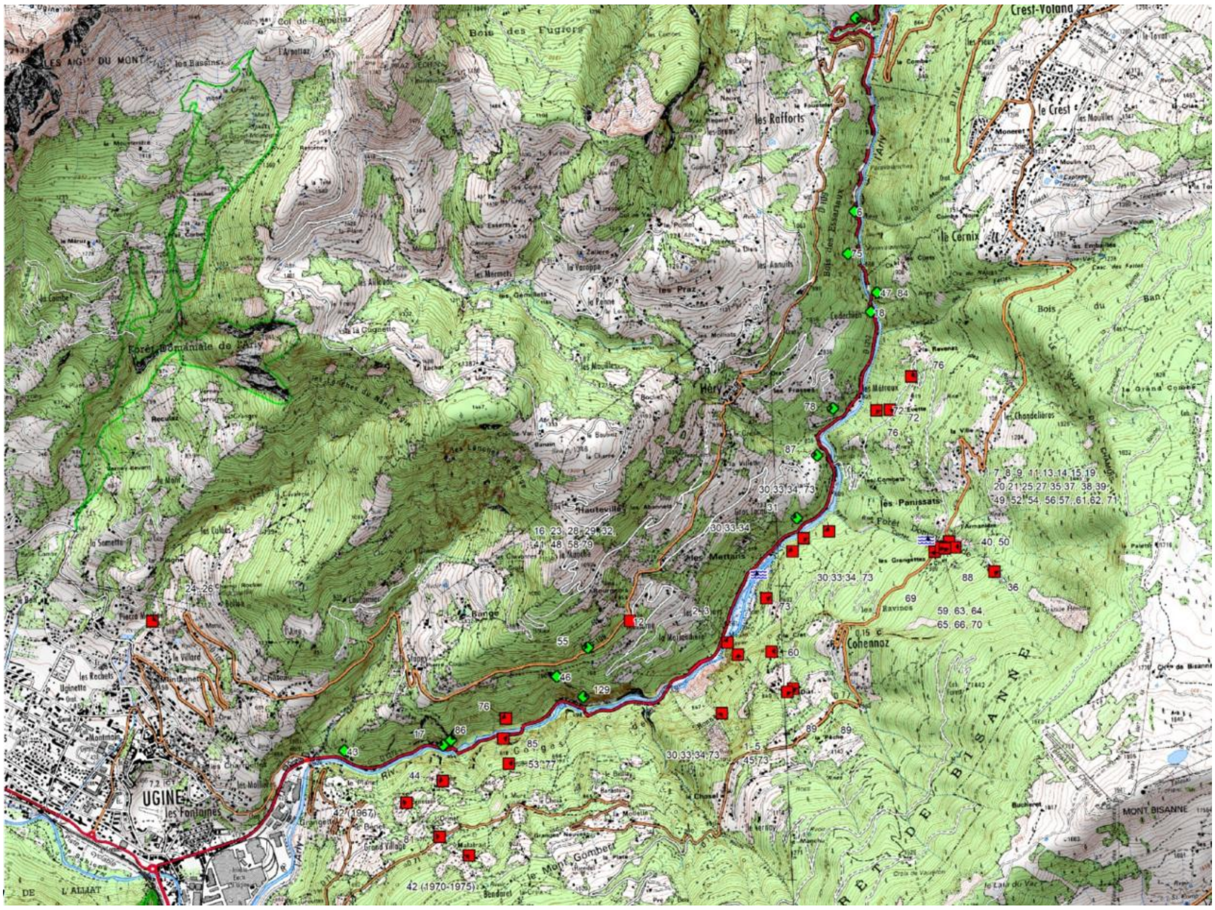


Figure 44 - Location of contemporary events (> 1926) in the Gorges de l'Arly and surrounding area. *In* BRGM (2023).

Code	Type	Date début	Date fin	Durée	Information sur le lieu	Information sur l'intensité	Jour début	Mois	Utilisation seuil
1	glissement	01/12/1930	01/09/193	274	Extension est glissement Cohennoz	qq dizaines à centaine de milliers	1er jour du mois	12	Exclu inf. 1959
2	glissement	01/01/1926	?	0	Poussée sur les barrages de Moulin Ravier	juste en PI	1er jour du mois	1	Exclu inf. 1959
3	glissement	01/01/1927	?	0	Poussée sur les barrages de Moulin Ravier	juste en PI	1er jour du mois	1	Exclu inf. 1959
4	éboulement	01/01/1930	?	0	Eboulement Amont vers pont de flon	400 m3	1er jour du mois	1	Exclu inf. 1959
5	glissement	15/12/1930	31/05/193	898	Extension glissement Cohennoz coté MR	2 cours d'eaux déviés	15ème jour du	12	Exclu inf. 1959
6	éboulement	08/03/1931	09/03/193	1	Eboulements amont Cliets	150 m3 environ	Autre	3	Exclu inf. 1959
7	crue	22/06/1932	29/06/193	7	crues du Nant Cortay	mais aussi le 29 juin	Autre	6	Exclu inf. 1959
8	crue	02/07/1932	?	0	crues du Nant Cortay	0	Autre	7	Exclu inf. 1959
9	crue	03/08/1934	08/08/193	5	crues du Nant Cortay	mais aussi le 08 aout	Autre	8	Exclu inf. 1959
10	éboulement	28/02/1935	?	0	Eboulement Gorges de l'Arly	250 m3	Autre	2	Exclu inf. 1959
11	crue	03/06/1935	31/10/193	150	crues du Nant Cortay	juin, aout,septembre, octobre	Autre	6	Exclu inf. 1959
12	glissement	31/12/1935	07/01/193	7	glissement coulées RD109 aval Hery	0	Autre	12	Exclu inf. 1959
13	crue	26/05/1937	?	0	crue du Nant Cortay	0	Autre	5	Exclu inf. 1959
14	crue	10/06/1938	?	0	crue du Nant Cortay	0	Autre	6	Exclu inf. 1959
15	crue	10/06/1938	?	0	crue Nant Cortay	0	Autre	6	Exclu inf. 1959
16	crue	06/07/1938	?	0	crue sur l'Arly	barrage Arly detruit	Autre	7	Exclu inf. 1959
17	éboulement	20/01/1939	?	0	Eboulement Combe Noire	0	Autre	1	Exclu inf. 1959
18	éboulement	22/01/1939	?	0	eboulement amont Moulin Ravier	150 m3	Autre	1	Exclu inf. 1959
19	crue	09/06/1939	?	0	crue du Nant Cortay	0	Autre	6	Exclu inf. 1959
20	crue	30/06/1939	?	0	crue du Nant Cortay	0	Autre	6	Exclu inf. 1959
21	crue	16/07/1939	?	0	crue du Nant Cortay	0	Autre	7	Exclu inf. 1959
22	éboulement	06/09/1940	?	0	Eboulement au Moulin Ravier	0	Autre	9	Exclu inf. 1959
23	crue	15/09/1940	?	0	crue Arly	0	15ème jour du	9	Exclu inf. 1959
24	glissement	13/06/1941	?	0	glissement Nant des Bauges à Ugine	0	Autre	6	Exclu inf. 1959
25	crue	25/06/1941	?	0	crue du Nant Cortay	0	Autre	6	Exclu inf. 1959
26	éboulement	08/08/1941	?	0	Eboulement (Nant des Bauges ??) + apports MR	150 m3 et +	Autre	8	Exclu inf. 1959
27	crue	12/06/1942	?	0	crue du Nant Cortay	0	Autre	6	Exclu inf. 1959
28	crue	07/11/1944	?	0	crue Arly	0	Autre	11	Exclu inf. 1959
29	crue	07/12/1944	?	0	crue Arly	0	Autre	12	Exclu inf. 1959
30	glissement	01/01/1946	?	0	Activités des versants (glissement de Moulin	pont détruit lors d'une crue	1er jour du mois	1	Exclu inf. 1959
31	éboulement	01/04/1948	?	0	Eboulement au Moulin Ravier	5000 à 9000 m3	1er jour du mois	4	Exclu inf. 1959

32	crue	11/11/1949	?	0	crue Arly	0	Autre	11	Exclu inf. 1959
33	glissement	05/09/1950	15/09/195	10	Activités des versants (glissement de Moulin	fin des prises d'eau des Usines	Autre	9	Exclu inf. 1959
34	glissement	01/02/1954	31/12/195	2159	glissement de Moulin Ravier actif (flanc amont)	RN202 encore coupée en 1959 !!	1er jour du mois	2	Exclu inf. 1959
35	crue	26/05/1955	?	0	crue du Nant Cortay	0	Autre	5	Exclu inf. 1959
36	glissement	01/01/1956	16/07/195	197	Erosion en amont du Nant Cortay	Erosion de berge	1er jour du mois	1	Exclu inf. 1959
37	crue	14/08/1959	?	0	crue du Nant Cortay	0	Autre	8	inf. 100 j
38	glissement	01/11/1960	15/01/196	75	glissement au Nant Cortay	(anthropique a priori)	1er jour du mois	11	inf. 100 j
39	crue	26/07/1963	?	0	crue du Nant Cortay	0	Autre	7	inf. 100 j
40	glissement	01/03/1966	01/07/196	122	glissement au Nant Cortay	0	1er jour du mois	3	sup. 100 j
41	crue	21/09/1968	23/09/196	2	crue Arly	entre vincenale et centenale	Autre	9	inf. 100 j
42	glissement	01/01/1970	01/01/197	1461	glissement Malatrait Benessin	0	1er jour du mois	1	sup. 100 j
43	éboulement	23/05/1976	?	0	Eboulement dans les gorges	que BDMVT….	Autre	5	inf. 100 j
44	glissement	01/04/1981	30/07/198	120	glissement aval Benessin	0	1er jour du mois	4	sup. 100 j
45	glissement	05/10/1981	25/10/198	20	Réactivation glissement berge Panissats	0	Autre	10	inf. 100 j
46	éboulement	30/11/1981	?	0	Eboulement fonds des Gorges Ugine	100 m3	Autre	11	inf. 100 j
47	éboulement	09/01/1983	?	0	Eboulement en amont des Cliets	200 m3	Autre	1	inf. 100 j
48	crue	26/11/1983	27/11/198	1	crue Arly	0	Autre	11	inf. 100 j
49	crue	23/05/1986	?	0	Forte crue du Nant Cortay	0	Autre	5	inf. 100 j
50	glissement	14/02/1990	14/05/199	89	glissement au Nant Cortay	0	Autre	2	inf. 100 j
51	glissement	15/10/1992	01/12/199	47	glissement au Nant Cortay	0	15ème jour du	10	inf. 100 j
52	crue	01/05/1994	31/05/199	30	forte crue de mai 1994 du Nant Cortay	0	1er jour du mois	5	inf. 100 j
53	glissement	01/01/1999	31/12/199	364	glissement au Montgombert	0	1er jour du mois	1	sup. 100 j
54	glissement	14/05/1999	15/05/199	1	Forte crue du Nant Cortay	0	Autre	5	inf. 100 j
55	éboulement	26/05/1999	?	0	Amont RD	0	Autre	5	inf. 100 j
56	crue	21/03/2001	?	0	crue du Nant Cortay	0	Autre	3	inf. 100 j
57	crue	07/09/2002	?	0	crue du Nant Cortay		Autre	9	inf. 100 j
58	crue	13/01/2004	14/01/200	2	crue Arly	5000 m3	Autre	1	inf. 100 j
59	glissement	15/10/2005	15/04/200	182	glissement au Nant Cortay	0	15ème jour du	10	sup. 100 j
60	glissement	15/03/2006	15/05/200	61	glissement du chemin Diat	0	15ème jour du	3	inf. 100 j
61	crue	16/05/2006	?	0	crue du Nant Cortay	6000-8000 m3	Autre	5	inf. 100 j
62	crue	14/07/2006	?	0	crue du Nant Cortay	0	Autre	7	inf. 100 j
63	glissement	01/03/2007	01/06/200	92	glissement au Nant Cortay	0	1er jour du mois	3	inf. 100 j
64	glissement	01/03/2008	30/04/200	60	glissement au Nant Cortay	0	1er jour du mois	3	inf. 100 j
65	glissement	08/09/2008	15/10/200	37	glissement aval RD au Nant Cortay	0	Autre	9	inf. 100 j
66	glissement	15/04/2010	01/07/201	77	glissement au Nant Cortay (talus amont RD)	0	15ème jour du	4	inf. 100 j
67	éboulement	27/01/2012	?	0	Chute de bloc avec 4 x4 détruit	+/- 1m3	Autre	1	inf. 100 j
68	éboulement	23/01/2013	?	0	Eboulement aux Cliets	10 000 m3	Autre	1	inf. 100 j
69	glissement	01/03/2013	15/05/201	75	glissement au Nant Cortay	0	1er jour du mois	3	inf. 100 j
70	glissement	01/03/2014	15/05/201	75	glissement au Nant Cortay	0	1er jour du mois	3	inf. 100 j
71	crue	08/09/2014	?	0	crue du Nant Cortay	6000-8000 m3	Autre	9	inf. 100 j
72	glissement	31/10/2014	31/03/201	151	Metraux glissement printemps 2015	le plus amont de 2016 (+/- 6000	Autre	10	sup. 100 j
73	glissement	01/05/2015	03/05/201	368	crue exceptionnelle Arly et glissements (gliss. /	> 300 000 m3	1er jour du mois	5	sup. 100 j
74	glissement	01/01/2016	31/01/201	30	Erosion du pied du glissement (Panissats)	0	1er jour du mois	1	inf. 100 j
75	éboulement	22/01/2016	?	0	Gorges de l'Arly (amont)	0	Autre	1	inf. 100 j
76	glissement	02/03/2016	01/09/202	1644	Métraux	diz milliers à qq diz milliers m3	Autre	3	sup. 100 j
77	glissement	16/03/2016	31/12/202	2481	Montgombert	0	Autre	3	sup. 100 j
78	éboulement	01/01/2018	01/02/201	31	Gorges de l'Arly	0	1er jour du mois	1	inf. 100 j
79	crue	01/01/2018	01/02/201	31	crue Arly	0	1er jour du mois	1	inf. 100 j
80	éboulement	09/02/2018	?	0	Gorges de l'Arly	0	Autre	2	inf. 100 j
81	glissement	15/02/2018	31/03/201	44	Montgombert Coulée sur la RD1212 (glissement	qq 100 m3	15ème jour du	2	inf. 100 j
82	éboulement	12/03/2018	?	0	Gorges de l'Arly	qq dizaines à centaine m3	Autre	3	inf. 100 j
83	glissement	01/02/2018	31/05/201	119	Amont Métraux	qq centaines voire mille m3 ??	1er jour du mois	2	sup. 100 j
84	éboulement	09/02/2019	?	0	Eboulement aux Cliets	5000-8000 m3	Autre	2	inf. 100 j
85	glissement	01/04/2021	?	0	Combe Noire face à glissement Montgombert	qq dizaines à centaine m3	1er jour du mois	4	inf. 100 j
86	gliss. /	08/07/2021	?	0	débouché amont casquette aval Combe Noire	30 m3	Autre	7	inf. 100 j
87	éboulement	04/08/2021	?	0	100-300 m aval des Metraux	4 à 5 m3	Autre	8	inf. 100 j
88	glissement	01/01/2022	01/04/202	90	Nant Cortay talus amont RD71	0	1er jour du mois	1	inf. 100 j
89	glissement	01/01/2022	01/04/202	90	Diat	0	1er jour du mois	1	inf. 100 j

Table 5 - Summary of the events database

Of the 53 events recorded over the period 1956-2022 (Figure 45), 20 were rockfalls (22.5%), 37 were landslides/falls (42%), 31 were floods (37%) and 1 was a mixed landslide/rockfall (1%).

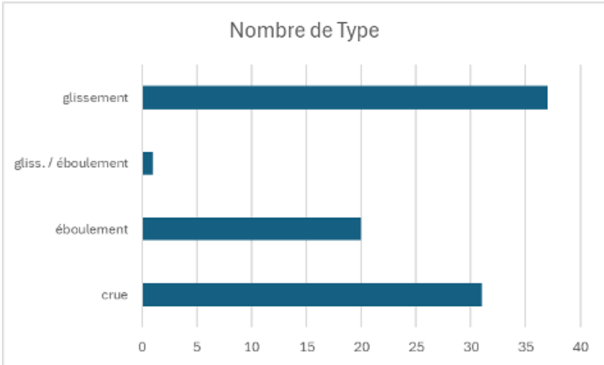


Figure 45 - Breakdown by type of event recorded in the MIROIR project events database (1959-2022) (BRGM 2023)

In the Val d'Arly, landslide activity remains largely seasonal (as in all Alpine valleys at relative altitude), with a peak in activity correlated with the snowmelt period and a summer slowdown that is all the more marked when the last rains have been limited (BRGM, 2024b).

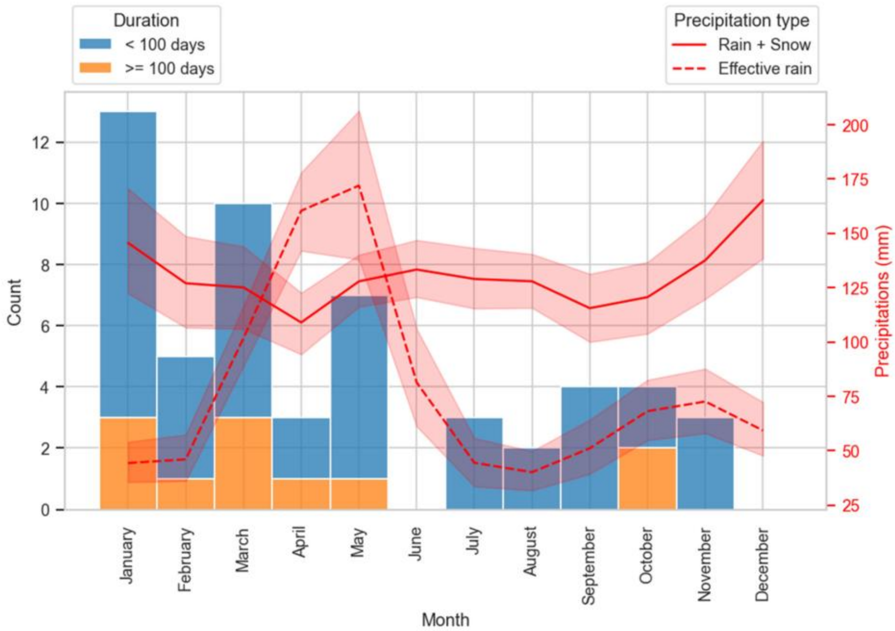


Figure 46 - Number of events recorded per month (with start date), according to their duration as indicated in the inventory, and interannual average of monthly rainfall totals between 1959 and 2022 (envelope curve with min and max). ***In*** **BRGM (2023).**

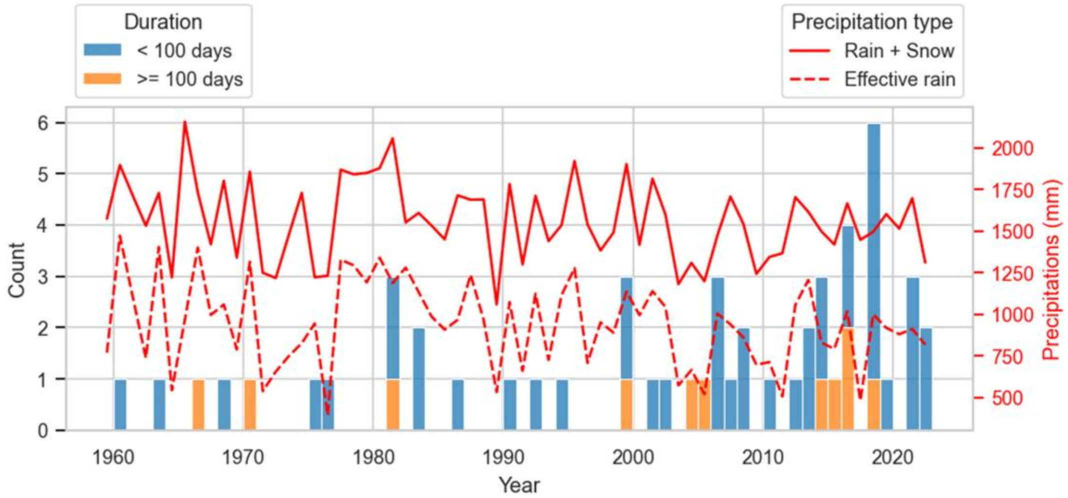


Figure 47 - Number of landslides recorded per year (with their start date), according to their indicated duration, and total rainfall. *In* BRGM (2023).

Compilation of remarkable landslide, rockfall and flood events recorded over the last century in the Arly gorges inventoried in the MIROIR project, and completed by PARN within the X-RISK-CC project, highlights changes in the frequency of events recorded over the period 1926-2023 (Figure 48).

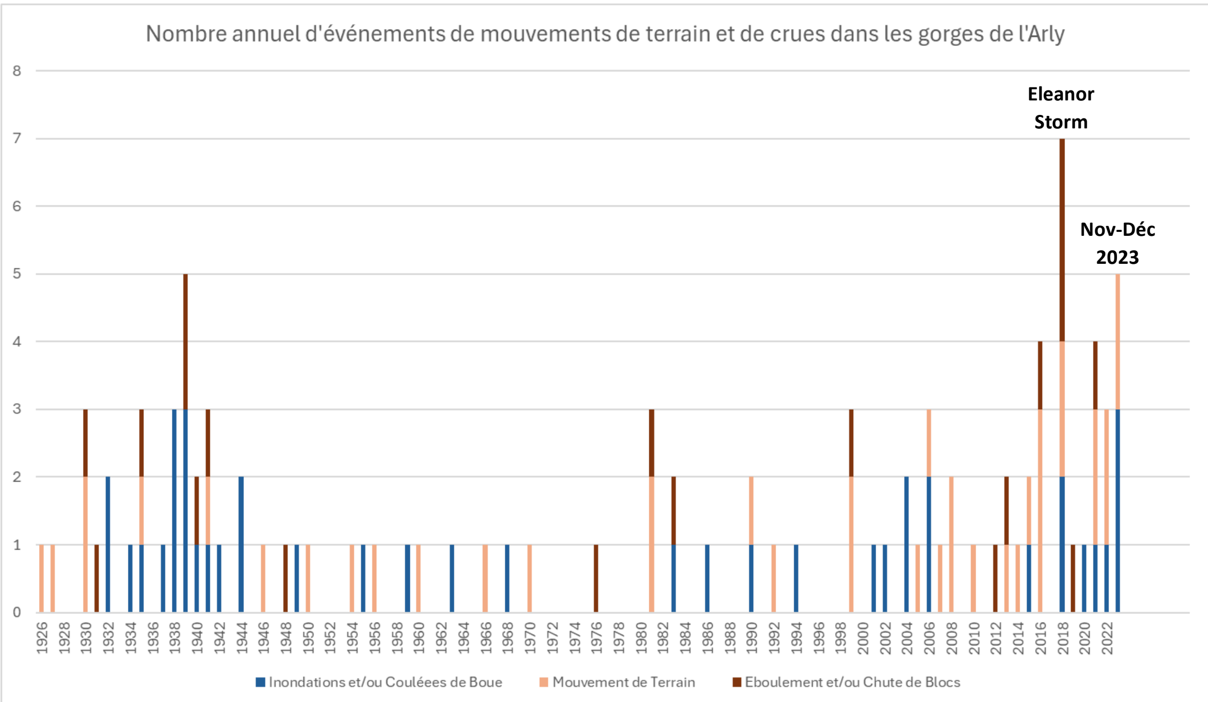


Figure 48 - Annual number of major flood, landslide and rockfall events recorded in the Arly gorges from previous inventories of ACTHYS-Diffusion (2022) and BRGM (2023) supplemented in 2024 with recent data from the SMBVA (2018; 2023) and the Arlysère Agglomeration Community (Arlysère, 2019). Data compilation and processing: PARN.

We can see a high frequency in the 1920s-1940s, followed by a quieter period in the 1940s-1960s and a virtual absence of events especially in floods during the 1970-1980 decade, followed by a rise in the number of events recorded from the 1980s onwards and a marked increase from the 2010s and the early 2020s (Figure 49). However, the small number and heterogeneity of the events considered (landslides, rockfalls, floods), as well as a probable sampling bias linked to the more systematic observation of floods and landslides in recent years, suggest that the observed changes in the frequency of these phenomena over the last 100 years in the Arly basin should be interpreted with caution.

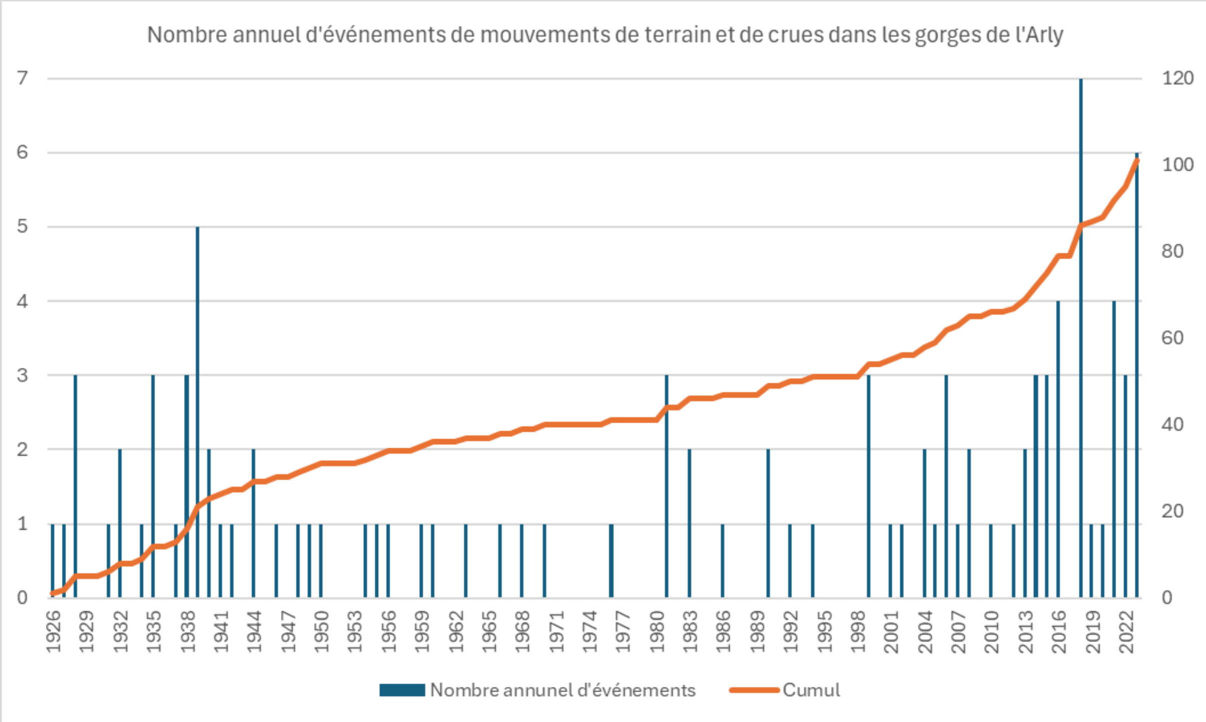


Figure 49 - Annual number of landslide and flood events recorded in the Arly gorges according to previous inventories of ACTHYS-Diffusion (2022) and BRGM (2023), supplemented in 2024 with recent data from the SMBVA (2018; 2023) and the Arlysère Agglomeration Community (Arlysère, 2019). Data compilation and processing: PARN.

As part of the MIROIR project, an attempt was made to establish hydroclimatic thresholds for the triggering and/or reactivation of different types of landslides in the Arly Gorges, by inventorying past landslides and linking these events with available climatic data and dates of landslide activity (BRGM, 2023). Although the number of events inventoried is substantial (well over a few dozen), the vast majority are poorly documented, both in terms of dates of activity and technical knowledge of the deformations undergone.

The search for global, multi-site, multi-hazard hydroclimatic thresholds for the Arly Gorges was then completed with the set of 53 landslides (1956-2022). Vigilance and alert thresholds were thus established, based on 90 days of cumulative precipitation with 15 days of deferral, at 431 mm and 609 mm respectively. With 74% of events predicted over a time span of 30% for the vigilance threshold and 9% of events predicted over a time span of 5%, the performance of these thresholds remains too low to be retained in the end (and difficult to use for operational purposes). An example of the chronogram of threshold triggers is given between January 2000 and June 2015, and between June 2015 and June 2020 (Figure 50). Twelve of the 18 events between 2000 and 2015 are detected by the thresholds. Between 2015 and 2020, only one landslide is not identified in early 2016. On the other hand, clusters of events occurring in the first months of 2016 and 2018 are well identified.

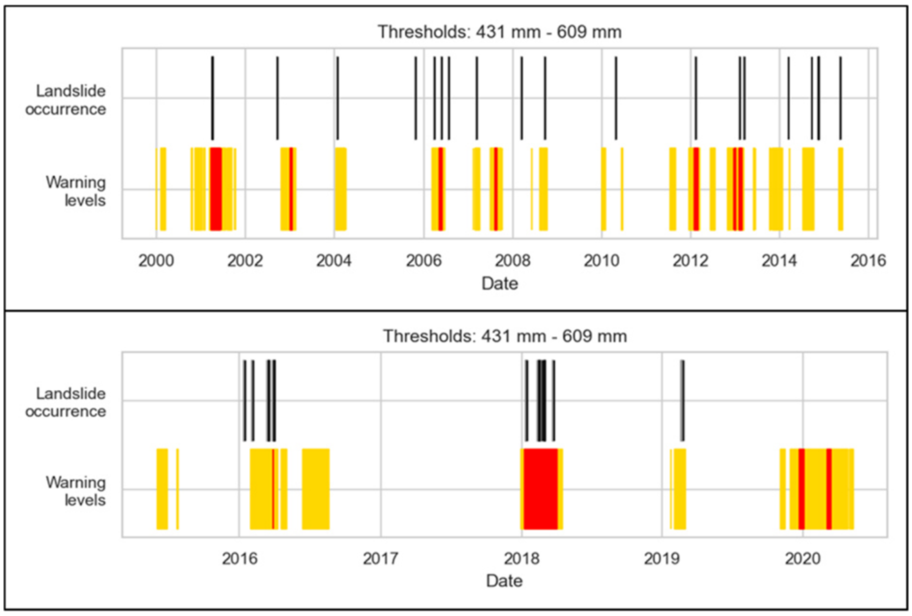


Figure 50 - Simulated triggering of vigilance (orange, cumulative 431 mm over 90 days) and alert (red, cumulative 609 mm over 90 days) thresholds over the period 2000 to 2021. The dates of landslide occurrence (shifted 15 days after the inventory dates) are indicated by the black bars on the first line. In BRGM (2013X).

On the other hand, based on the monitoring of slope deformations at the Montgombert site, it was possible to determine hydroclimatic thresholds representative of the site's activity, making it possible to predict surface accelerations (Figure 51). The thresholds were set on the basis of the first period of continuous data in 2016-2018 (the most active of the three) and for a cumulative total of 3 days of rainfall, indicating the high reactivity of the surface parts of the landslide, with a first vigilance threshold of 14.5 mm (with an effective prediction of 96%) and an alert threshold of 35 mm (but with an effective prediction of 64%). However, these hydroclimatic thresholds become less reliable as the slope deteriorates over the years. They are therefore unsuitable for operational use.

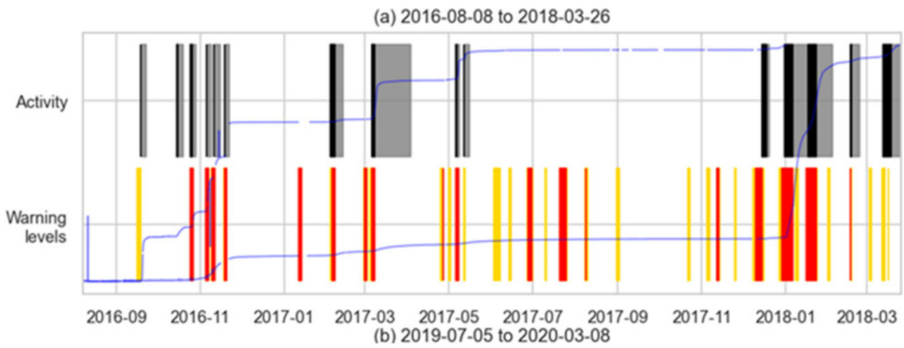


Figure 51 - Chronogram of the activity (grey) and acceleration (black) phases of the Montgombert landslide over the period 2016-2018. Exceeding the vigilance rainfall threshold (22.6 mm over three days) is shown in orange, and exceeding the alert rainfall threshold (35.1 mm over three days) is shown in red. The blue curves represent normalized displacements measured on two targets. In BRGM (2013X).

The results obtained in the MIROIR project confirm that precipitation does indeed play a major triggering role in the instability of Arly valley slopes, and that investigating the precipitation-destabilization relationship is relevant to better anticipate landslide triggering in this sector. However, given the uncertainty surrounding the inventory of events in the sector, the thresholds calculated for the valley as a whole cannot be used as they stand for an operational warning system. Future work will focus in particular on consolidating the inventory of landslides in the Gorges de l'Arly risk basin (including both past and future landslides), in order to specify the typology of events and their dates of occurrence. To refine the quantification of the link between triggering and precipitation, more precise rainfall data could also be used (radar data with better spatial resolution, and/or rain gauges for site-scale analyses). Finally, more advanced statistical methods (e.g. machine learning) could also be tested.

Rockfalls

The RTM database lists 124 rockfalls in the Arly basin. This data, once again, is incomplete, at least until the 1980s, which may partly explain the increased number of events recorded in the 1980-2020 period (Figure 52). However, this apparent increase in rockfall activity over the last twenty years could also be linked to climatic conditions more favorable to their triggering, linked to the notable warming observed in the Northern French Alps over this period (Einhorn et al., 2015).

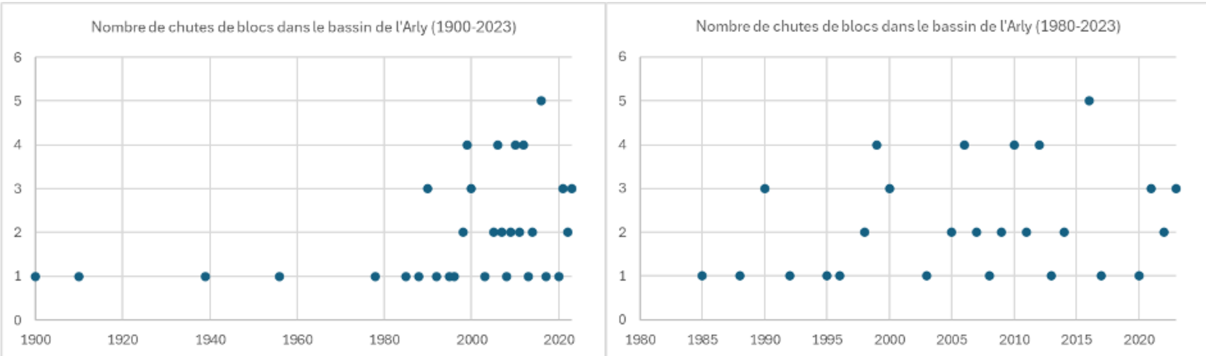


Figure 52 - Annual number of rockfalls in the Arly basin recorded in the BDRTM. Source: ONF-RTM; Processing: PARN.

Rockfall databases including past events and their consequences remain insufficiently developed. In the French Alps, related information is dispersed and heterogeneous. In the context of the National Project C2ROP, a first effort to capitalize, standardize and exploit already existing information has been conducted (Eckert et al., 2020). The C2ROP-INRAE database covers the six departments of the French Alps and already brings together more than 8000 events in a common geo-referenced environment which includes the date and place of occurrence and the volume of past events (Figure 53). In addition, the textual information available in digital format has been analysed to assess the damage caused as completely as possible. This work confirms the reality of rockfall hazard and risk for the French Alps. The data collected is now available for further analyses.

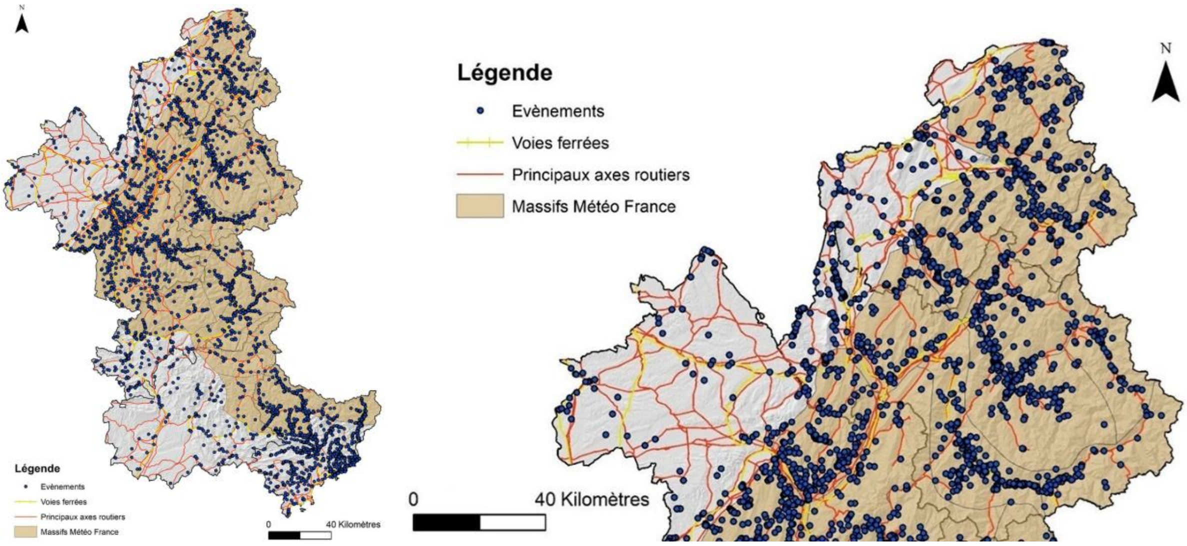


Figure 53 - Location of events in the C2ROP-INRAE database. Data compiled on 01/01/2020. The main roads are those defined by the IGN's ROUTE 120® database which references highways, national roads, and most important departmental roads.

Another available database is the Alpine Space database from the RockTheALPS project.

Floods

Very little is known about river discharge in the region. There are very few gauging stations, and they only concern the major rivers (Isère, Arly, Chaise) and are recent, so they do not allow for relevant long-term analysis (Arlysère, 2022). The basin includes 3 DREAL stations (public data) and 3 EDF stations (whose data are not open).

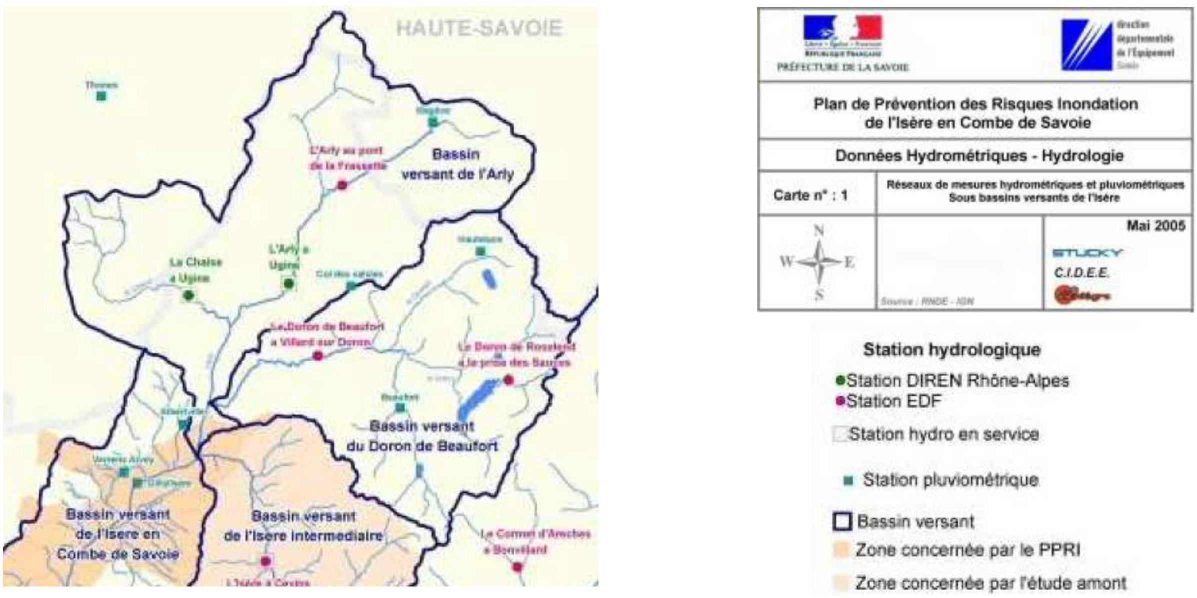


Figure 54 - Le bassin versant de l'Arly. Données hydrométriques et hydrologie. In DDT73 (2008).

The characteristic flood flows of the main rivers in the basin, as compiled in the Arly River Contract (SMBVA, 2012), are summarised in the table below:

Cours d'eau	Superficie BV (km²)	QIX_2 (m³/s)	QIX_5 (m³/s)	QIX_{10} (m³/s)	QiX_{100} (m³/s)	Source bibliographique
Arly à Ugine-Moulin Ravier	225	100	150	190	320	Etude Eau et Territoire 2010
Arly à la confluence avec l'Isère	646	-	-	324	606	Etude Eau et Territoire 2010
Arrondine à Flumet	63	-	-	70	117	Etude Eau et Territoire 2010
Chaise à St Ferréol	47	-	-	52	85	Etude Eau et Territoire 2010
Chaise à Ugine pont de Soney	80	-	-	80	130	Etude Eau et Territoire 2010
Doron à Villard (confluence Nant Bruyant)	238	-	-	70	200	Etude Eau et Territoire 2010
Dorinet à Beaufort	57	-	-	30	64	Etude Eau et Territoire 2010
Argentine à Beaufort	64	-	-	27	70	Etude Eau et Territoire 2010

Table 6 - Typical flood flows for the main rivers in the Arly basin. In Contrat de rivière Arly (2012).

Over the past fifty years, the major events recorded in the Arly basin (Table 7) are the floods of 1968, estimated at 180 m3/s, 15 February 1990 (197 m³/s at Moulin Ravier), January 13, 2004, estimated at 235 m3/s at Ugine, and May 1, 2015, estimated at >250 m3/s, the floods of January 4, 2018 (following storm Eleanor) with 345 m³/s, just followed by those of January 23 (160 m³/s at Pont de Venthon) and then, the major flood of November 14, 2023 with 451 m³/s, closely followed by the flood of December 11, 2023 which reached 333 m³/s.

The following table shows the hydrological characteristics of the main floods on the Arly that have been recorded for 80 years.

Date	Max Discharge	Return period	Impacts & damages
15/09/1940	Arly: 500 to 550 m³/s at Pallud Doron: 240 m³/s at the Queige factory dam Source: Pardé (1941)		Serious impacts in the Doron basin: bank erosion, river bed erosion, bridges destroyed, several buildings torn down, 9 power transmission pylons knocked down, Queige factory flooded to a depth of almost 2m.
15/02/1990	Arly gorges: 197 m³/s - station de Moulin Ravier	50-year flood	
04/01/2004	Arly gorges: 189 m³/s - station de Moulin Ravier 235 m³/s at Ugine	2-year flood	Engraving of the Mollières threshold by depositing 10,000 m³ of materials
01/05/2015	Arly gorges: 170 to 235 m³/s - SPC 429 m³/s estimation HYDROREEL - 257 m³/s after SPC/A. Gautheron: in the alluvial plain at Pallud	> 10-year flood	
04/01/2018 (Eleanor)	Chaise: 80 m³/s (3-5.1.2018) Arly: 300 m³/s (3-5.1.2018) Arly gorges at Barrage des Mottets (4km downstream from Pont de Fer): 91 m³/s (4.1.2018) Arly in the alluvial plain at Pallud: 345 m³/s (4.1.2018)	3-year flood in the Arly gorges; 5-year flood at Pallud	Debris flows, landslides and rockfalls; Damages on infrastructure (roads, buildings, energy distribution), residents, tourists, forest, agriculture
22/01/2018	Chaise: 36 m³/s Arly: 160 m³/s downstream of the confluence with the Doron	3-year flood	
03/02/2020	Arly: 305 m3/s in the alluvial plain at Pallud	3-year to 5-year flood in the Arly alluvial plain at Pallud	
30/12/2021	Arly gorges: 103 m³/s at Pont de Arly in the alluvial plain at Pallud: 257 m³/s (29/12/2021)	3-year in the Arly gorges; 2-year to 3-year in the alluvial plain at Pallud	
23/12/2022	Arly: 329 m³/s in the alluvial plain at Pallud	5-year in the Arly gorges and in the alluvial plain at Pallud; 5-	

	Arly gorges: 130 m³/s Chaise: 54 m3/s at Soney-Ugine Doron: 49 m3/s peak flow at Villard sur Doron	year to 10-year flood in Chaise at Soney-Ugine	
14/11/2023	451 m³/s at Pallud - Hydroportail	50-year in the Arly gorges (and Doron de Beaufort); 20-year in the alluvial plain (and the Chaise)	Lateral erosion and embankments; Damage to roads and networks. Concomitance of floods and landslides: triggering of debris flows and torrential floods, rerouting of watercourse beds and formation of logjams.
30/11/2023	196 m³/s at Pallud - Hydroportail	2-year flood for the whole catchment area	
11/12/2023	333 m³/s at Pallud - Hydroportail	5-year flood on Arly; (20-year on the Chaise)	

Table 7 - Main floods on the Arly. Sources: SMBVA (2012; 2018; 2022; 2023; 2024); Hydroportail. Compilation: PARN.

Thus, flood peaks in excess of 300 m³/s have been occurring more and more frequently in recent years, even peaking above 400 m³/s in April-May 2015 and in November 2023 (Figure 55).

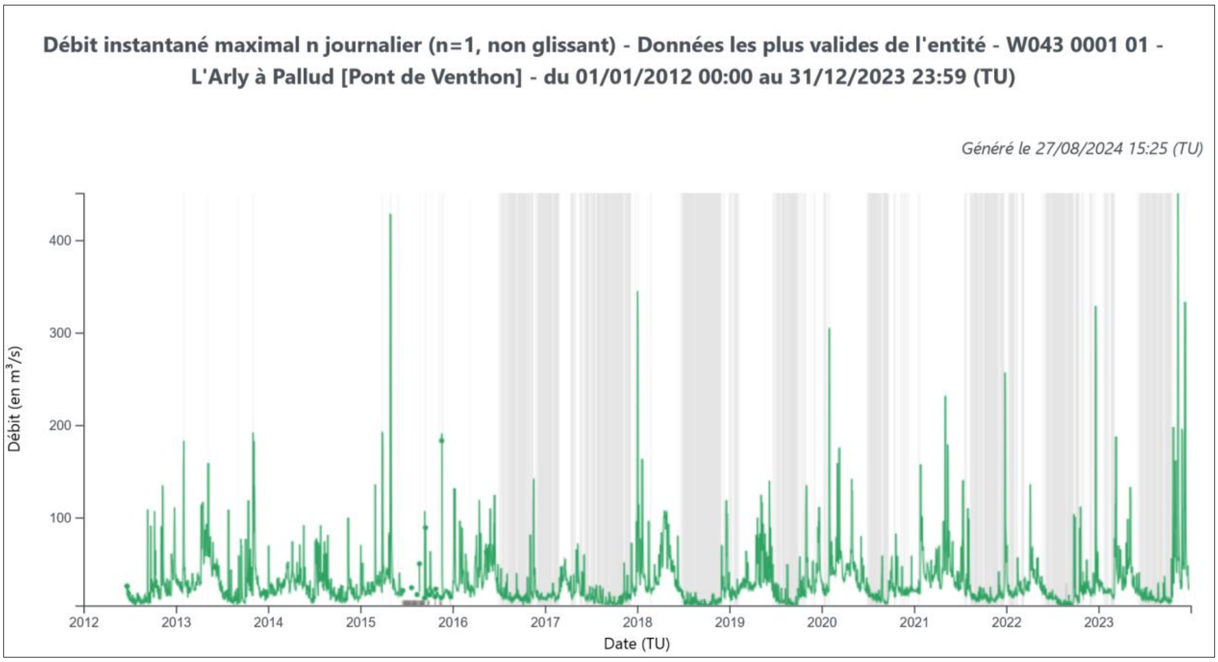


Figure 55 - Series of maximum daily instantaneous flows on the Arly at Pallud (Pont de Venthon) from 01/01 2012 to 31/12/2023. Source: HYDROPORTAIL.

These latest floods have served as a reminder of the importance of integrated management of water and aquatic environments to better prevent the risks associated with flooding and torrential flooding in the Arly basin (see section VI).

Torrential floods and debris flows

In Savoy, the statistical analysis of more than 500 events listed since 1970 in the RTM showed the essential role played by climate variables at the regional level in the probability of debris flow occurrence. In some sectors, the increased frequency of debris flows since the late 1980s (Figure 56 A) may be an effect of summer warming, which leads to more convective effects and therefore more summer thunderstorms (Figure 56 B). However, in certain areas the control of the temporality of debris flows by sediment supply can outweigh its control by the climate (Einhorn *et al*., 2015).

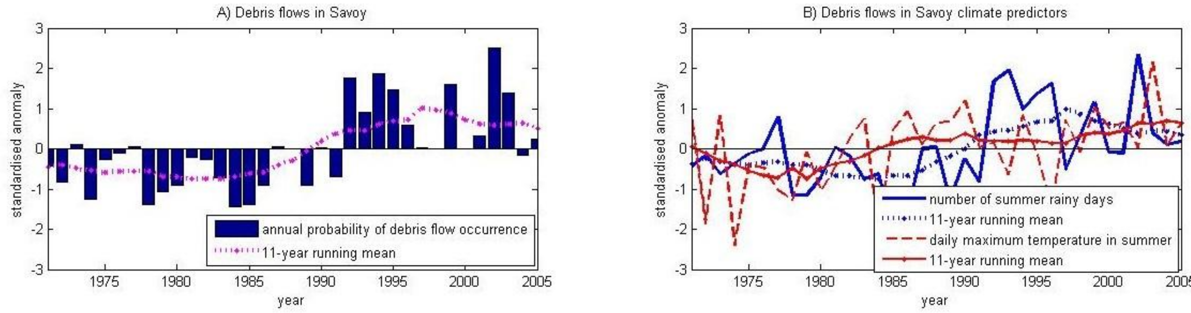


Figure 56 - Response of debris flow activity to changes in summer meteorological factors: (A) Annual frequency of debris flows in Savoy from Jomelli *et al*. (2015). (B) and identified predictors by Einhorn et al. (2015).

Jomelli et al. (2019) proposed an original approach to quantify the respective influence of geomorphic and climatic components on debris flow occurrence in 104 alpine catchments in Savoy since 1970 (Figure 57). A Bayesian approach was used to quantify the spatial, temporal, and random effects independently. This model makes it possible to assess the influence of these two geomorphic and climatic components as well as the weight of each specific variable. Results reveal that the geomorphic component is the main cause of the spatiotemporal variability of debris flow occurrence with lithology as the main contributive variable. However, this relationship strongly depends on the frequency of debris flows among catchments. To detect the influence of spatial variability in debris flow frequency, the data set were partitioned into two subsamples composed of catchments with at least or less than 4 debris flows over the period (Figure 58). If the variability in the number of debris flows between catchments is reduced by subsampling the dataset, then the climate component becomes the major driver of debris flow occurrence with rainfall over 3 days and maximum temperature as the best predictors. Results reveals that precipitation during the event and the 2 days before exceeding 20 mm in total are the most important variables for both subsamples. It explains at least 57% of the total variance and 73% of its climate component. Difference in debris flow occurrences from one catchment to another is then mostly due to geomorphologic conditions, whereas homogeneous groups of catchments react strongly to climatic conditions in a rather similar way. Finally, testing the effect of the observation duration on the total explained variance showed that at least 23 years of observation are needed to get significant relationships.

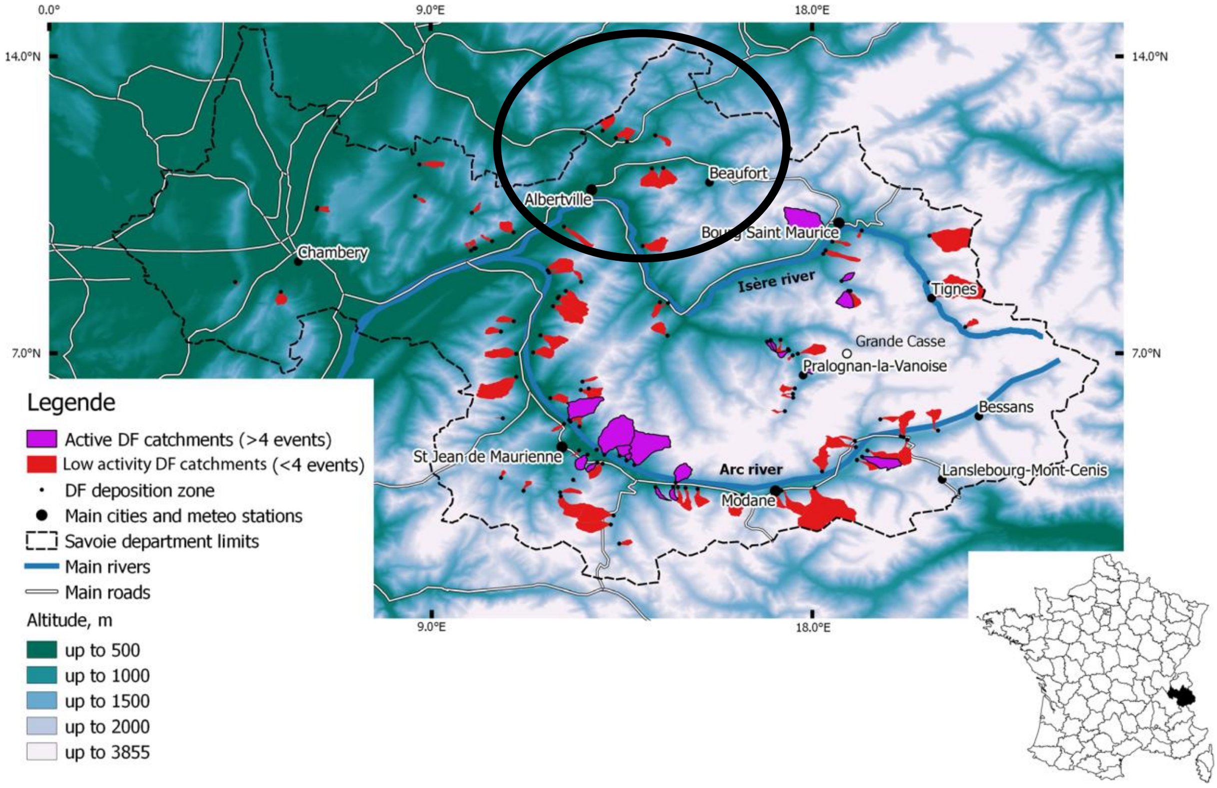


Figure 57 - Debris flow occurrence in Savoie region over the last decades (Jomelli et al., 2019). Black circle indicates the Arly basin location.

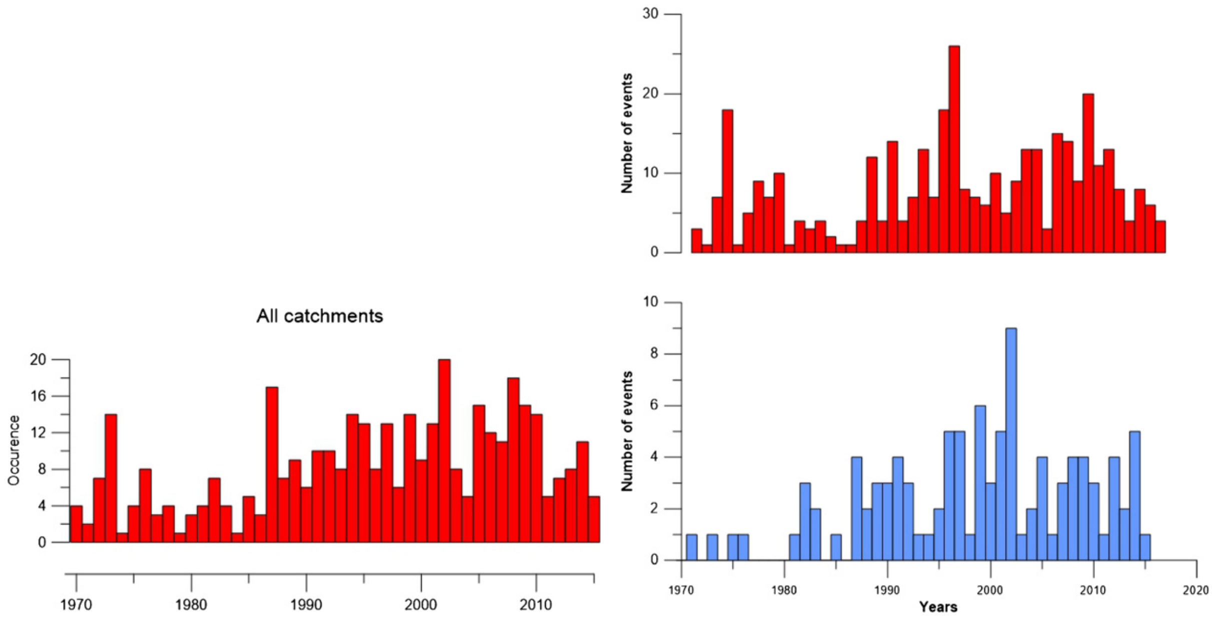


Figure 58 – Left: Debris flow occurrence as function of time in Savoie region. Right: Debris flow occurrence in low active catchments (blue) and very active catchments (red). *In* Jomelli et al. (2019).

In the Arly basin, the RTM database lists 215 flood and debris flow events over the period 1715-2023 (Figure 59). Over the period 1980-2023, where events are relatively well inventoried and documented, the clusters of events previously identified in February 1990, April-May 2015, January 2018 and November-December 2023 are clearly distinguishable.

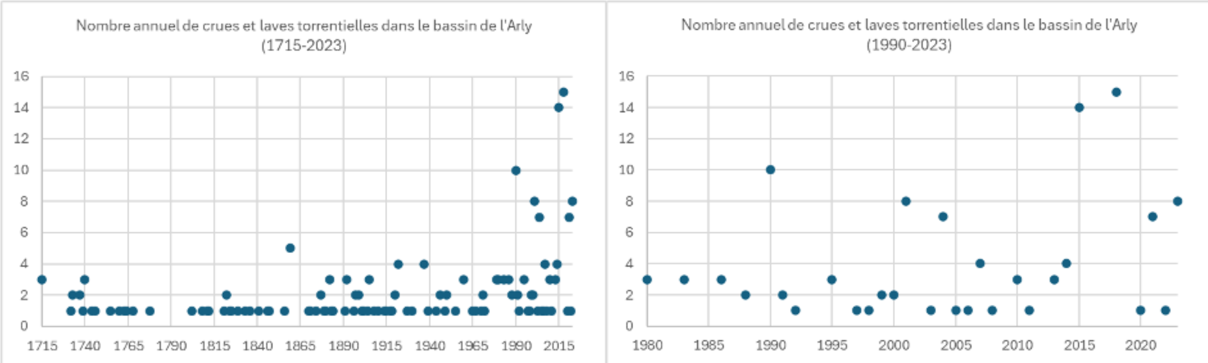


Figure 59 - Annual number of floods and debris flows in the Arly basin recorded in the BDRTM. Source: ONF-RTM; Processing: PARN.

Over the period 1980-2023, a greater proportion of torrential flood events were observed in the months of February-March, May and July-August, compared with the previous period 1715-1980, when they were more frequent in June and October-November-December (Figure 60). However, these apparent differences in the seasonality of the torrential floods recorded are also likely to be strongly influenced by biases linked to variations over time in the continuity and quality of the observations made by RTM officers.

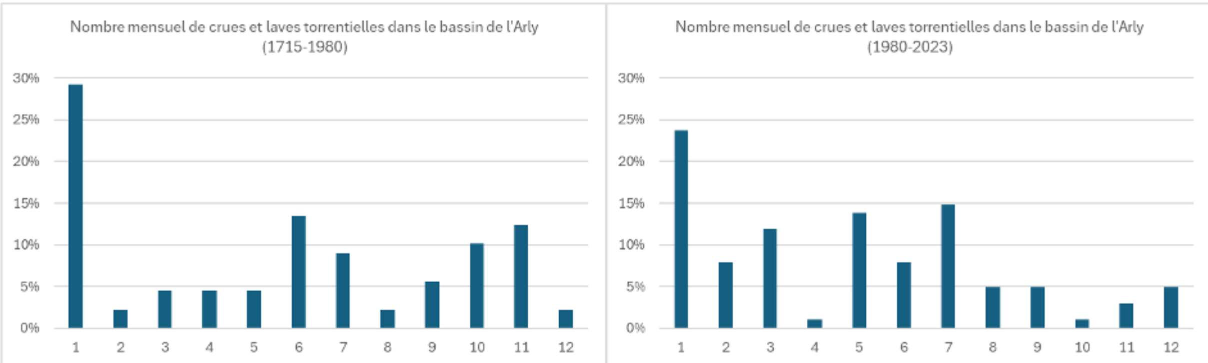


Figure 60 - Monthly number of floods and debris flows in the Arly basin listed in the BDRTM. Source: ONF-RTM; Processing: PARN.

Snow avalanches

At the scale of the French Alps, it was observed a decrease in avalanche runout-altitudes over the period 1960-1980 corresponding to colder and snowy winters, followed by a sharp rise in elevation during 1980-2005, that is a period of increased warming (Einhorn et al., 2015). The influence of the cold, snowy winters recorded since 1998 is clear (Figure 61). Trends of these changes are different depending on the altitude, with a drastic reduction in the number of avalanches since 1980 at low altitude (<2000 m), while avalanche activity has recently increased at high altitude, in probable connection with an increase in climate variability during winter.

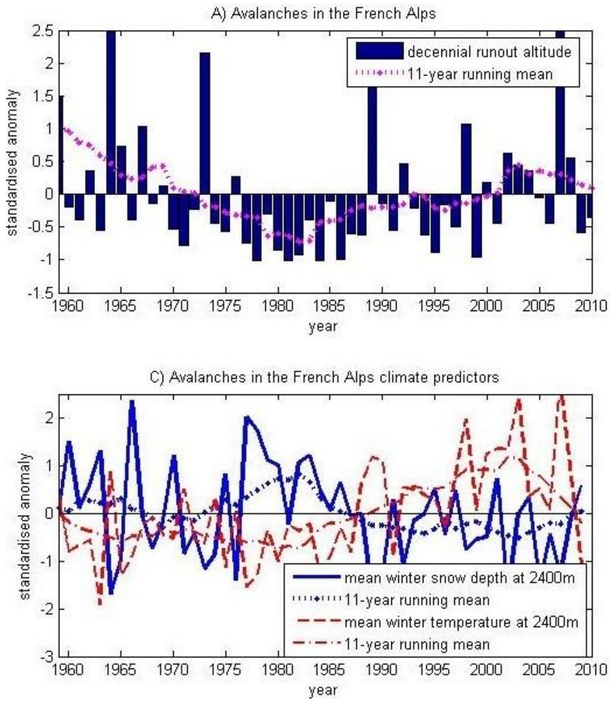


Figure 61 - Response of avalanche hazard to changes in winter snow and weather factors. Decennial runout-altitude of snow avalanches in the French Alps from Eckert *et al*. (2013) (top) and factors identified as predictors: mean winter snow depth and mean winter temperature at 2400m (bottom). *In* Einhorn et al. (2015).

In the Arly basin, the RTM database lists 112 snow avalanches over the period 1812-2023, which occur exclusively in winter and spring. For the recent 1980-2023 period, which is relatively better documented, episodes of high avalanche activity stand out in January-February 1984, January 1995 and January 2018 (Figure 62).

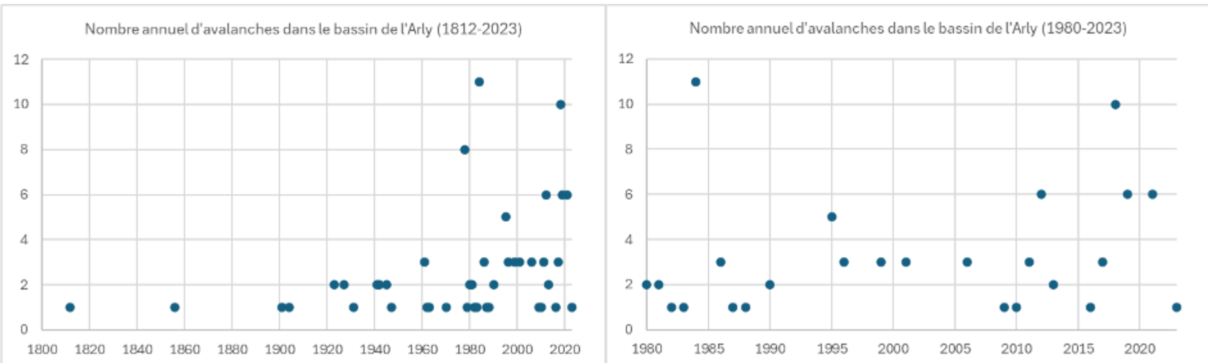


Figure 62 - Annual number of snow avalanches in the Arly basin recorded in the BDRTM. Source: ONF-RTM; Processing: PARN.

Since the 1980s, avalanche activity has been earlier in winter than in the previous observation period (1812-1879), with an increase in the number of avalanche events in December and a decrease in January (Figure 63).

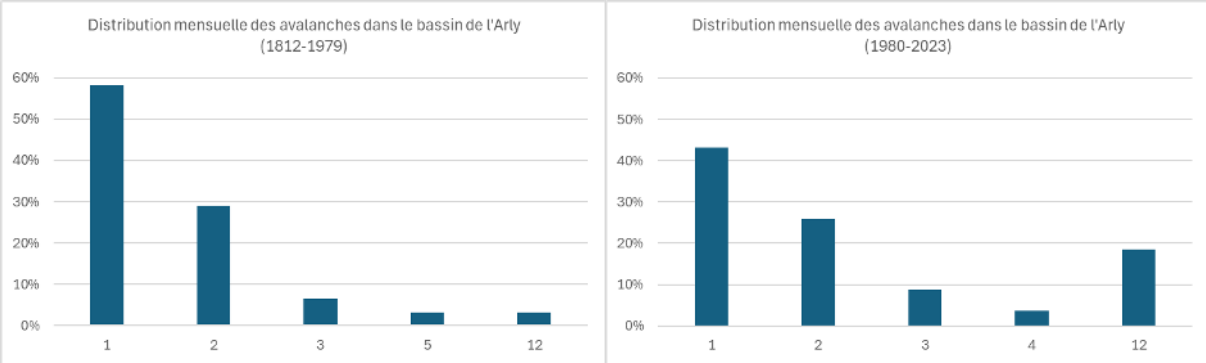


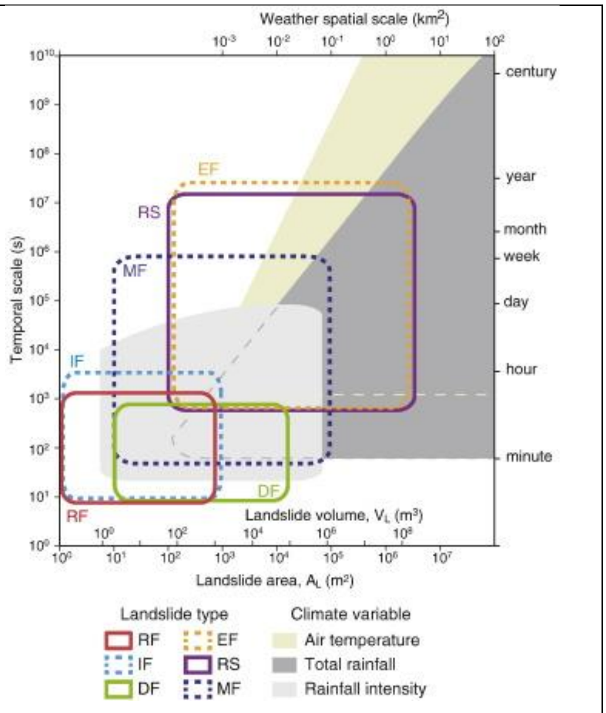
Figure 63 - Monthly distribution of avalanches in the Arly basin recorded in the BDRTM. Source: ONF-RTM; Processing: PARN.

b) Potential future frequencies and magnitudes

Recent extreme events in the Alps and the above examples in the Arly basin highlight the already existing vulnerability of mountain areas to the impacts of various hydro-gravity hazards on communication routes and other infrastructures, the successive or simultaneous impacts of which can become particularly critical in mountain areas (Einhorn, 2015). These ‘multi-hazard’ and ‘multi-risk’ situations raise the question of the capacity of mountain populations to adapt to the multiplication of this type of phenomenon, given the expected increase in the frequency and intensity of extreme meteorological events on the one hand, and the supply of materials from the slopes on the other, with the two types of cause possibly combining and aggravating their impacts.

Landslides

Modelling the influence of climate on land movement remains uncertain, not least because of the many controlling factors acting at different time and space scales (Gariano and Guzzetti, 2016; Table 8).

Climate and landslides operate at different geographical and temporal scales, and reconciling the different scales is difficult, and remains uncertain. The type, extent, magnitude, and direction of the changes in the stability conditions of the slopes, and on the location, abundance and frequency of the landslides, are not completely clear. The effects of the warming climate on landslide risk, and particularly the risk to the population, also remain difficult to quantify. Climate modelling predicts different climate variables. The significance of the projections varies geographically, and depends on the type of variables, with predictions of temperature more dependable than predictions of precipitation. For precipitation, the uncertainty associated to downscaled projections for short and intense rainfall is much larger than for prolonged rainfall. We expect that the landslide-climate studies are affected by the significance of the climate variables used, and that projections based on temperature are more dependable than those based on precipitation. Generally, it is expected that landslide-climate studies in high-mountain environments (where temperature plays a major role) will produce reliable results, and that projections of the behavior of deep-seated landslide activity (related to long rainfall periods) will	 For four climate variables, known to affect landslides (total

be more dependable than projections for shallow landslides. Given the uncertainty associated to the forecast of high intensity and short duration precipitation, for shallow landslides triggered by short and intense rainfall events it is anticipated that only regional landslide-climate studies will provide significant results.	rainfall, rainfall intensity, air temperature, weather system, in four groups of rows), and for eight landslide types (RF, rock fall/avalanche; IF, ice fall/avalanche; DF, debris flow; EF, earthflow; MF, mudflow; RS, rock slide; SL, shallow landslides; DS, deep-seated landslides, columns), the figure above show with different colours the geographical (local, blue; regional, green), the temporal (short-term, dark grey; long-term, light grey), and the direct (red) and indirect (orange) expected impact.

Table 8 - Conclusions of Gariano and Guzzetti (2016) on the influence of different climatic variables on ground movement activity.

Floods

Projections for the future development of Alpine floods in intensity, frequency and seasonality have to integrate a multitude of complex and multi-scale effects related to increased temperature, the change in rainfall patterns, or changes in land cover. Numerous projects have produced impact simulations using several types of indicator of future flood disposition at different time steps, with sometimes contradictory results according to the studied areas or to the climate models and scenarios used, e.g. for changes in seasonal extreme rainfall (Einhorn et al., 2015).

With regard to our pilot area, Maurice Pardé estimates the Arly river “capable of delivering in its most exceptional floods 1,000 lit-sec, or more per km² at its confluence with the Isère” (and that this was probably “the case in November 1859, and during other famous floods in Grenoble”), i.e. a potential peak flow of the order of 650 m^3/s (given the 645 km² surface area of the Arly basin) (Pardé, 1941).

Cascading effects between landslides and torrential floods

In the Arly gorges, while the possibility of landslides on the valley floor has not been identified, leading to fears of a severe, if not complete, blockage of the Arly river (and its consequences: from dam formation to jam failure and its consequences), the fact remains that the volumes of input to the river could be significant (several tens of thousands of m^3 and even in excess of a hundred thousand m^3, between 40% and over 90% of unstable slope masses) and, as in 2015, cause significant indirect damage downstream (BRGM, 2024a).

ANALYSIS OF KEY RISK PATHWAYS

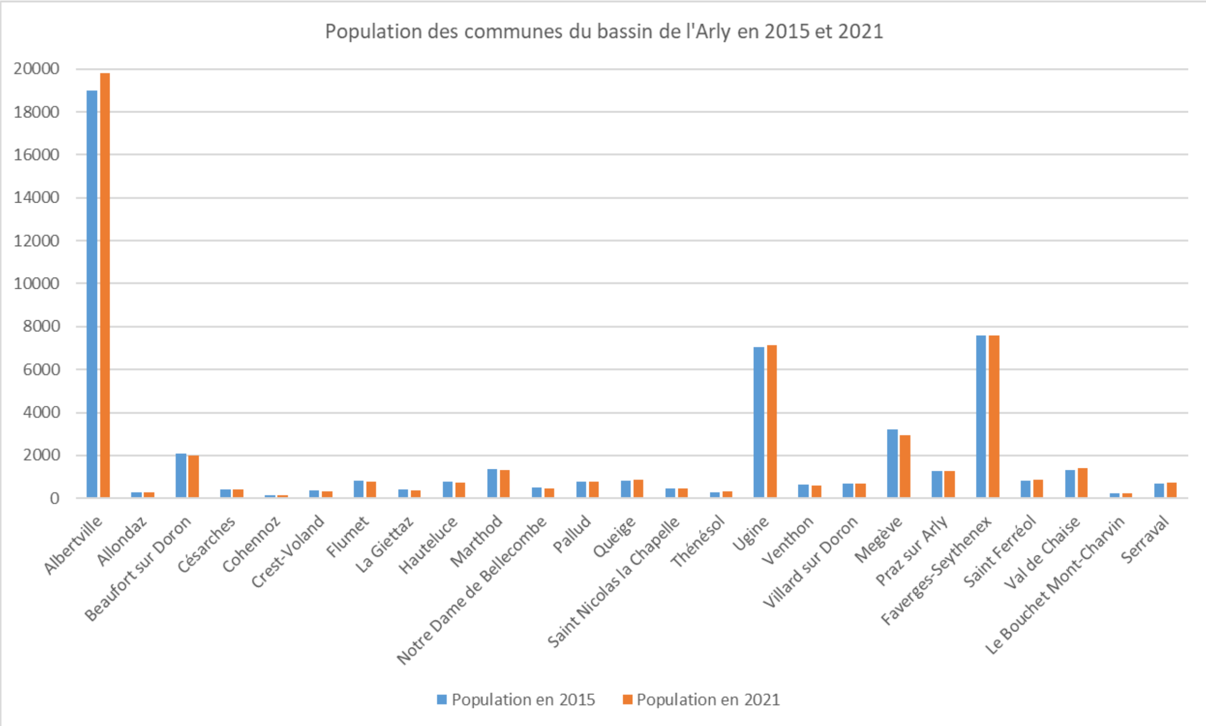
IV. What are the most important exposed elements at risk of being directly or indirectly affected by the hazards, and how do you expect this to change in the future?

a) Past/present exposure and impacts

Located in the heart of the ‘Deux Savoie’ region, the Arly catchment area is made up of 25 communes centred around 2 urban centres at the bottom of the valley, Ugine and Albertville, which form crossroads between the Val d'Arly, the sources of Lake Annecy, the Beaufortain, the Tarentaise and the Combe de Savoie.

i. Directly exposed elements.

Population: The area has a population of around 50,000, with almost 50% living in the conurbations of Ugine (7,000 inhabitants) and Albertville (17,000 inhabitants).



Dép.	EPCI	Commune	Population 2015	Population 2021	Variation
73	CA Arlysère	Albertville	18969	19812	4,44%
		Allondaz	261	293	12,26%
		Beaufort-sur-Doron	2088	2009	-3,78%
		Césarches	425	420	-1,18%
		Cohennoz	159	145	-8,81%
		Crest-Voland	374	331	-11,50%
		Flumet	810	797	-1,60%
		La Giettaz	428	377	-11,92%
		Hauteluce	767	748	-2,48%
		Marthod	1382	1339	-3,11%
		Notre-Dame-de-Bellecombe	486	472	-2,88%
		Pallud	756	799	5,69%
		Queige	825	861	4,36%
		Saint-Nicolas-la-Chapelle	448	481	7,37%
		Thénésol	293	318	8,53%
		Ugine	7042	7148	1,51%
		Venthon	635	606	-4,57%
		Villard-sur-Doron	698	687	-1,58%
74	CC Pays du Mont Blanc	Megève	3210	2961	-7,76%
		Praz-sur-Arly	1266	1267	0,08%
	CC Sources du Lac d'Annecy	Faverges-Seythenex	7592	7581	-0,14%
		Saint Ferréol	834	890	6,71%
		Val de Chaise	1327	1390	4,75%
	CC Vallées de Thônes	Le-Bouchet-Mont-Charvin	242	249	2,89%
		Serraval	665	732	10,08%
		Total	**51982**	**52713**	**1,41%**

Table 9 - Population Source: INSEE (2024); Processing: PARN.

In winter, the number of tourists visiting the ski resorts multiplies the watershed's permanent population by 2.5, reaching 115,000 residents, and locally by 7-fold at the head of the watershed, in the Val d'Arly and Beaufortain.

Settlements: Built-up areas exposed to natural hazards are identified in Risk Prevention Plans (‘*Plans de Prévention des Risques*’ - PPR) and are the subject of preventive information in Municipal Information Documents on Major Risks (‘*Documents d'Information Communaux sur les Risques Majeurs*’ - DICRIM). Various scientific and technical studies commissioned by national, departmental and local services in charge of natural hazard prevention and management provide additional knowledge on the territory's exposure to natural hazards.

Avalanche risk: Several homes and built assets are exposed to avalanche risk among the 14 communes covered by the avalanche location map (CLPA) in the Arly basin (see section II). In particular, the CLPA analyzes avalanches identified as “remarkable” in terms of their intensity, the damage they have caused or could have caused and/or the number of actual or potential victims (IRSTEA, 2016). In the Bornes-Aravis massif, the number of dwellings subject to avalanche risk is limited. However, the steep slopes of certain sectors are sometimes the site of major avalanches (IRSTEA, 2016a). The village of La Giettaz is affected by large-scale avalanches. Most of these occur on the southern slopes of the Aravis Mountain range. In the 1980s, they caused significant damage in the village. The most notable events date back to 1978, when avalanches from the Pointe des Verres hit the village, damaging many buildings. Another remarkable avalanche has already been triggered from the pointe de Borderan, (avalanche du Stinquant). Depending on where it started, it flowed either towards the paravalanche on the Col des Aravis Road or towards the Mortines housing estate, where damage has already occurred. In the Le Plan sector, smaller avalanches affected urbanized areas and the access road to the resort. On the way up to the Arrondine valley, large avalanches have already been triggered, but not in built-up areas. In the Beaufortain massif, the main urbanized areas subject to avalanche risk, in the light of the most remarkable avalanche events in the past, are located in the municipalities of Beaufort (where large-scale avalanches have occurred throughout the communal area in the past), Hauteluce (subject to avalanches of various types, with the largest phenomena often occurring long ago, except in certain sectors where avalanches still occur fairly regularly), Notre-Dame-de-Bellecombe (where avalanches are less frequent in urbanized areas, but are mainly concentrated in the ski area and in places affect roads).

Landslide risks: Some urbanized areas in the Arly basin are located in lands affected by large-scale landslides. For example, the southern slope of the Villard-sur-Doron commune, affected by a large-scale displacement following the post-Würmian glacial retreat, remains prone to landslides of a more moderate scale today (Figure 64).

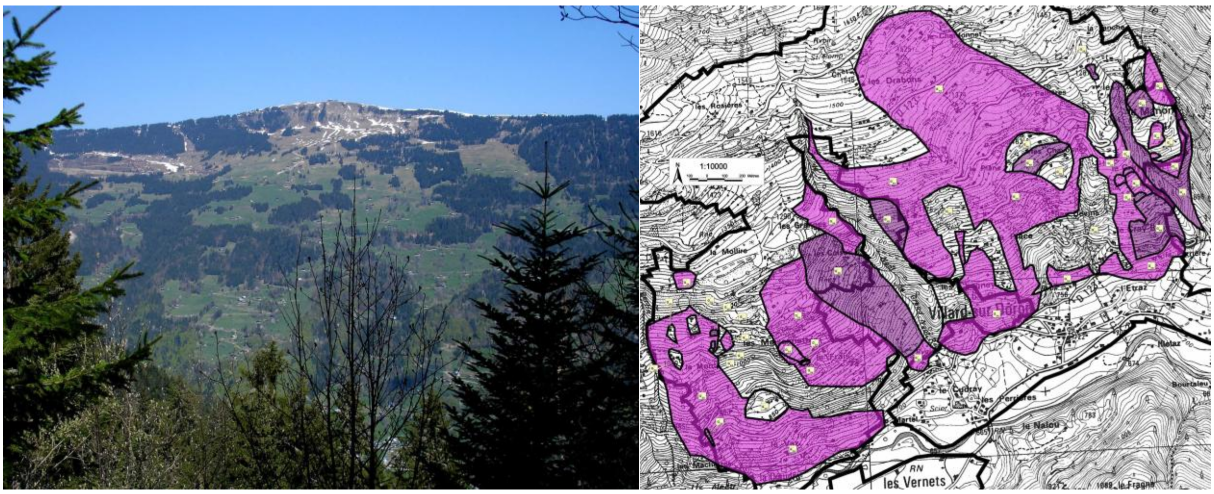


Figure 64 – Southern slope of Villard-sur-Doron (left). Mapping of landslide zones (right). Source: Villard-sur-Doron Natural Risk Prevention Plan.

Built-up areas are also frequently affected by superficial landslides. For example, following storm Eleanor, a landslide destroyed two tourist chalets in La Giettaz (Figure 65).

Figure 65 - January 5, 2018 landslide at La Giettaz (Savoie) between Le Plan and La Crépinière. Source: IRMa.

Rockfall:

Flooding: According to the hydraulic model used in the Isère Flood Risk Prevention Plan in Combe de Savoie (DDT73, 2008), 100-year flood overflow areas are located on the right bank of the Arly between the SNCF bridge and the confluence with the Isère. In Albertville, the overflows modelled remain confined to the right bank of the Arly upstream of the confluence with the Isère, and only affect very small areas.

Torrential risk: Some built-up areas are highly exposed to the risk of flooding, landslides and mudslides (Figure 66). For example, the town of Megève is particularly exposed to flood risk, given the torrents' high capacity to carry materials into the urban area, and the numerous developments constraining these watercourses (SMBVA, 2024).

Figure 66 - From left to right: (1) Overflow of the Glapet at Megève on May 1, 2015 (Megève PPR), (2) mudflow of the Torrent du Tour at Megève, (3) overflow of the Nant de la Couffaz, a tributary of the Arrondine on its alluvial fan at La Giettaz and (4) overflow of the Ruisseau de la Pierre at Beaufort during the floods of November 15, 2023 (SMBVA, 2024).

Natural disasters (CatNat): The GASPAR database lists the events for which natural disaster decrees have been requested by communes to benefit from the CatNat compensation procedure following damage to insured private property. In the communes of the Arly basin, there were 177 natural catastrophe decrees for the period 1982-2024 (Figure 67).

These events are mainly concentrated around a few notable hazard episodes: the storm and floods of November 6, 1982, the floods of February 10 and 14, 1990, the floods and landslides of April 30 and May 1, 2015, the floods, landslides and avalanches of January 3 and 4, 2018 following the passage of storm Eleanor, and the floods and landslides of November 12-13, 2023 (Figure 67).

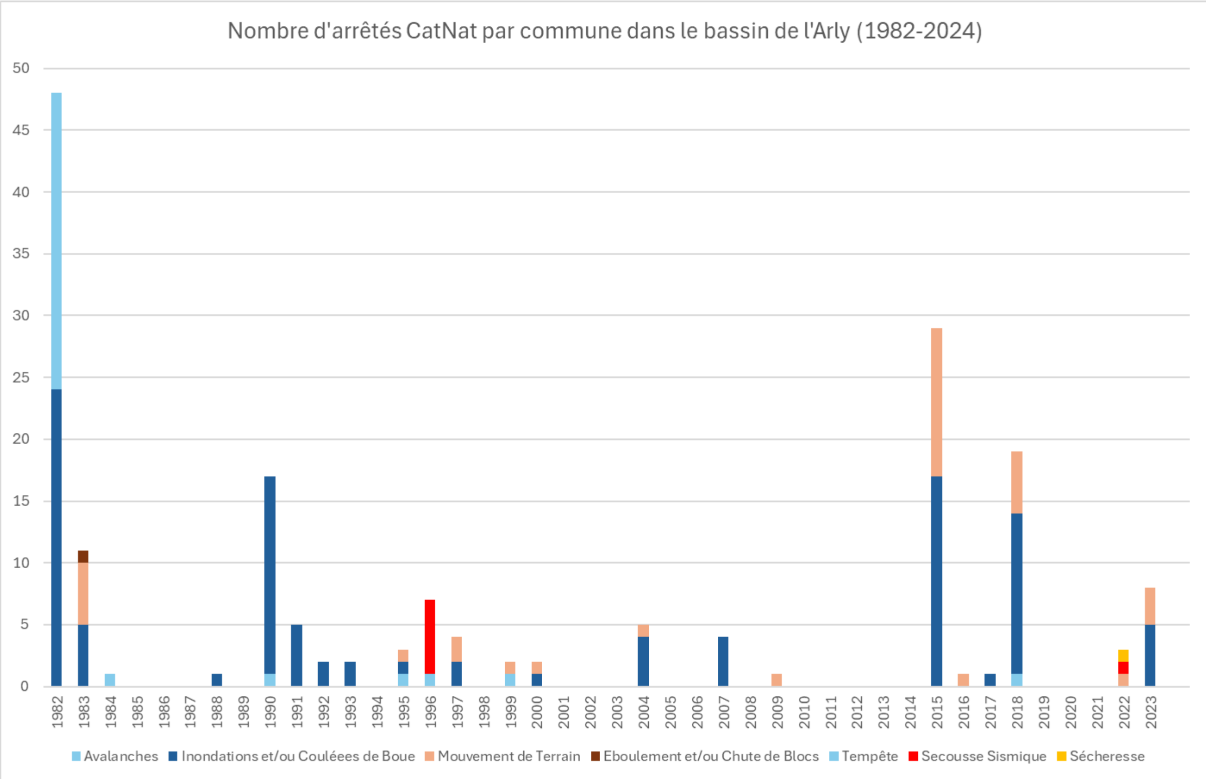


Figure 67 - Natural disaster decrees for communes in the Arly watershed, 1982-2002. Source: BD GASPAR; PARN processing.

The events responsible for these natural disasters (Figure 8) are mainly floods and mudslides (59%), landslides (19%) and storms (13%), plus a few avalanches (3%), a rockfall (1%) and a drought (1%).

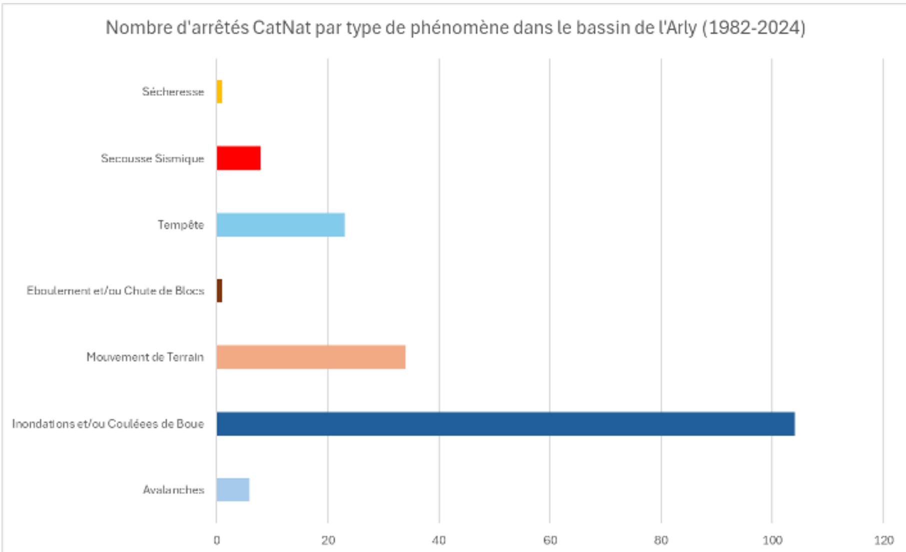


Figure 68 - Distribution of natural disaster decrees by type of event in the communes of the Arly watershed over the period 1982-2002. Source: BD GASPAR; PARN processing.

The communes with the highest number of CatNat decrees (≥10) are Megève, Ugine, Praz-sur-Arly, Beaufort-sur-Doron and Le Bouchet-Mont-Charvin (Figure 69).

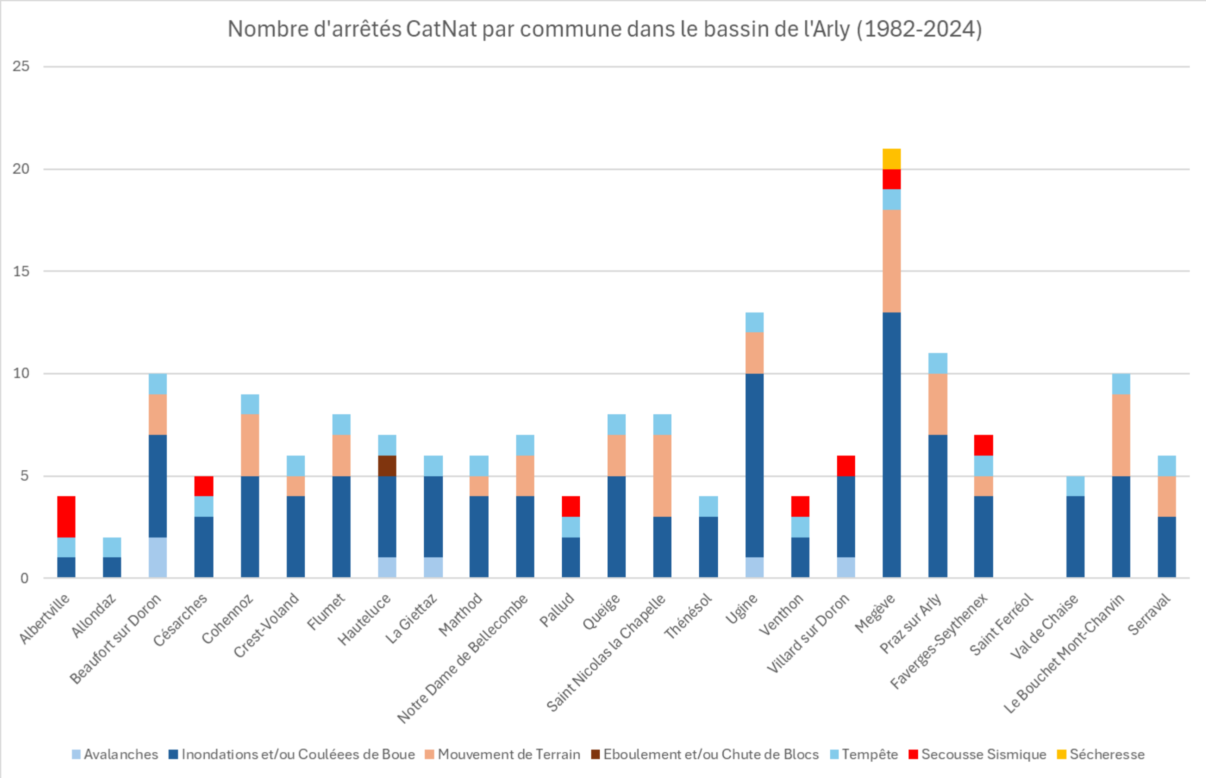


Figure 69 - Number of natural disasters (CatNat) in the communes of the Arly watershed over the period 1982-2024. Source: BD GASPAR; PARN processing.

After the events of January 3 and 4, 2018, following the passage of storm Eleanor, 13 of the 26 communes in the Arly watershed filed 18 requests for recognition of natural disasters (13 for flooding, 5 for landslides and 1 for avalanches: Figure 70), i.e. 10% of the total number of natural disasters recognized over the period 1982-2002.

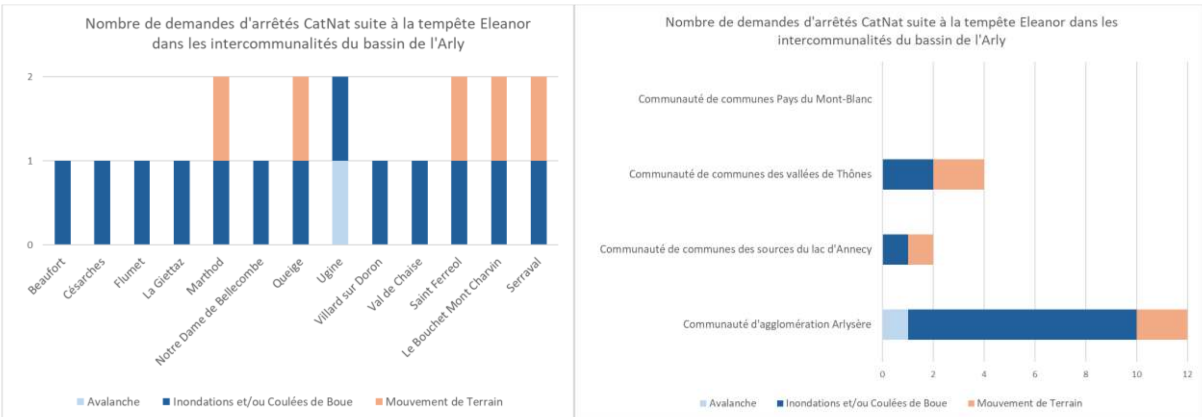


Figure 70 - Number of requests for CatNat decrees following storm Eleanor in communes (left) and intercommunalités (right) in the Arly basin.

Roads: Roads in the Arly basin are regularly affected by avalanches, landslides, rockfalls and torrential flooding (see sections II and III), leading to regular traffic disruptions and very costly roadworks. The RD1212, which is particularly exposed in the Arly gorges, is known as the 'most expensive road in France'.

Following the passage of storm Eleanor on 4 January 2018, the roads closed in the Val d'Arly were: the RD 1212 in the Gorges de l'Arly closed following a mudslide, the RD 132 closed between La Giettaz and Le Plan, the RD 909, access road to the Aravis pass, closed due to a snow slide, the RD

909 closed between Flumet and La Giettaz, the RD 109 closed between Ugine and Héry following a snow slide and the RD 1508 giving access to Haute-Savoie closed to heavy goods vehicles.

Emergency operations on the roads managed by the Savoie department in the Albertville/Ugine sector (closure, clearing, emergency works, safety measures, reopening) involved 60 people, 9 lorries, 2 loaders and 1 backhoe loader at a cost of €1.1 million (Lescurier, 2018). In Savoie, the January episodes resulted in 164 interventions by the department at a total cost of €4.35 million (Figure 71).

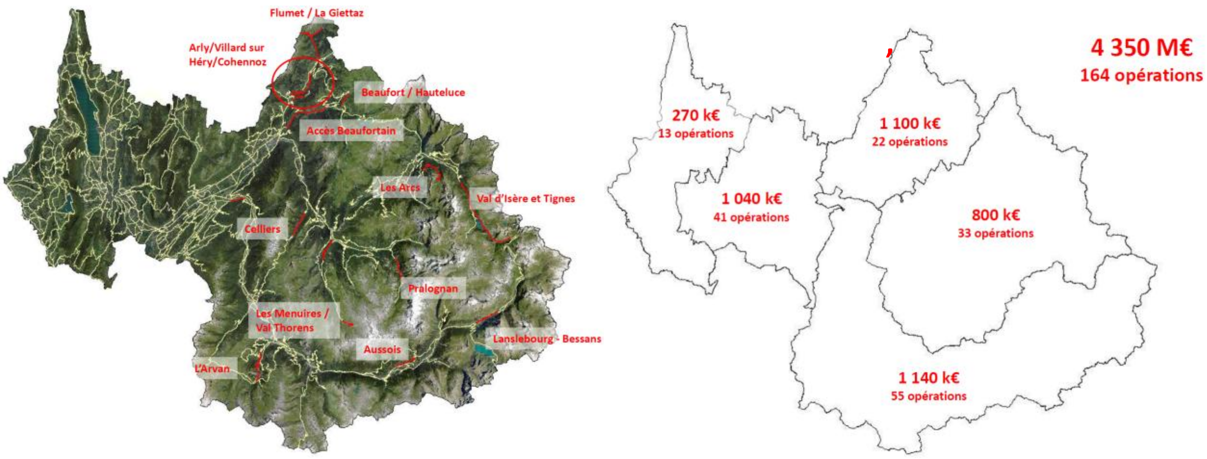


Figure 71 - Cost of repair operations on the road network and structures following the events of December 2017 and January 2018 in the various sectors of the Savoie department. Source: CD73.

Avalanches: In the Bornes-Aravis massif, the number of roads subject to avalanche risk is limited, mainly due to their modest altitude of no more than 1,500 m (IRSTEA, 2016a), but some sectors are exposed, particularly the RD1212, which is protected by several avalanche barriers (Figure 72).

Figure 72 - Combe Noire avalanche defence structure, Arly gorges.

Landslides: In the Arly Gorges, the roads at risk of landslides on the left bank are the RD 1212 (which crosses the Arly gorges at the bottom of the valley) and the RD 71 (located halfway up the left bank and serving the market town of Cohennoz from Ugine and then access to the hamlet of Cernix and the market town of Crest-Volland).

The roads at risk of landslides on the left bank are the RD 71, which runs halfway up the left bank and serves the market town of Cohennoz from Ugine and then access to the hamlet of Cernix and the town of Crest-Volland, and the RD 1212 at the bottom of the slope, which provides a direct link

between the valleys of the Isère (from Albertville in Savoie) and the Arve (access to Sallanches via Megève in Haute-Savoie).
The RD 1212 provides a direct link between the valleys of the Isère (from Albertville in Savoie) and the Arve (to Sallanches via Megève in Haute-Savoie). This route is essential because it serves the main ski resorts in the region and links the towns in the Pays du Mont Blanc with the major conurbations (service to Megève). Current daily traffic is estimated at 5,000 vehicles (including 2.5% HGVs) on an annual average, with peaks of 10,000 vehicles during winter tourist periods, on the access roads to the winter sports resorts of Les Saisies and Megève from Annecy and Chambéry (MEDDE, 2014). The road runs for around 17 km along the bottom of the Arly gorges, which are highly exposed to natural hazards.
In the Arly Gorges, rockfalls, rockfalls, avalanches, falling ice sheets, floods, scouring and landslides have caused numerous accidents (four deaths since 1945) and led to long closures for repair and safety work (84 days of closure on average per year between 1999 and 2003). The cliffs and rocky slopes overlooking the road are the source of frequent landslides, which can involve volumes of several thousand cubic metres. Since the 1970s, major rockfall protection works have been carried out (galleries and boulder barriers, some of them innovative). In 2000, the Savoie Departmental Council embarked on a ten-year, €21 million programme of rockfall protection works. However, this work has not dealt with all potential rock hazards: several rockfalls (including one involving several thousand m^3 in January 2014 and the Cliets tunnel in 2019, Figure 73) have led to temporary closures of the road for several weeks (Figure 73).

Figure 73 - Eboulement de février 2019 (Source : www.solscope.fr)

Torrential flooding: The RD1212 road in the Arly Gorges is particularly exposed to torrential flooding (Figure 74).

Figure 74 - Flood of 1st May 2015 in the Arly gorges, washing away the RD1212 ©ETRM, In Préfecture de la Savoie (2020).

Socio-economic activities: Characterised by a predominance of rural and forested areas, this mountain region has based its activity on summer and winter tourism around the tourist centres at the head of the catchment area with the resorts of Megève, Praz-sur-Arly, the village resorts of Val d'Arly: Notre-Dame-de-Bellecombe, Crest-Voland Cohennoz, la Giettaz, les Saisies, Hauteluce and Arêches in the heart of the Beaufortain. The watershed's economic activities are also closely linked to the use of water resources: tourism, snowmaking for ski resorts, hydroelectricity (with strategic production facilities at peak periods) and industry. (SMBVA, 2012)

Tourism: Tourism is a key economic driver for the region. The tourist economy, both summer and winter, represents a range of activities supported by major facilities (SMBVA, 2012). There is a wide range of facilities, from well-equipped valleys to more rural ones. The basin has over 100,000 tourist beds, which can accommodate twice the basin's permanent population. Although the tourist economy benefits from a large number of market beds, there is also a high proportion of non-merchant beds (second homes). These beds are mainly located in ski areas and resorts. Four areas have a greater number of tourist beds (Figure 75): the canton of Beaufort with the Les Saisies-Hauteluce resorts, the canton of Ugine with the Val d'Arly village resorts, the Haute-Savoie resorts in the upstream basin: Megève and Praz sur Arly, and the town of Albertville. Other communes benefit from the proximity of these resorts or have developed their own tourism potential, enabling them to offer accommodation. Albertville, as the dynamic urban centre of the basin, is attractive for its high-capacity hotels.

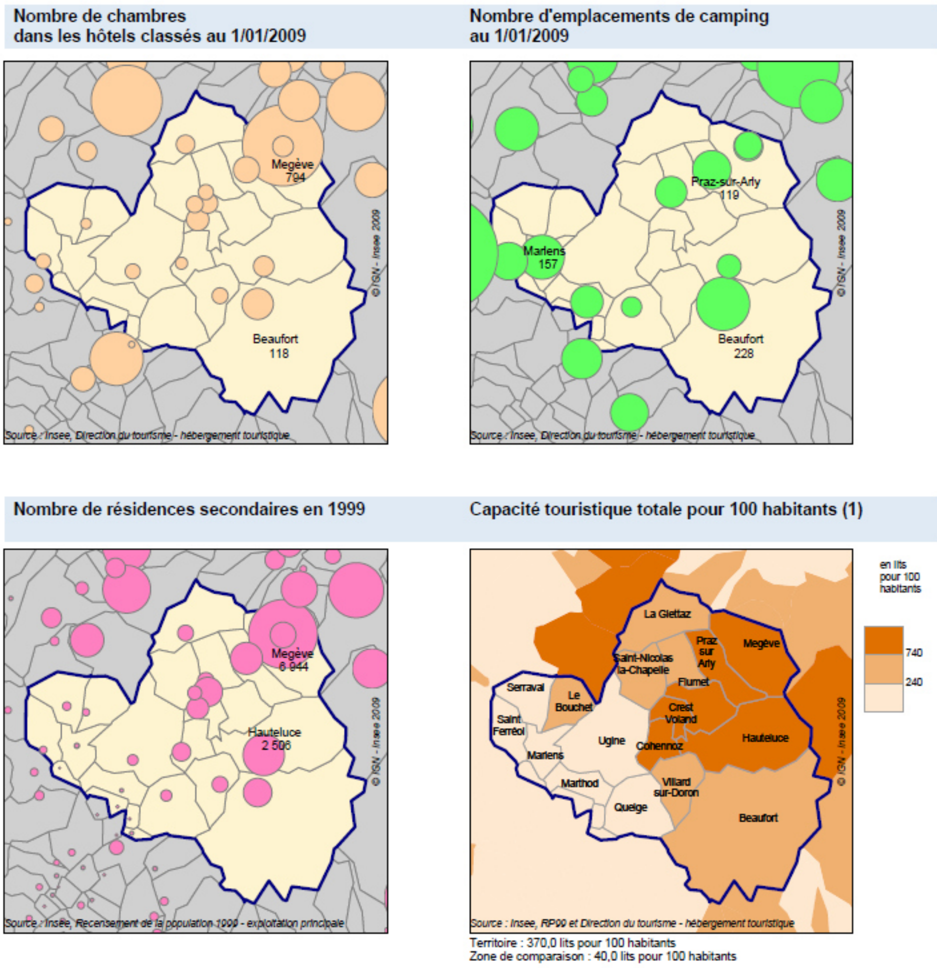


Figure 75 - Distribution of tourist accommodation in the watershed. ***In*** **Contrat de rivière Arly (2012).**

The region's tourist facilities (camping areas, leisure centres, ski resorts, etc.) are exposed to a range of natural hazards: avalanches, landslides, landslides, torrential flooding and flooding.

By illustration, the torrential floods of 29 and 30 July 2023 in Megève caused noticeable damage particularly on certain tourism issues. A very localised thunderstorm on Mont Joly and Aiguille Croche dumped almost 30 mm of water in 1 hour. The heavy rainfall generated torrential debris flows in the Plaine Joux and Glapet torrents. These torrents originate in a network of highly developed gullies. A large quantity of material was carried down and deposited in the Côte 2000 area (Figure 76). The structures crossing the Plaine Joux were blocked. The Glapet torrent was diverted, flooding the ski resort parking area and the restaurant. The post-flood work undertaken by the SMBVA (recalibration of the watercourse bed and restoration of hydraulic capacity) was carried out in close cooperation with the Megève town council and the ski slopes service in order to coordinate the work (SMBVA, 2024).

Fig 76 – Top: Torrential flooding on 29 and 30 July 2023 of the Plaine Joux and Glapet torrents in Megève. Bottom: Flow of a torrential lava from the Glapet torrent in an old bed on the current ski slope towards the Côte 2000 restaurant. In SMBVA (2024).

Agriculture: 2nd most important activity in the catchment area after tourism, agriculture plays a strategic role both economically and in terms of land use. It is characterised by a diversity of production (fruit, milk, market gardening, meat), the most important of which is dairy production based on quality labels (AOC Beaufort, Reblochon, Tome des Bauges, Chevrotin).

Hydroelectric production: The use of water resources has historically been at the heart of the economic development of the Arly catchment area, with the use of water power as early as the 18th century, the development of the iron and steel industry at the bottom of the valley at the beginning of the 20th century, the boom in hydroelectricity in the Beaufortain and Val d'Arly from 1940 onwards, the increase in tourist capacity in the resorts and the development of snowmaking in the ski areas more recently. (SMBVA, 2018). Hydroelectric schemes in the Arly and Doron basin are divided into 4 concessions: (1) Arly-Les Mottets, (2) Roselend-la Bâthie, and the Beaufortain chain divided into 2 concessions: (3) Girotte-Belleville-Hauteluce-Beaufort-Villard and (4) Queige-Roengers-Venthon (SMBVA, 2012).

Industry and craft: 295 industrial establishments can be found in the watershed (SMBVA, 2012). They are divided into several areas of activity: metallurgy, agri-food industries (dairies, cheese dairies, slaughterhouses), woodworking, transport, automotive repair, etc. The industrial sector - with metallurgy and parts manufacturing - remains marginal in the watershed. 3 major industrial plants are grouped together on the Les Fontaines industrial estate in Ugine (steel, titanium and zirconium production). This represents only 6% of the companies in the watershed, and employs nearly 6% of the local population, i.e. almost 2,900 people. Apart from the main industrial establishments, the industrial fabric is predominantly of medium to small size. These establishments are generally grouped together in business parks. These are mainly located in the valley and close to waterways: ZA des Bavelins in Ugine (34), ZA de la plaine and ZA des Ratelières in Marthod, ZA de Plan Piton in Queige, ZA de Marcot in Beaufort (21), ZA de St Ferréol et de Marlens in Pays de Faverges (30), as well as in Megève and Praz sur Arly (49). In addition, there are 26 facilities classified for environmental protection (ICPE) and the reduction of hazardous substances in the catchment area. These facilities are monitored by the DREAL. They are equipped with wastewater treatment systems or discharge into a collective network. Discharges are generally compliant, but accidental spills can occur. The following table details the sectors of activity of companies in the watershed, by commune.

	Nombre total d'établissements	Industrie (entreprises directement liées à la production) Nombre total d'établissements	Construction Nombre total d'établissements	Commerce (vente et distribution, réparation) Nombre total d'établissements	Autres services (y compris restauration et tourisme Nombre total d'établissements
Albertville	1258	90	126	3	662
Allondaz	5		2		3
Beaufort	252	21	32	4	154
Césarches	5	1	3	1	
Cohennoz	18		6	4	8
Cons-Sainte-Colombe	4		1	2	1
Crest-Voland	107	1	10	1	84
Faverges	296	30	49	8	129
Flumet	104	8	19	1	65
Hauteluce	269	12	16	4	199
La Giettaz	73	6	16	7	44
Le Bouchet	9	1	2	1	5
Marlens	28	8	7	8	5
Marthod	35	4	15	4	12
Megève	1064	43	88	2	717
Notre-Dame-de-Pallud	17		7	4	6
Praz-sur-Arly	164	6	20	2	110
Queige	36	6	5	5	20
Saint-Ferréol	37	8	12	9	8
Saint-Nicolas-la-Chapelle	32	2	12	3	15
Serraval	24	1	9	2	12
Thénésol	3	1	1		1
Ugine	271	34	58	5	123
Venthon	17	2	2	1	12
Villard-sur-Doron	51	5	8	1	26
Bassin versant	**4288**	**295**	**533**	**95**	**2504**

Table 10 - Répartition des secteurs d'activités sur le bassin versant. *In* SMBVA (2012).

Leisure activities: The main leisure activities in the area are fishing, hiking and whitewater sports (canyoning). Swimming is not permitted on the rivers and lakes in the catchment area, particularly in the large reservoirs, and is only permitted on a few small communal lakes (Flumet, Marlens). With the exception of canyoning, other water sports remain marginal in the watershed. There are 5 “practiced” canyons in the basin: canyon de la Belle au Bois in Megève, canyon du Boudon in Cohennoz, canyon de Fattes in Cohennoz, Nant de Potty in Praz sur Arly and Nant de l'Enfer in Ugine. Downstream of the St Guérin dam, canyoning is prohibited by prefectoral decree, given the risks associated with upstream hydroelectric developments. Canoeing and kayaking are occasionally practiced between Ugine and Albertville over a 9 km stretch (SMBVA, 2012).

Hiking trails: Thanks to the diversity of its terrain and landscapes, the study area boasts an extensive network of trails, particularly in the mid-mountain region. Many of the trails are more or less connected to high-altitude lakes, and trails along rivers are rarer. The Val d'Arly has many marked trails and themed trails/health trails. In all, there are over 250 km of trails starting from the Val d'Arly villages, with more than sixty itineraries. In the Beaufortain, 253 km of trails are signposted. They offer itineraries for all levels, from 500 to 3000m altitude. These trails are promoted by tourist offices during the summer season. (SMBVA, 2012)

Forests: Mountain forests (partly public, partly private) play a key role in carbon storage (in wood, soil and organic matter). They are also useful for the production of wood energy and timber construction. This type of forest is vulnerable to climate change on three fronts: increased pest attacks, periods of drought and growing fire risk. It is important to note that some forests have a natural hazard function, particularly in the event of landslides. The challenge will be to identify them. The protection of these forests is therefore essential, through protective measures concerning authorized human activity in particular (land clearing, wood energy harvesting). (Arlysère, 2019)

Biodiversity and high-altitude ecosystems: Generally speaking, climate change can have many impacts on biodiversity and ecosystems. It is important to take a systemic view of vulnerability to climate change: people depend on the natural environment (water resources, air quality, food resources, raw materials, etc.). The natural environment is also the basis for the region's economic activities (agriculture, forestry, leisure, tourism, industry, etc.): so if the natural environment is threatened, these activities will also be threatened in the more or less long term. On the other hand, it is important to note that, generally speaking, the healthier the environment (i.e., one that favors the circulation of species and is diverse in terms of species), the more resilient it will be, capable of coping with disturbances (pollution, parasites, invasive species, disease, etc.) and extreme events. In view of the various elements outlined, it therefore seems essential to preserve natural environments that are vulnerable to climate change (Arlysère, 2019).

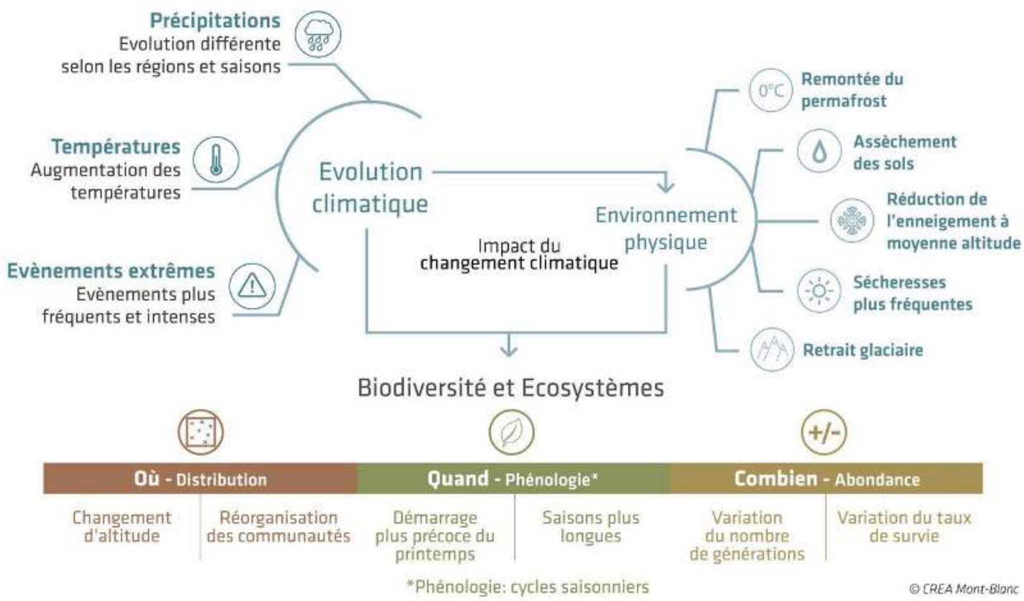


Figure 77 - Impacts of climate change on biodiversity and ecosystems (Source: Centre de Recherches sur les Ecosystèmes d'Altitude Mont-Blanc). In Arlysère (2019).

ii. Indirectly exposed elements

Vulnerability of road networks to the risk of isolation in Alpine valleys: Analysing the vulnerability of mountain areas to the risk of isolation is a complex task, involving several spatial and temporal scales. The notion of vulnerability emerges as the dominant one, as the various natural hazards do not have the same consequences depending on the structure of the network, its frequentation, its location, or the infrastructures it serves (Murat, 2019). The loss of accessibility during frequent road closures due to natural hazards is likely to affect all socio-economic activities in the basin, particularly access to resorts (Figure 78). When these road closures occur during peak tourist periods, particularly in winter, special resources are needed to take care of "road-wrecked" users who may be blocked.

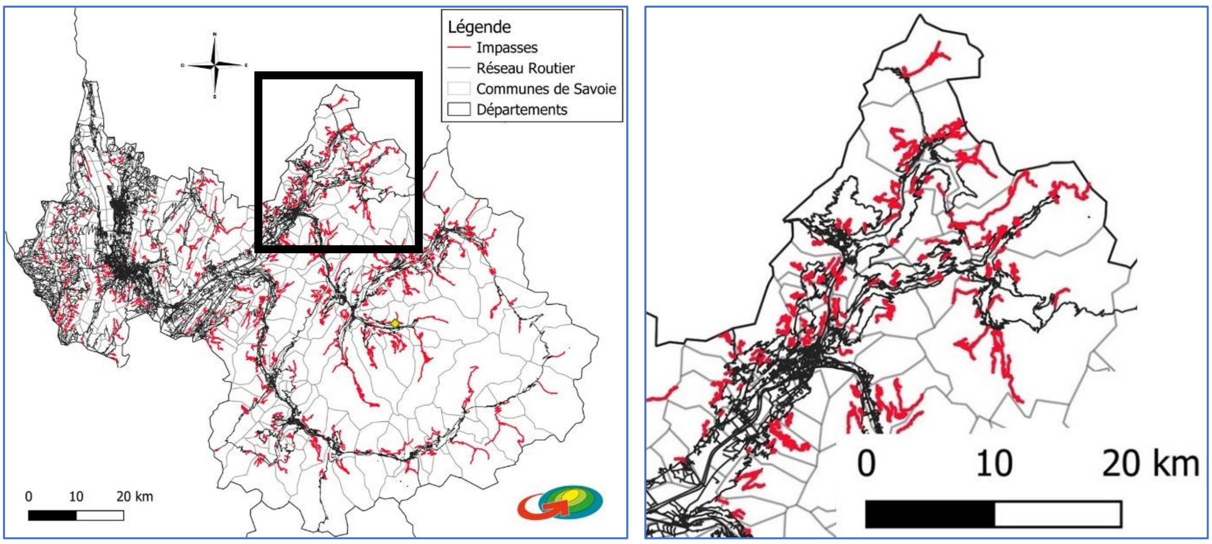


Figure 78 - Map of dead-ends on the road network in the Savoy department (top) and in the Arly basin (bottom). Adapted from Murat (2019). Treatment: PARN.

The debris produced by landslides are likely to affect a number of direct and indirect issues.

For example, debris flows fed by the Bersend landslide, which obstruct the Doron, threaten the departmental road leading up to the Roselend dam and high-altitude tourist sites, as well as the town of Beaufort downstream. In addition, these sediment deposits from the Bersend landslide make it necessary to maintain sufficient capacity in the bed of the Doron during EDF's tests to open the bottom gates of the Roselend dam. The map below shows accessibility to the village of Beaufort (and conversely, distances from the heart of the village) if the Roselend road remains open (Figure 79a). The second map (Figure 79b) shows the same accessibility, but where the Bersend landslide prevents the Roselend road from opening (Murat, 2019). The two maps placed side by side highlight the increase in travel time to reach the Roselend and Gittaz lakes (+5km to reach the Gittaz lake, i.e. more than a third of the distance).

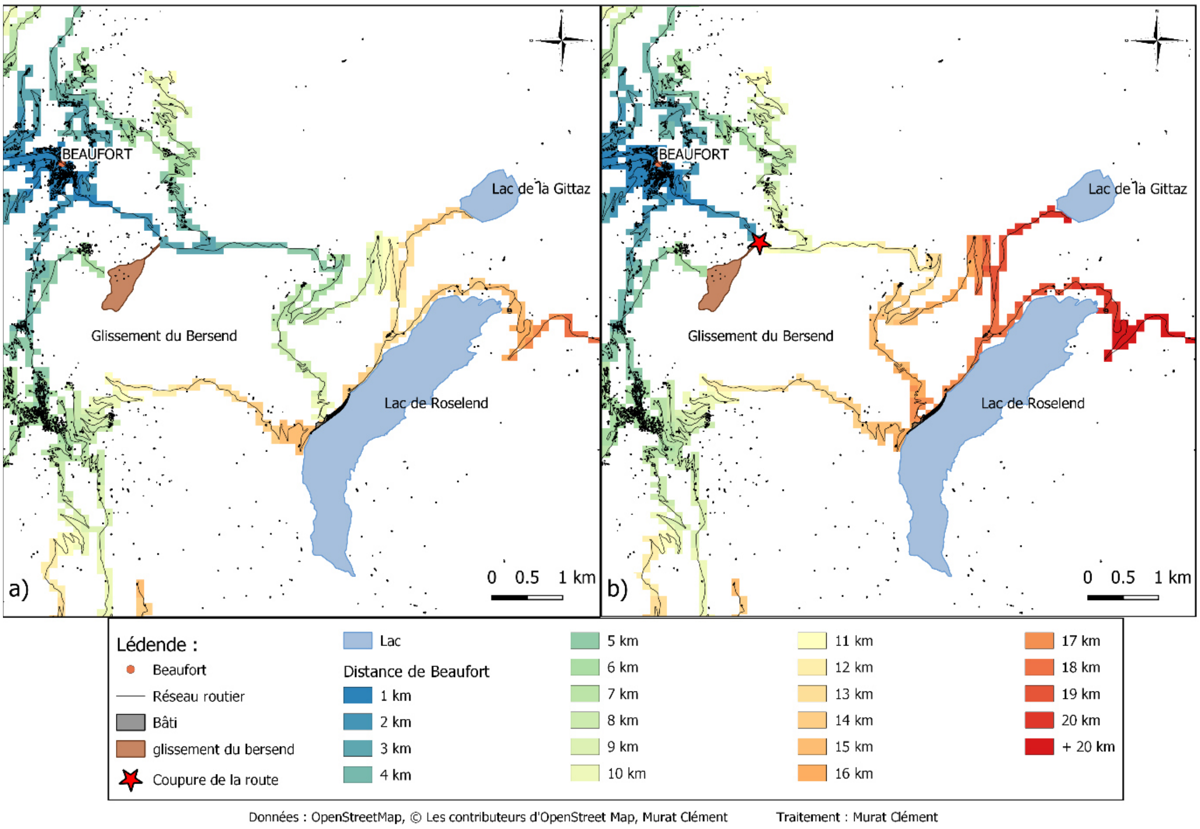


Figure 79 - Differences in accessibility to the village of Beaufort in the case of the opening (a) and closing (b) of the Roselend road (section cuts). In Murat (2019).

Forest and alpine pastures

Forest fire: The ongoing climate changes already lead to an increasing fire danger in the French Alps (Dupire et al., 2017), In the Northern French Alps, a low and slightly increase is observed in fire danger (whereas a high fire danger already occurs in Southern and inner Alps) and the number of days prone to fire slightly increased, especially at spring. Based on the increase of days with high fire weather danger, fires should become more intense on average in the next decades, according to future climate warming.

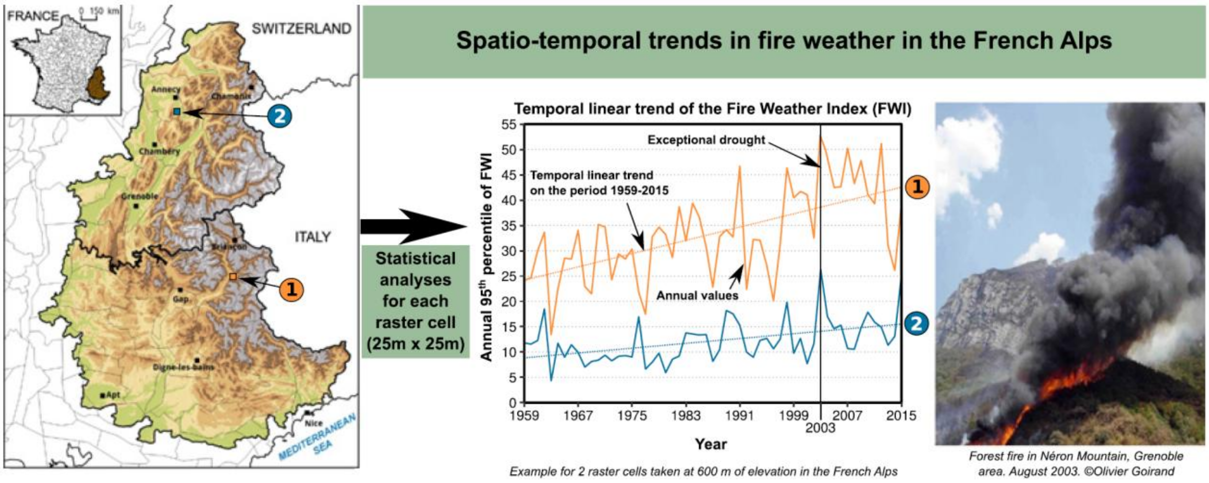


Figure 80 - Spatio-temporal trends in fire weather in the French Alps (Dupire et al., 2017).

On a regional scale, there has been an increase in the annual number of days favorable to forest fires (for which the IFM index ≥ 20) from 1 to 2 days on average over the period 1993-2022) in the departments of Savoie and Haute-Savoie (). This increase is less marked than in the rest of the Auvergne-Rhône-Alpes region (40 days or more on average over the 1993-2022 period for the southern départements of Drôme and Ardèche), but it reflects an increase in the risk of forest fires at higher altitudes and latitudes, which in future could also affect the Arly basin.

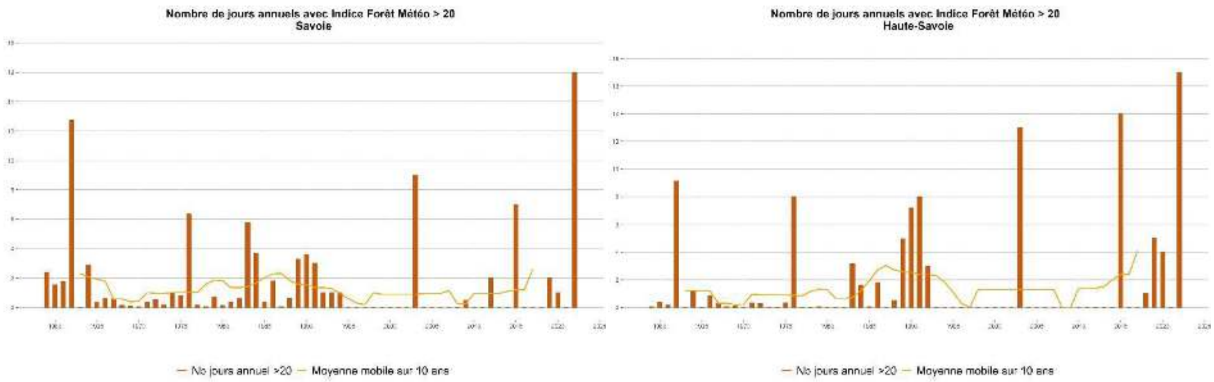


Figure 81 - Trend in the annual number of days on which the Forest Weather Index (FWI) is above 20. In ORCAE (2024).

To date, the Savoie and Haute-Savoie départements have little surface area sensitive to the meteorological risk of forest fires compared with the rest of the Auvergne-Rhône-Alpes region, but this proportion has been increasing in recent years (Figure 82).

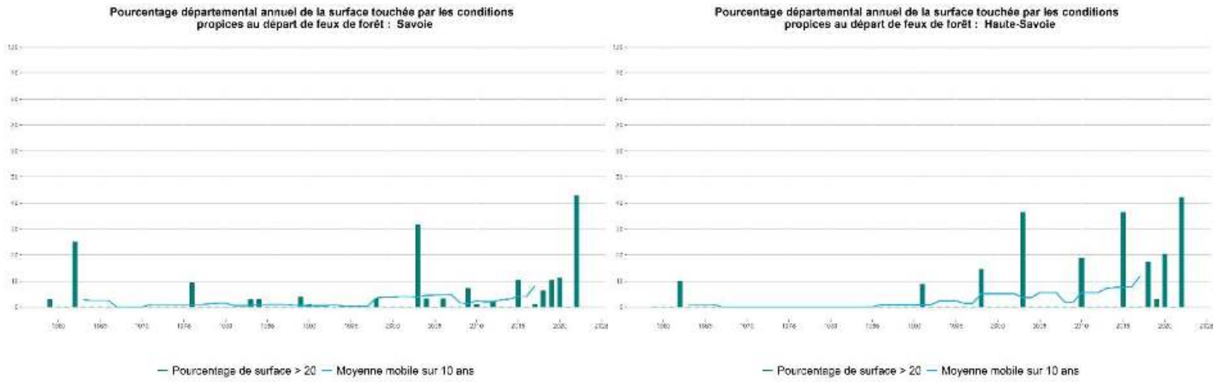


Figure 82 - Evolution of the percentage of departmental area where the Forest Weather Index ≥ 20 in the departments of Savoie and Haute-Savoie. In ORCAE (2024).

Pests: A number of parasites are already weakening Alpine forests. For example, the spruce bark beetle is an insect pest. It mainly attacks common spruce trees in poor health. The bark beetle lies dormant throughout the winter, waking up between April and June as temperatures rise. As a result, they are waking up earlier and earlier. The danger of the bark beetle lies in its epidemic phase. This phase is developing more and more as a result of drought, storms or severe water stress caused by climate change, coupled with an environment that is favourable to its reproduction, causing trees to weaken significantly and the bark beetle population to increase. During this epidemic phase, the insect pests also attack healthy trees. Flights have been occurring earlier and earlier since the 1990s, leading to a growing risk of outbreaks through a potential increase in the number of generations. (Arlysère, 2019).

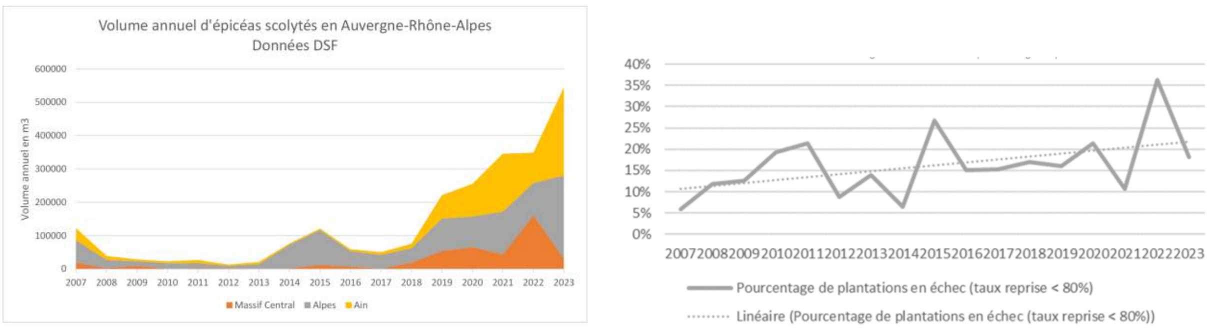


Figure 83 - Left: Annual volume of bark-killed spruce in the Auvergne-Rhône-Alpes region. Right: Percentage of failed plantations. In Berger (2024).

Evolution of alpine forests and sensitivity to fire: Mountain forests play an essential role in protecting against natural hazards. Today, they are increasingly subject to changes in the distribution of species and disturbances to the functioning of trees and forest ecosystems (drought, parasites, fires, storms, etc.). These disruptions result in trees becoming more fragile, more sensitive to wind (e.g. Vaia storm) and parasites (health crisis in northern Alpine forests), losing their mechanical strength, reducing their ability to protect themselves against gravity-related hazards (reduced interception of snow and rock falls) and increasing the rate of failed plantations (Berger, 2024).

b) Potential future exposure and impacts

i. Directly exposed elements

Forest and alpine pastures

As climate change is expected to continue and increase, forest cover will become more fragile as a result of an increase in the number of disruptive events (droughts, storms, pests, forest fires, etc.).

Foresters are faced with major uncertainties when choosing tree species in terms of their resilience and protection in the future climate. Various tools developed by the scientific community are available for this purpose. The ClimEssences model can be used to simulate the probable distribution of forest species in the future compared with the current situation under different climate change scenarios at the scale of a forest region, and to provide a basis for thinking about the choice of species in a changing climate. The range of certain species, such as spruce, is expected to shrink significantly. We will therefore have to think about the assisted migration of species, some of which are not present in the region. Various tools are currently used to model the risk of forest fires, using the Feu-Météo index and a soil humidity index, the protection function (number of boulders stopped) of forest stands using the Sylvarock model (digital simulations harmonised at departmental level) and the accessibility of protection forests to fire brigade emergency vehicles using the Sylvaccess tool. Work is underway to draw up management plans for the corresponding species to support public and private forest managers (MOSAIC project) and to anticipate fire risks in protection forest sectors.

ii. Indirectly exposed elements

The new climate regime could mean increased pressure on natural and man-made ecosystems. Those involved in the timber industry and farmers are particularly hard hit by droughts, which threaten fodder supplies, encourage the development of parasites and cause forests to dry out, threatening the preservation of the region's landscapes and biodiversity, as well as local know-how and quality industries (Beaufort and Tome des Bauges PDOs, local timber and firewood, etc.). Alpine pastures and forests are already suffering from heavy visitor numbers, and are having to respond to an ever-increasing number of demands (preservation of biodiversity, economic issues, carbon storage, slope stabilisation, water filtration, heritage, tourism, leisure and health, etc.). Weakened, they are struggling to survive in the face of urban populations and tourists looking for nature, outdoor activities and freshness. (Arlysère, 2021)

V. Which of the exposed elements display high or low physical or social vulnerability to the hazard, and how do you expect this to change in the future?

a) Current vulnerability factors

b) Potential future vulnerability factors

VI. Which risk management measures (mitigation, preparedness, response, and recovery) are in place or are planned in the future and how do/will they influence the exposure/vulnerability to the hazards?

a) Current risk management measures

Actions taken by State services

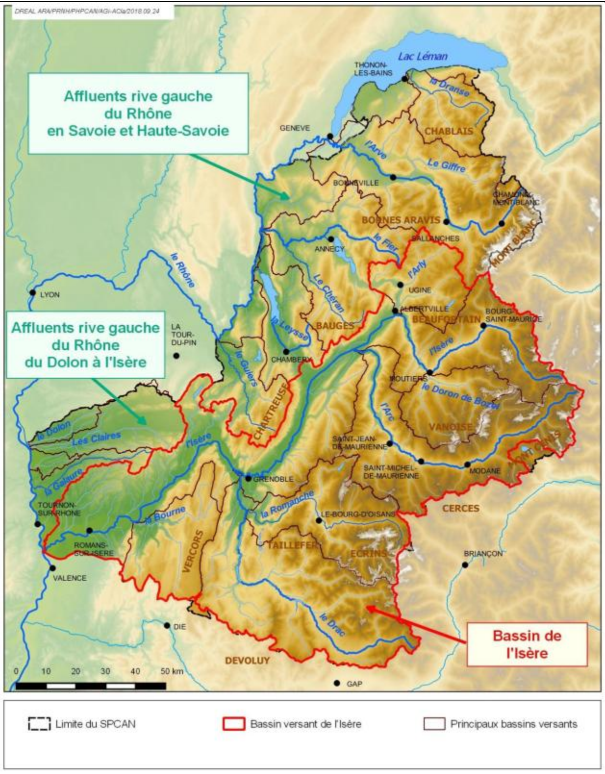
The State organises risk prevention and emergency response. The “Dossier Départemental sur les Risques Majeurs” (DDRM), drawn up by the Prefect, is a preventive information document designed to make citizens aware of the major risks to which they are exposed. It contains all the essential information on foreseeable major risks in the département, as well as the preventive and protective measures planned to limit their effects. The Savoy DDRM, approved by prefectoral decree on 7 December 2020, lists all the municipalities in the département at risk where preventive information must be provided to the population (Préfecture de la Savoie, 2021).

Flood risk prevention

Flood risk prevention measures include knowledge of the risk, implementation of the European Flood Directive, Flood Prevention Action Programmes (PAPI), taking account of flood risk in planning via Flood Risk Prevention Plans (PPRI), protection measures and measures to reduce vulnerability, forecasting (meteorological vigilance and flood forecasting) and emergency organisation (Préfecture de la Savoie, 2021).

Risk knowledge	Knowledge of flood risk is based on hydraulic studies and hydrogeomorphological analyses, the identification of flood-prone areas carried out as part of the **Atlas of Flood-prone Areas (AZI)** and the **Flood Risk Prevention Plans (PPRI)**, and the flood forecasting models of the **Flood Forecasting Service (SPC)**.
Implementation of European Directive 2007/60/EC on the assessment and management of flood risks	The **Flood Directive**, transposed into French law by Law no. 2010/788 of 12 July 2010, introduced a new approach aimed at reducing the negative consequences of all types of flooding. This led to the production of a National Flood Risk Strategy (**SNGRI**), which was then translated into a Flood Risk Management Plan (**PGRI**) for each river basin district, setting out the flood management policy to be followed. Then, at a more local level, a Preliminary Flood Risk Assessment (**EPRI**), carried out every 6 years, is used to define the Territoires à Risque Important d'inondation (TRI - territories at high risk of flooding), which are then the subject of a map of flood-prone areas according to the various frequent, average and exceptional floods, and the development of an appropriate Local Flood Risk Strategy (**SLGRI**). The SLGRI provides a global, strategic and shared vision of the objectives and actions to be implemented in the area in order to reduce the vulnerability of residents to flood risks. In Savoie, as part of the application of the Flood Directive, the Prefect, by order of 20 July 2016, tasked the Direction Départementale des Territoires (DDT) with coordinating the preparation of Local Flood Risk Management Strategies (SLGRI) in Savoie and drew up the list of stakeholders in the Territory of important Flood Risk (**TRI**) of Albertville (14 municipalities), which was approved on 6 January 2017.

Flood Prevention Action Programmes (PAPI)	The **PAPI**, created in 2003, is a tool available to local authorities, in particular public bodies for inter-municipal cooperation (EPCI) responsible for 'management of aquatic environments and flood prevention' (**GEMAPI**). It is drawn up on the basis of a comprehensive approach to risk, both in terms of space (generally the catchment area or valley), the stakeholders involved (partnership between government departments and local stakeholders) and the actions and measures included in the programme (knowledge and awareness of the risk, monitoring, forecasting, crisis management, town planning, reducing vulnerability, active and passive protection, etc.). There are two stages in the development of a PAPI: firstly, a PAPI of intention, initiated by the local authorities and leading to a diagnosis of the area in question and preparation of the action programme; this constitutes an application file. In a second stage, the labelling committee examines the programme of actions resulting from the PAPI of intention, leading to the labelling of a full PAPI. Approval enables the initiator of the initiative to obtain funding from the Fonds de Prévention des Risques Naturels Majeurs (FPRNM or 'Barnier' fund) to implement the actions set out in the programme.
Taking account of natural risks in planning	There are a number of tools that can be used to take account of flood risk in land-use planning: Flood Risk Prevention Plans (**PPR**), town planning documents and planning permission. Flood Risk Prevention Plans (PPRI) and Natural Risk Prevention Plans (PPRN) PPRIs and PPRNs, drawn up by the State, define regulatory zones that prohibit construction or authorise it subject to conditions, known as prescriptions. These prescriptions have a regulatory value, have the status of a public utility servitude and are appended to town planning documents, such as the Local Town Planning Scheme (**PLU**). The town planning code requires that risks be taken into account in town planning documents. According to article L.121-1 of the town planning code, the Schémas de Cohérence Territoriale (**SCoT**), Local Town Planning Scheme (PLU) and the municipalities maps determine the conditions for preventing foreseeable natural risks, while respecting the objectives of sustainable development. Where applicable, the PPRi is incorporated into the PLU, or failing that, the Information notice (PAC: Porté à Connaissance), drawn up by the State services, is appended to the town planning documents. The provisions of the PGRI and the PPRi are also taken into account when drawing up SCoTs. Indeed, the PLU and SCoT integrate all available knowledge on flood risk (AZI, hydraulic studies, etc.) and must be compatible with higher-ranking documents such as the Master Plan for Water Development and Management (**SDAGE**), the PGRI, the PPRi, etc., by relaying flood prevention policies at their level. Article R.111-2 of the French town planning code stipulates that a project may be refused or only accepted subject to special conditions if it is likely to affect public health or safety by virtue of its location, characteristics, size or location near other installations. Under this article, town planning authorisations allow mayors to prohibit new construction in high-hazard zones, or to impose restrictions on a project depending on its degree of exposure to risk. A guide to the application of article R.111-2 (Application of Land Law), sent to local authorities to help them develop their projects in flood-prone areas outside the PPRI, has been drawn up in the département, based on the principles for controlling urban development in flood-prone areas laid down by the Ministry for the Environment.
Measures to protect and reduce vulnerability	Protection and vulnerability reduction measures include both collective and individual measures. **Collective measures** include the maintenance of watercourses to limit any obstacles to the free flow of water (regular cleaning, maintenance of banks and structures, pruning and recutting of vegetation, removal of logjams and debris, etc.), river development works to reduce solid transport from the river bed and catchment area (creation of weirs or deposition beaches, etc.) and protection works designed to limit flooding and the damage caused by flooding (protective dykes, flood control dams, water diversion works, etc.). However, these structures are not infallible and can generate excess flooding if they fail. These works can be carried out by associations of property owners, inter-municipal syndicates or territorial public establishments created by the law of 30 July 2003. Collective measures can also be initiated by EPCIs responsible for the management of water resources. **Individual measures** include the provision of temporary devices to block air vents, doors, etc. (cofferdams), securing tanks, installing non-return valves, choosing equipment and construction techniques according to the risk (rot-proof materials), making electrical switchboards, heating systems, ventilation and air conditioning units watertight, the creation of a downstream or separate electrical network for rooms subject to flooding, and the carrying out of vulnerability reduction diagnostics, which may also be required by certain PPRs and may be financed by State aid via the Fonds de Prévention des Risques Naturels Majeurs (**FPRNM** - Major Natural Risk Prevention Fund).
Forecast	The **anticipation of risk situations** is based on meteorological vigilance and flood forecasting. The **meteorological vigilance map** is drawn up twice a day at 6.00am and 4.00pm (Météo-France website: vigilance.meteofrance.com) and draws attention to the possibility of a dangerous meteorological phenomenon occurring in the 24 hours following its issue. However, it is difficult to quantify the rainfall precisely and, above all, to locate the small catchment areas that will be affected. Flood forecasting is essential if we are to respond more effectively to flooding. Since 2006, the French Ministry for the Environment has been offering a flood watch service, which operates in a similar way to the weather watch service provided by Météo-France. It informs the public and those involved in crisis management about the risk of flooding on the main rivers. The State is responsible for the statutory task of monitoring, forecasting and transmitting flood information.



Northern Alps Flood Forecasting Service catchment area (SPCAN). In DREAL Auvergne-Rhône-Alpes (2019).

In Savoie, 3 stretches of the Isère, 2 stretches of the Arc and 1 stretch of the Rhône are subject to regulatory monitoring by the Service de Prévision des Crues (SPC) Alpes du Nord et Rhône Amont Saône managed by the DREAL Auvergne-Rhône-Alpes, whose role is to constantly monitor rainfall and run-off in the rivers feeding the watercourses for which it is responsible. Watch bulletins are issued at least twice a day (www.vigicrues.gouv.fr). The Arly is not monitored, but an alert bulletin is issued if necessary.

Depending on the levels forecast for each section over the next 24 hours, the level of vigilance ranges from green to red (maximum level) depending on the extent of the feared consequences for the area:

- **Green level:** no particular vigilance required - normal situation.
- **Yellow level:** risk of flooding or rising water levels, not causing significant damage, but requiring particular vigilance in the case of seasonal and/or exposed activities. Local overflows, occasional road closures, isolated houses affected and disruption to river-related activities.
- **Orange level:** risk of major flooding. Foreseeable or observed flooding likely to have a significant impact on people and property. Unusual phenomenon. Widespread flooding, severe traffic disruption, evacuations.
- **Red level:** risk of exceptional or major flooding. A flood situation, foreseeable or observed, with major consequences for the safety of people and property. A rare and catastrophic event.

During periods of flooding, these levels of vigilance are associated with forecasts of water levels measured at various river flow monitoring stations over variable time horizons (from 6 am to 12 pm). From the orange level onwards, the prefect informs the operational services and the mayors concerned on the basis of the information provided by the SPC.

Other warning systems exist, such as APIC and Vigicrues Flash:

- **Intense rainfall warning at local authority level (APIC)**, offered by Météo-France (https://apic.meteo.fr). This tool currently exists for certain communes in Savoie and is a free observation service offered by Météo-France, which informs you in real time of unusually intense rainfall at commune level. This tool does not therefore provide any direct information on the state of the region's watercourses. However, knowing about heavy rainfall in and upstream of the municipality enables us to better understand and anticipate possible changes in river flow and to step up surveillance of the area. In addition, the APIC tool is particularly well suited to municipalities prone to flooding as a result of run-off. Intense rainfall warnings are sent by SMS, email or voice message.
- **Vigicrues Flash**, offered by the Ministry of the Environment, which runs the VIGICRUES network: This system, which is an alternative to Vigicrues, enables certain municipalities in Savoie to receive free warnings of the risk of flooding on the rivers covered by the system within the next few hours. Vigicrues is a system that calculates the hydrological reactions of a basin according to the rainfall. If the system identifies a risk of significant flooding in the next few hours, a warning is sent by voice message, text message or e-mail. An update is made every 15 minutes and the subscriber is warned in particular if the situation worsens. Communes affected by major flooding or runoff risks are advised to subscribe to these

	services so that they can receive warnings and alerts directly via different media (SMS, email and telephone) and to different numbers and addresses.
Rescue organisation	Once a risk assessment has been carried out, the public authorities have a duty to organise emergency resources to deal with any crises that may arise. This requires a balanced sharing of responsibilities between the State and local authorities. Emergency services are organised at three complementary levels: (1) municipal/local, (2) departmental and zonal and (3) individual. ***At local level:*** The mayor, who has police powers, can implement the local emergency response plan (Plan Communal de Sauvegarde - **PCS**). The PCS is an operational tool which, depending on the known risks, determines the immediate measures for safeguarding and protecting people, and sets out the necessary organisation for disseminating alerts and safety instructions. This plan lists the resources available and defines the implementation of measures to assist and support the population. The PCS is required by law in all municipalities affected by a Risk Prevention Plan (PPR) or a Special Intervention Plan (PPI). The local authority can also set up a Local Civil Protection Reserve (RCSC), of which there are 7 in the Savoie department. Placed under the authority of the mayor, it is made up of volunteers with the skills and competencies required for the tasks assigned to the reserve. Its purpose is to support civil protection services in case of an event that exceeds their usual resources or in special situations (support for the population, logistical support, restoring activities, etc.). For establishments open to the public, it is the manager who must ensure the safety of people until the emergency services arrive. For schools, school headmasters and head teachers have been asked to draw up a Special Safety Plan (**PPMS**) to ensure the safety of children and staff before the emergency services arrive, and to prevent parents from coming to collect their children. The national education authority is responsible for drawing up the PPMS, and the head teacher or school headmaster must implement it. For each of the major risks to which the school is exposed and for each of the situations identified (canteen, recess, etc.), the PPMS must answer the following six questions: When should the alert be triggered? How should the alert be triggered? Where and how should pupils be taken to safety? How should communication with the outside world be managed? What immediate instructions should be given? What documents and resources are essential? This provision can be extended to other schools as part of the emergency response plan. If the Mayor is unable to deal with the situation by his own means due to the seriousness or extent of the event (involving several municipalities), he may, if necessary, call on the Prefect, the State's representative in the département. The Prefect can then mobilise the emergency resources of the State, local authorities and public establishments and, if necessary, requisition the private resources required for the emergency. ***At departmental and zonal level:*** The Civil Security Modernisation Act of 13 August 2004 reorganised existing emergency plans, based on the general principle that when the organisation of emergency assistance is of a particular scale or nature, it is the subject of an **ORSEC plan** (Organisation of the Civil Protection Response) in each department and in each defence zone. The departmental ORSEC plan, drawn up by the prefect, determines the general organisation of emergency services in the light of existing risks in the department and lists all the public and private resources likely to be deployed. It includes general provisions applicable in all circumstances and specific provisions for certain particular risks. The zonal ORSEC plan is implemented in the event of a disaster affecting at least two départements in the defence zone or requiring the deployment of resources that go beyond the département level. The specific provisions of ORSEC plans set out the measures to be taken and the emergency resources to be deployed to deal with risks of a particular nature or linked to the existence and operation of specific facilities or installations. It may define a Particular Intervention Plan (PPI), particularly for Seveso-classified establishments, hydroelectric dams or nuclear sites. In the event of a major civil defence or security event, the prefect takes charge of the emergency response. He then implements or activates the elements of the ORSEC system adapted to the situation. ***At an individual level:*** the Family Safety Plan (**PFMS**) is designed to enable citizens to take responsibility for their own safety. In order to avoid panic in the event of a major incident, such a plan, prepared and tested within the family, is the best way for everyone to deal with the risk while waiting for emergency services. It is the result of careful thought about the safest places to take shelter in each room and the evacuation routes through the building. It includes preparing an emergency kit, consisting of a radio with spare batteries, a torch, drinking water, emergency medicines, important papers, a change of clothes and blankets.

Mountain risk prevention

A specific prevention policy is in place to deal with natural hazards in the mountains.

Actions by municipalities

At municipal level, natural risks are taken into account through the Risk Prevention Plans (PPR), which are imposed on the Local Town Planning Plans (PLU) to regulate construction and define prevention, protection and safeguard measures. The purpose of the PPRs is to delineate the areas exposed to risk, as well as areas not directly exposed to risk but where the stakes (buildings, structures, developments, operations and activities) could exacerbate the risks or cause new ones, in order to define the prevention, protection and safeguard measures that must be taken in these same areas, as well as measures relating to the development, use or operation of existing buildings, structures and cultivated areas.

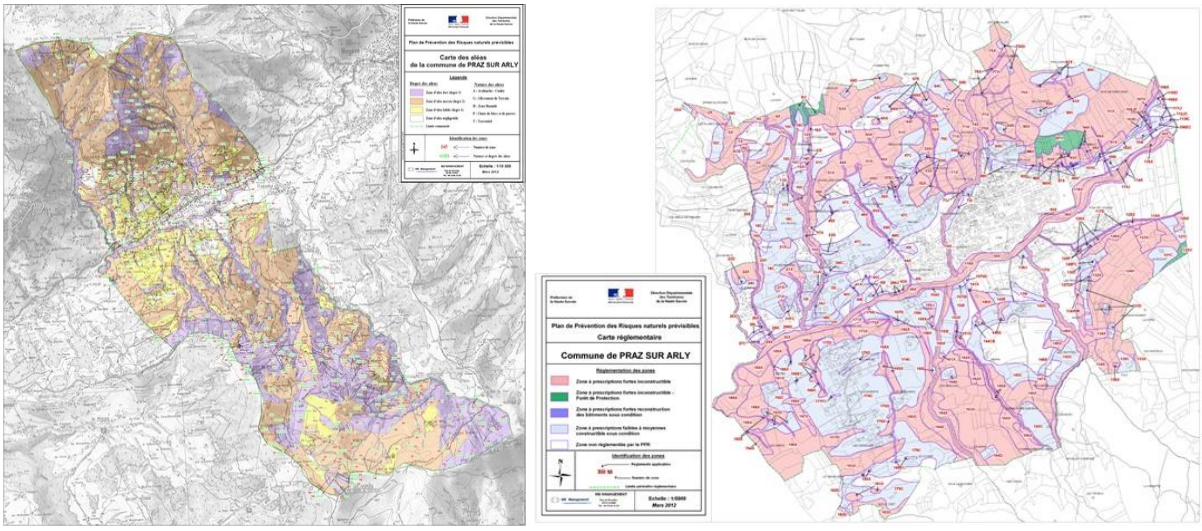


Figure 84 - Carte des aléas naturels (haut) et zonage règlementaire (bas) sur la commune de Praz-sur-Arly (Haute-Savoie).

Another type of prevention plan used in Savoie is the Plan d'Indexation en Z (PIZ), also appended to the PLU (Arlysère, 2019). This document is designed as a summary form of the PPR, combining on a single graphic document a zoning system determining the conditions for urban development, with information on the nature and level of natural risks. The document is accompanied by regulation sheets. A number of these PIZs have been updated since 2012 in the Arly basin.

In the Arly basin, almost all communes have a Risk Prevention Plan (14 communes) or a Z-Indexation Plan (5 communes).

Dép.	EPCI	Commune	PPRN	PIZ	PPRI
Savoie (73)	Arlysère	Albertville		MAJ 2019?	2013
		Allondaz	Hors PPR/PIZ		
		Beaufort sur Doron	2005-2018		
		Césarches	Hors PPR/PIZ		
		Cohennoz		2008	
		Crest-Voland	Hors PPR/PIZ		
		Flumet		2019	
		Hauteluce	2018		
		La Giettaz	2008		
		Marthod		2008	
		Notre Dame de Bellecombe		2019	
		Pallud	2004		
		Queige	2010		
		Saint Nicolas la Chapelle		2012	
		Thénésol	Hors PPR/PIZ		
		Ugine	2001		
		Venthon		?	
		Villard sur Doron	2017		

Haute-Savoie (74)	CC Pays du Mont Blanc	Megève	2012
		Praz sur Arly	2012
	CC Sources du Lac d'Annecy	Faverges-Seythenex	2011
		Saint Ferréol	2015
		Val de Chaise	Consultation 1999
	CC Vallées de Thônes	Le Bouchet Mont-Charvin	1999
		Serraval	1994

Table 11 - Prevention plans taken into account in the town planning documents of the communes in the Arly basin: Natural Risk Prevention Plan (PPRN), Z-Indexation Plan (PIZ) and Flood Risk Prevention Plan (PPRI). Source: Savoie and Haute-Savoie government departments, Arlysère (2019). PARN processing.

Under French law no. 2004-811 of 13 August 2004 on the modernisation of civil protection, the Municipal Safeguard Plan (PCS) defines, under the authority of the mayor, the organisation planned by the municipality to ensure that the population is alerted, informed, protected and supported in the face of known risks. It draws up an inventory and analysis of risks throughout the municipality. It integrates and completes the information documents drawn up for prevention purposes, including the DICRIM (Document d'Information Communal sur les RIsques Majeurs). This plan is compulsory in communes with an approved plan for the prevention of foreseeable natural risks (PPR) or in communes within the scope of a special intervention plan (PPI). It is strongly recommended for all others.

The law of 13 August 2004 emphasises the need to improve ORSEC planning through drills and feedback: drills enable those involved in crisis management (fire brigade, emergency services, gendarmes, police, etc.) to get to know each other better and acquire the right reflexes; feedback enables lessons to be learned from real or simulated accidents during drills. Decree no. 2022-1532 of 8 December 2022, which makes civil protection training and exercises compulsory, reinforces this dynamic. The mayor must therefore carry out drills (at least 1 every 5 years) to test the communal crisis organisation. The intermunicipal authorities can provide support through their Intercommunal Safeguard Plan (PICS). Field exercises (involving the various services: gendarmerie, SDIS, associations, etc.) will help to improve decision-making during an event.

With regard to the risk of avalanches, exercises are carried out regularly and the population has already been made aware of this (Arlysère, 2019).

Actions by intercommunal bodies

<u>The Syndicat Mixte du Bassin Versant de l'Arly (SMBVA)</u>

The Syndicat Mixte du Bassin Versant de l'Arly (SMBVA) brings together 26 municipalities across 3 communities of communes (Pays du Mont-Blanc, Vallées de Thônes and Sources du Lac d'Annecy) and 1 community of agglomerations (Arlysère) and grouped together in a mixed syndicate, to deal with the problems of the Arly and its tributaries on a watershed basis. In this way, watercourses are dealt with along their entire length, without administrative limitations (Figure 85).

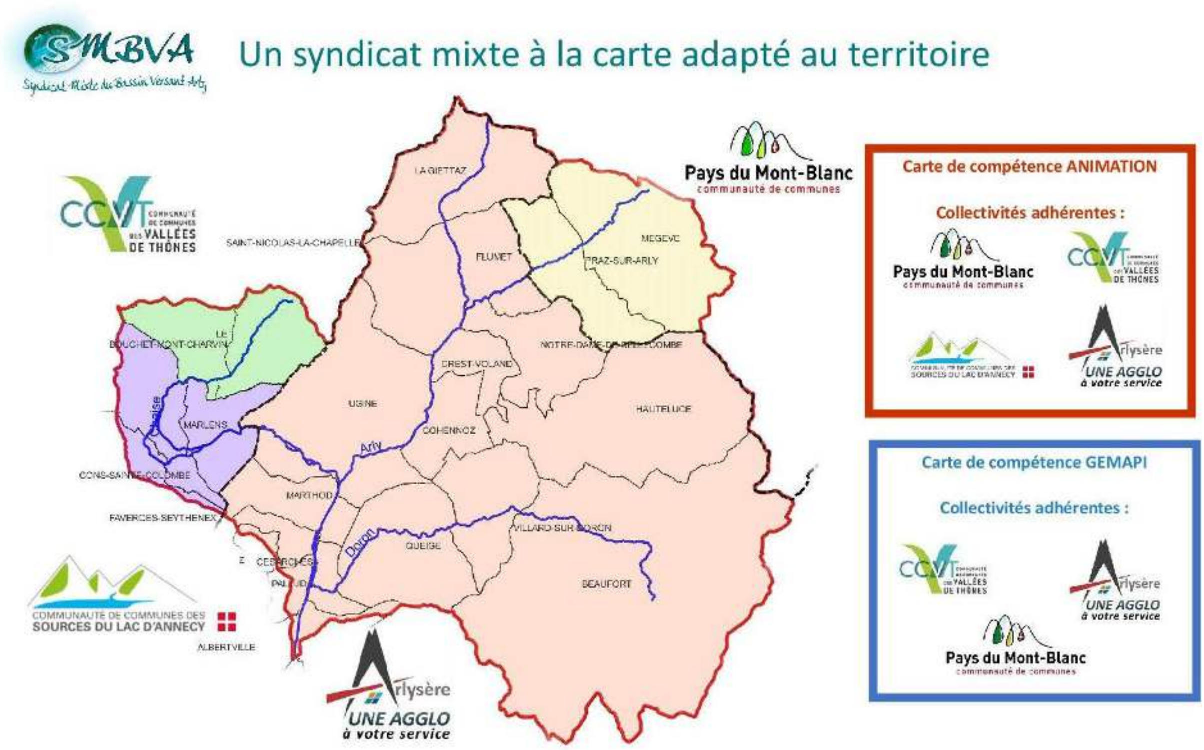


Figure 85 - Administrative territory of the Syndicat Mixte du Bassin Versant de l'Arly (SMBVA).

The SMBVA was founded in 2013 and transformed in 2018 to integrate the competence of aquatic environment management and flood prevention (GEMAPI). It has a team of elected representatives from the various member intercommunalities and a technical team in charge of projects. On a daily basis, the SMBVA team assists stakeholders and local authorities in the watershed with all projects and issues relating to river management and flood prevention.

The SMBVA carries out two tasks within the Arly catchment area for the communities of communes and the Arlysère conurbation that are part of it: (1) leading contractual approaches for the comprehensive and concerted management of aquatic environments and (2) implementing the GEMAPI remit for river managment. The aim of the action programme of the 1st Arly River Contract was to restore, maintain and develop the watercourses in the Arly basin, and corresponded to the GEMA (Aquatic Environment Management) section. The GEMA section deals with maintenance work on running watercourses, which has been carried out for many years by the inter-communal bodies and, since 2013, by the SMBVA (dredging, afforestation of banks, management of invasive species, preservation of the ecological continuity of watercourses by making structures fishable). The actions decided as part of the 2nd programme of the River Contract are actions to adapt to and mitigate the effects of climate change. In fact, all the actions to restore aquatic environments aim to mitigate the effects by improving the ecological state of the region's watercourses and preventing extreme phenomena such as floods through the following actions: bank maintenance, improving the functionality of watercourses and their smooth flow, preserving identified biodiversity reservoirs, ecological continuity, the free movement of fish, wetlands, flood prevention, improving sediment transport, improving water quality, etc. (Arlysère, 2019). Flood prevention is now the responsibility of the EPCIs.

The catchment area is equipped with a specific device for flooding the Arly at Moulin Ravier. Météo France forecasts are also monitored, and a system has been set up to ensure vigilance in the event of extreme events. On the other hand, the Savoie department suffers from a lack of weather radars due to the complexity of setting them up and their excessive cost (Taboulot, 2023). As an example, the torrential episodes in Savoie in June 2023 (June 4, 11 and 13 in Albertville, La Bathie and Ugine) were not covered by APIC warnings, most likely due to an erroneous estimate of water levels in real time (Taboulot, 2023).

The SMBVA has 2 action programmes concerning flood prevention and management:

- A multi-annual watercourse maintenance programme (2020-2025), recognised as being of interest by prefectoral decree n°2019-1560, including sediment management work, maintenance of bank afforestation and combating the spread of invasive species.
- A Flood Prevention Action Plan (PAPI) for the Arly catchment area has been in preparation since 2023. During the preliminary study phase (2023-2026), 43 actions were defined as part of an overall flood prevention strategy for the catchment area, representing an investment of €1,430,000 (excluding VAT), 60% of which was subsidised by the French government under the Major Natural Hazards Prevention Fund and the Green Fund.

A flood prevention action plan (PAPI) has been set up for the Arly watershed. During the preliminary study phase (2023-26), 40 actions were defined as part of an overall flood prevention strategy for the watershed, representing an investment of €1,430,000 (excl. VAT), 60% of which was subsidized by the French government through the "Fond de prévention des risques naturels majeurs" and the "Fond vert".

The Arlysère Agglomeration Community

The Arlysère Agglomeration Community comprises 39 municipalities, some of which are located in the Arly basin (Figure 86).

As part of the 'Integrated Natural Risk Management (INRM) Pilot Site' experiment run by Arlysère, a post shared across the territory was used to work on natural risk issues from 2005 to 2012, but since then, the Arlysère conurbation territory has only seen very occasional actions carried out by the municipalities (Arlysère, 2019).

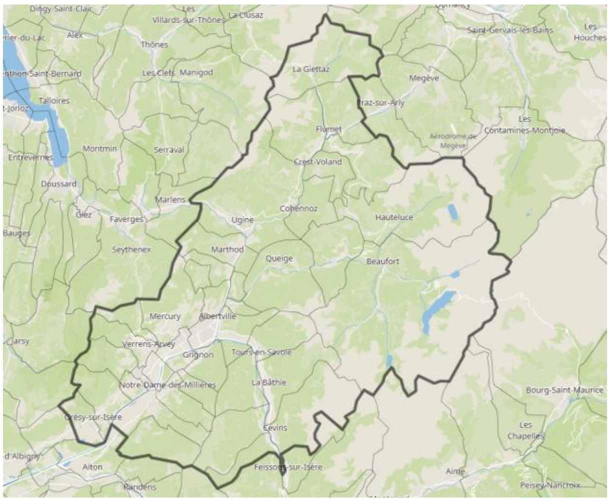


Figure 86 - Arlysère Agglomeration Community.

A Territorial Climate Air Energy Action Plan (PCAET) was approved by the Arlysère Agglomeration Community on 24 March 2022. This includes an analysis of the area's vulnerability to climate change (Figure 87). As part of its PCAET, Arlysère wishes to ensure that the territory's natural risks are fully understood and addressed. A precise identification of existing and future risks will therefore be carried out, and appropriate management tools will be developed to ensure the safety of property and people in the face of natural hazards. Within the framework of action N°51 "*Gestion des risques naturels du territoire et prévention des inondations*" (GEMAPI), special attention will be paid to the risk of flooding in the region's 2 watersheds, in conjunction with the river management syndicates (Arlysère, 2021).

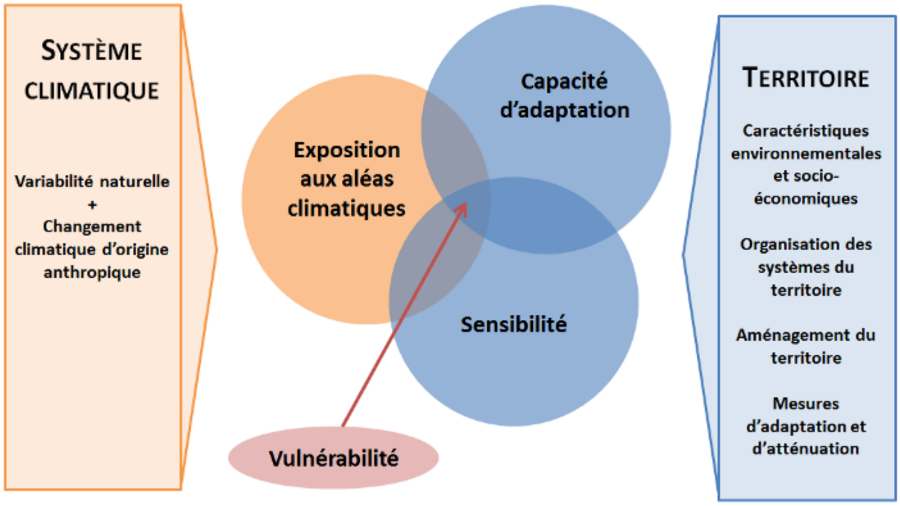


Figure 87 - Articulation of the territory, its characteristics and external impacts. In Arlysère (2021).

Actions taken by the Savoie department

Management of departmental roads: The Département de la Savoie manages and decides on the opening and closing of departmental roads.

Just before the 2019 rockfall at the Cliets tunnel, geodetic instrumentation of the landslide has made it possible to measure major displacements that were precursors to the rupture (> several tens of cm), to distinguish the terminal acceleration phase (Figure 88) and to make decisions to close the road 24 hours before the rupture (Desrues et al., 2022).

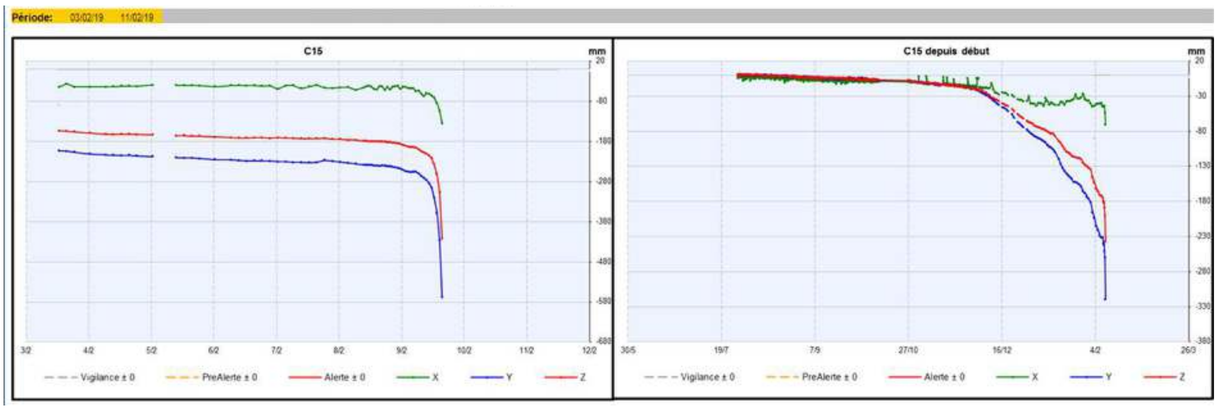


Figure 88 - Acceleration measured prior to the Cliets rockfall failure in February 2019.

Over the last ten years or so, the Savoie department has seen an upsurge in damage to its road network caused by landslides, rockfalls, mudslides and debris flows (see section II). For example, the 100-year flood of May 2, 2015 in the Arly river resulted in the destruction of 400 linear meters of road. Storm Eleanor in January 2018 led to the closure of all access to Savoie's ski resorts for 24 hours, and a more than fifteen-fold increase in the number of events affecting the network in January alone. After the landslide in 2019, the Arly gorges road remained closed for two and a half years. Once again, the floods and landslides of November and December 2023 caused numerous disruptions to the network.

These events lead to increased mobilization of so-called "emergency" budgets, which have risen from around €2m per year on average to €4m since 2014, and even more in exceptional years: €6.8m in 2018 and over €9m in 2015 (CRC, 2022). Insofar as these events are likely to become increasingly recurrent in the future, it is becoming necessary to put in place a perennial organization to meet these challenges. Since 1999, the Savoie department has had a strategy and organization in place to prevent and respond to natural hazards. This strategy is based on a dedicated service that enables the département to identify the natural hazards present on its territory, using specific systems (geographic information system, annual observatory) and to take emergency action as soon as a risk occurs. Steps have also been taken to adapt to climate change (pooling of personnel in the event of crises, establishment of traffic management plans, etc.).

The local authority takes care of its roads, which are economic players: 40% of the Savoie department's investment budget is devoted to road maintenance and safety (France Bleu Pays de Savoie, 2021). Compared with Haute-Savoie, that's four times more. There are a thousand more retaining walls than in Haute-Savoie. The ski industry uses these roads. The Gorges de l'Arly road is nicknamed ‘the most expensive road in France’. It is a strategic route. Up to 10,000 vehicles a day during the ski season and 6,000 in normal times. Since 2006, when the département took over management of the road, €26m of work has been carried out to make the RD1212 road safer from rockfalls in the Arly gorges, with the digging of a new 240-metre tunnel, the creation of a 32-metre span bridge and the securing of seven cliffs. The renovation of the RD1212 accounts for one-sixth of the department's road policy budget: €60 million has been sunk into the 13 kilometres since 2006, without any real political opposition.

While these various initiatives are a response to the current consequences of climatic events, the Auvergne-Rhône-Alpes Regional Chamber of Accounts considers that long-term thinking and a more ambitious overall strategy are still lacking, given the prospects for a worsening of the phenomena observed (CRC, 2022). It therefore recommends adopting a strategy to deal with the consequences of climate change on the road network, taking into account technical and budgetary aspects, as well as the conditions for economic development in the region, and including consideration of ski resorts.

Departmental solidarity: Following storm Eleanor, the Savoie department set up a funding committee bringing together local authorities and government departments to help support the areas affected. Following the events of November-December 2023, the Département of Savoie once again mobilised its Exceptional Erosion Risk Fund (FREE) to provide financial support to the areas hardest hit (Gaymard, 2023).

b) (Potential) future risk management measures

MIROIR project recommendations

Some ideas for the future management of the Gorges de l'Arly (Equilbey, 2023):

- In the immediate future, remain vigilant over the whole of the Arly valley at the level of the Gorges in order to detect as soon as possible any area of slope in the early stages of landslide reactivation and react accordingly.
- As a recommended preventive action, to better anticipate any potentially complicated crisis management, limited monitoring over a few years of the Cohennoz landslide, not necessarily immediately (budget to be mobilised).
- Continue the reflections, especially by adding the torrential risk component initially planned. A small socio-economic component to assess the foreseeable direct and indirect costs would be potentially useful to move towards a management approach that is at least cost/benefit oriented.

- Develop a risk awareness culture and make local residents who use the slopes the primary players in prevention.

The local feedback meeting for the MIROIR project on the Arly, organized with the help and support of the SMBVA and Ugine town council, on 28th September 2023 in Ugine, provided an opportunity to discuss with local stakeholders the possible courses of action proposed in the light of the results presented by the MIROIR project. Two main types of action were envisaged (BRGM, 2024):

1. Slope monitoring actions, in view of the issues at stake, which could be pooled for shared needs by the Savoie Departmental Council and local partners (communes, Arlysère agglomeration community, even SMBVA), enabling synergies and overall cost control.
2. A complementary study focusing on the torrential risk, which could be consolidated by an economic component downstream, and upstream by an improvement of the scenarios of slope contributions to the river, as part of the actions envisaged in the PAPI program carried out by the SMBVA for the coming years.

Integrated Natural Risk Management approach

In addition to the current flood prevention measures planned as part of the Arly basin PAPI program, the SMBVA team and elected representatives are working on a future Integrated Natural Risk Management (INRM) action program, with the help of the PARN (Alpine Institute on natural Risks), to deploy a global multi-risk strategy (Einhorn et al., 2019), as part of the ERDF “Massif des Alpes” programme for 2021-2027 (Figure 89).

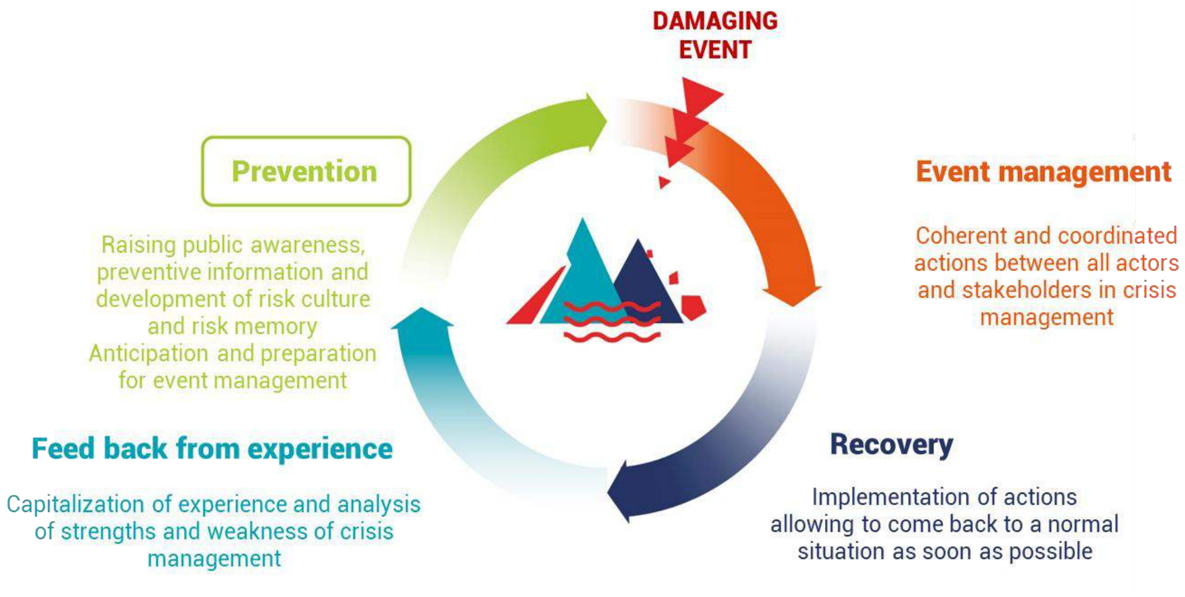


Figure 89 - The Integrated Natural Risk Management cycle (INRM, 2020).

This kind of action program will enable the SMBVA territory to benefit from the inputs of the INRM Alpine Territory network coordinated by the PARN, which has been pooling experience and skills in integrated mountain natural risk management in the French Alps since 2009 (Figure 90).

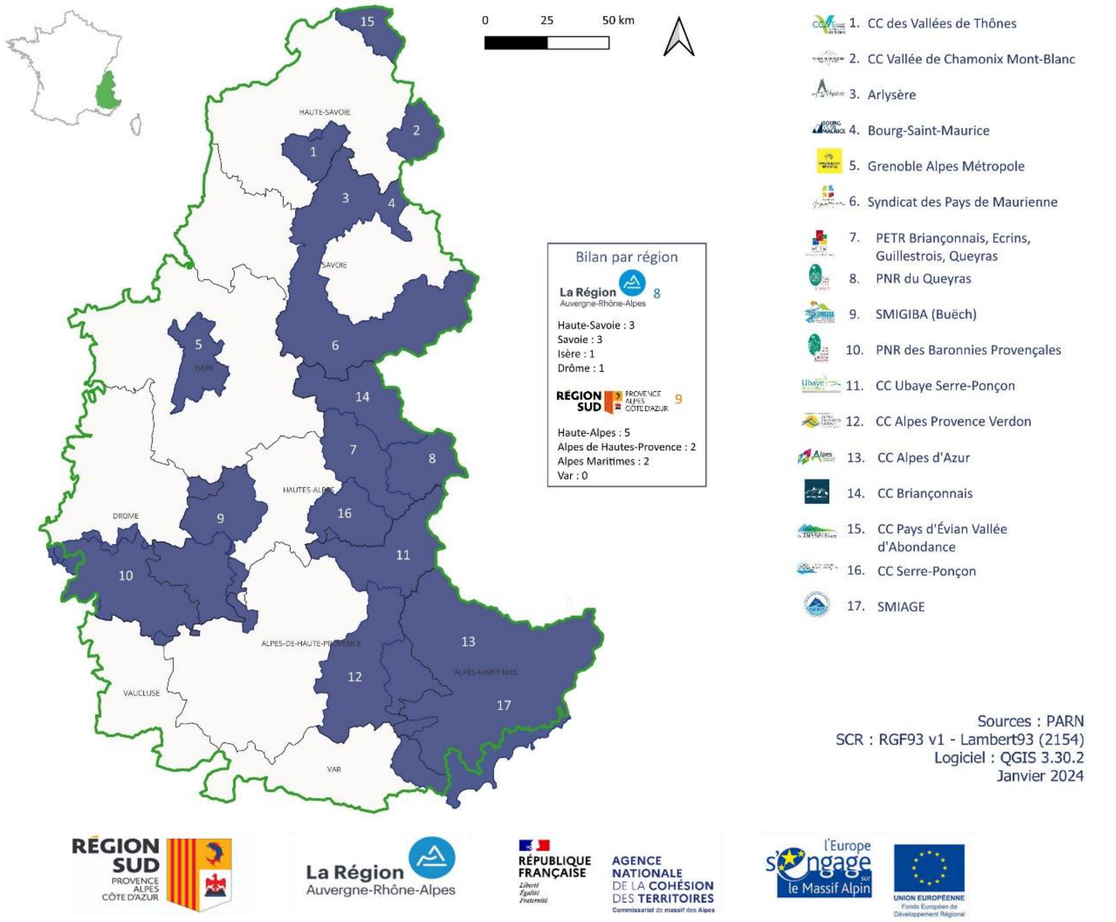


Figure 90 – Alpine territories programs of Integrated Natural Risk Management (INRM) since 2009 in the French Alps funded with ERDF-Alpes, French State, Auvergne-Rhône-Alpes and Provence-Alpes-Côte d'Azur Regions. Mapping: PARN.

X-RISK-CC project

As part of the X-RISK-CC project, a first workshop with stakeholders from the Arly basin was held in Ugine on 6 February 2024. A rapid assessment of the existing natural risk management system was carried out collectively using the Rapid Risk Management Appraisal (RRMA) method (Figure 91). This revealed a major need for dialogue between stakeholders, from the prefectural authorities to the general public, in order to take effective action and assume responsibility at different levels.

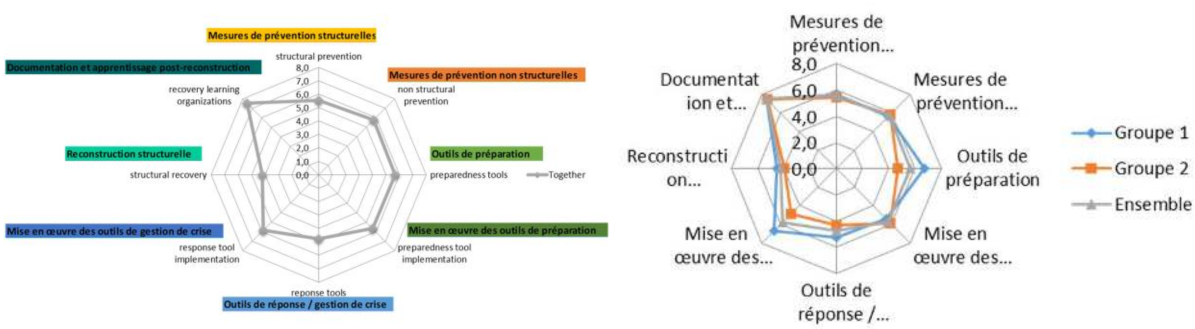


Figure 91 - Collective rapid assessment of the natural risk management system in place by local stakeholders at the February 6, 2024 workshop in Ugine, based on the X-Risk-CC project questionnaire (AURA-EE, 2024).

On the basis of feedback from storm Eleanor in 2018, and more broadly from recent flooding events in the autumn 2023, the participants made a number of recommendations that they can continue to explore (AURA-EE, 2024):

- Bringing the local flood protection plan to life.
- Capitalise on successful experiences.
- Work with residents.
- Facilitate contact between elected representatives and residents.
- Capitalise on the memory of the elderly.
- Facilitate responsiveness and the assumption of local responsibility, which procedures can sometimes slow down.
- Building skills and trust together.
- Capitalise on successful experiences.
- Organise a ‘climate risk’ citizens' reserve.
- Develop tools and a new representation of risks.
- Identify the risks associated with man and his actions.
- Finding the right way to maintain watercourses while respecting the riverbed.

VII. How does the simultaneous (or within a short time) occurrence and/or overlapping of hazard areas influence exposure and vulnerability?

a) Current impacts of compound/cascading hazard events

b) Potential future impacts of compound/cascading hazard events

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Appendix B

Climate Risk Storylines

1. Gorenjska, Slovenia

X-RISK-CC Climate Risk Storyline – Gorenjska / Sora catchment (SI) - Drought

In the year 2040....

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Sora river catchment in Gorenjska (municipalities of Škofja Loka, Gorenja vas – Poljane, Žiri, Železniki) Temporal setting: summer 2040 Intended purpose: Preparation for the worst/most extreme possible scenario of weather/hydrological events and their compounded consequences, considering current risk management practices and climate projections for the future ("stress testing").
General climate situation (normal conditions in year 2040)	Gorenjska is in a warmer climate, with average temperatures now 1°C higher compared to the early 21st century. In lowland areas, new temperature records of up to 40°C have been recorded. Mountainous and hilly areas remain relatively cool, although temperatures there have also increased in all seasons compared to the past. Winters are becoming mild and wet across the region, with more rain and less snow. The precipitation regime is highly variable, marked by drought periods that can last for several months, interrupted by intense rainfall events. Drought conditions occur in all seasons, including spring and autumn, and are frequently accompanied by heatwaves during the summer. Overall, droughts and heatwaves are becoming more frequent and intense, as is the combination of both events. There has been a notable increase in the number of dry months during the growing season, when plants have an elevated demand for water.
General effects of climate change	Climate change impacts the reduction of snow cover and precipitation, leading to a decline in aquifer recharge and river and lake flow rates, which threatens the supply of drinking water. Prolonged droughts and heatwaves accelerate soil erosion and degradation, destabilizing ecosystems, particularly in arid regions. Forests are especially vulnerable to heat, drought, and pests, increasing the risk of erosion, landslides, and wildfires. Changes in temperature and precipitation disrupt ecosystem balance, causing species extinction, the spread of invasive species (such as bark beetles), and negatively affecting agriculture and human health. Shorter but more intense rainfall periods result in more frequent floods, especially flash floods, erosion, and landslides. Stronger winds lead to more frequent windthrows, which further exacerbate erosion on slopes where the protective function of forests is weakened by other factors.
General non-climatic situation / non-climatic risk drivers	The population has remained at a similar level to that of 2025, with a slight increase and a pronounced aging trend. People continue to move from smaller settlements to larger ones and from higher to lower altitudes. In higher-altitude settlements, the population is predominantly older. The number of agricultural holdings in the area has slightly declined, but efforts are being made to maintain their numbers through various strategies. The area of agricultural land has remained roughly the same, but extreme weather events now

	cause greater economic damage than two decades ago. In livestock farming, some holdings are still oriented towards grazing, but they face challenges such as water shortages for livestock. A portion of the population still relies on drinking water from smaller water sources, which are more vulnerable to drought, particularly in higher-altitude areas. As a result, interruptions in water supply have become more frequent, requiring more water deliveries, especially to higher-altitude settlements. Drought periods can also lead to poorer drinking water quality, potentially affecting the health of both people and animals. Water scarcity could become a severe issue in the event of wildfires. Drought and high temperatures increase the risk of spreading plant and animal diseases, greater pest presence, and the proliferation of invasive species. Tourism has also undergone changes. In lower areas, the impact is negative during summer due to higher temperatures and drought, while in higher-altitude areas, cooler temperatures have a positive effect. Nevertheless, water saving remains a challenge, as many tourists are unaware of the seriousness of the situation. Tourism is mainly focused on hiking, cycling, and spending time along riverbanks. Due to reduced snow levels and higher temperatures, the ski resorts of Soriška Planina and Stari Vrh no longer operate in winter, as they cannot maintain conditions for winter activities. This has significantly affected winter tourism, which has had to adapt by developing alternative activities. Heatwaves can also damage infrastructure, including roads, railways, bridges, and energy networks.
Meteorological event	During the winter of 2039/2040, there was less snowfall, which impacted groundwater recharge. Spring precipitation could not fully compensate for the prior water deficit, resulting in moderately to severely dry conditions in groundwater aquifers as early as spring. Due to lower precipitation levels at the start of spring, moderately dry conditions were also observed in the surface soil layer. From May to July, large parts of Europe experienced high mid-tropospheric air pressure anomalies, particularly in western, southern, and central Europe. These relatively stationary atmospheric circulation patterns are typically associated with summer heatwaves and droughts in Europe, as they block or redirect traveling cyclones that usually bring cool and moist air. Prolonged high-pressure conditions persisted from late spring to late summer, exacerbating the already existing drought, as precipitation deficits had been apparent since the winter of 2039/2040. The first heatwave occurred at the end of May, followed by three more heatwaves by the end of July. Temperatures in lowland areas exceeded 40°C, and multiple tropical nights were recorded, as the heat showed no respite. Dry conditions intensified from mid-June onward. Between June 15 and July 31, 2040, only 10% of the usual precipitation fell (compared to the 1990–2020 reference period), while daily evaporation exceeded 6 liters of water per square meter. The water balance deficit in the surface soil layer grew, river water levels dropped, and groundwater levels fell to critical thresholds. Occasional summer storms occurred but did not significantly improve soil moisture due to rapid water runoff and the reduced infiltration capacity of the dry soil. By the end of July, extreme drought conditions were evident across all components of the water cycle.

Event – hazards	The lack of snow in the mountains, prolonged drought, high temperatures, and heatwaves contribute to reduced river flows and groundwater recharge, posing a risk to drinking water supply. Multi-month droughts combined with heat lead to extremely high fire risk and the potential for large-scale forest fires, especially in areas where water resources are smaller and more vulnerable to drought. With reduced availability of drinking water resources, there is a risk of water shortages for firefighting. Large-scale fires degrade air quality due to particulate matter in the air, posing health risks to people. Drought and heat reduce plants' resistance to various diseases. In areas with a significant proportion of spruce trees, there is a high risk of rapid bark beetle infestations, which can devastate large, forested areas. This leaves slopes more susceptible to erosion, particularly during intense rainfall, which was more frequent in 2040 (increasing the risk of landslides). Sudden downpours following drought periods exacerbate flooding risks, as dry and compacted soil absorbs water less effectively, leading to greater consequences from floods. Dried-out soils, loss of vegetation, and weakened or damaged forests—whether due to snow, windthrow, or forest fires—result in increased erosion and sediment transport, which burden river systems and heighten flood risks. Additionally, drought weakens tree root systems, making trees more prone to falling during windstorms or heavy rainfall. Bark beetle infestations further contribute to forest degradation. Drought and heat lead to reduced agricultural yields, limit the use of drinking water, and cause water shortages, impacting the health of humans and animals while disrupting ecosystem balance. In terms of water supply, the impact of drought is most strongly felt in higher-altitude areas, where residents rely on smaller local water sources. Following prolonged drought, the potential for multi-day heavy rains poses a significant risk, as they can lead to floods and landslides. The consequences of such events can be catastrophic due to the factors mentioned above.
Event – impacts	**Water Supply Challenges:** Smaller local water sources in higher-altitude areas do not provide enough water for the population's supply. As a result, numerous additional water deliveries are needed, particularly for residents in higher-altitude settlements (e.g., in July and August, there were 41 water deliveries to Breznica pri Žireh and 25 to Žirovski vrh). Reduced water quantities in aquifers also affect drinking water quality, and in several settlements, water must be boiled before consumption. Instructions for water conservation are becoming increasingly common for all water users in all four municipalities. There is a ban on washing cars and filling swimming pools. **Agriculture:** The effects of drought are evident in reduced crop yields, threatening food security and economic activities. Crops most affected include corn, vegetables, and grasslands. In areas without irrigation, signs of drought stress have appeared, especially on shallow and gravelly soils. This drought stress is compounded by severe heat stress. High air temperatures have caused scorching, most noticeable in low grass cuts. The heatwave has also increased risks for livestock on pastures, which are facing water shortages, leading to reduced milk production. Heat and

	drought stress have affected both cultivated and wild plants, manifesting in plant wilting, disrupted growth and development, yellowing and leaf loss, premature ripening, scorching, shortened growth phases, or even plant death. Air temperatures above 35°C are expected to result in a poorer wheat harvest, as late wheat varieties have undergone forced ripening. Drought conditions in some affected areas have significantly reduced corn yields (corn growth has stalled, with less foliage and smaller, lighter corncobs). Grass cuts were lower than in previous years, forcing some farmers to reduce livestock numbers. Water shortages and high temperatures have also impacted vineyards. Farmers who planted permanent crops this year and lack irrigation have found themselves in a difficult position, with young trees drying out in some areas. The increased need for irrigation due to drought in agriculture has created conflicts over water usage, as restrictions on drinking water supply remain in place. **Forests:** The consequences of drought in forests are reflected in reduced tree growth. A lack of rainfall is also evident in forest trees, causing premature yellowing and leaf death. Weak forests are more susceptible to pests, such as bark beetles, which have spread in the Polhov Gradec Hills. Due to dried vegetation in forests, the fire risk is high. A large forest fire broke out in the Žirovski Vrh area. Water restrictions during this time created challenges in delivering water for firefighting. Difficult-to-access terrain further complicated firefighting efforts. **Tourism:** Water shortages are also felt in tourism, where additional restrictions on water use are in place. Tourism activity decreases during heatwaves, with high temperatures leading to canceled bookings in Škofja Loka. Despite the low water levels, swimmers seek relief in the Sora River. Increasingly, visitors prefer easily accessible higher-altitude areas due to slightly cooler temperatures. **Health Impacts:** High air temperatures negatively impact the health of both humans and animals. High temperatures cause overheating and dehydration in people. Health centers report an increase in emergency transports due to heatstroke. Vulnerable groups, including the elderly, pregnant women, children, and those with chronic illnesses, are most affected.
Post-event (post emergency)	The long-term effects of drought are reflected in reduced annual forest growth. Biodiversity and the protective functions of forests diminish, potentially leading to increased erosion. High temperatures have caused damage to infrastructure, particularly roads, railways, and bridges. In the economy, the impacts are seen in reduced agricultural production, higher costs of water and energy supply, and a decline in tourism activity in affected areas. Agricultural product prices increase. Additionally, long-term soil degradation due to erosion and water scarcity reduces soil fertility, which has lasting/long-term implications for food security. After a drought period, it takes time for natural conditions to return to their previous state. Temperatures decrease, and rainfall increases gradually, allowing for water replenishment. Often, there are no comprehensive plans to improve existing systems, leading to the restoration of outdated, inefficient solutions instead of implementing long-term measures to enhance resilience to future droughts. Water shortages can cause conflicts among various water users, such as drinking water supply, agricultural irrigation, industrial use, and the needs of firefighters during drought periods. These challenges highlight the need for sustainable planning and inclusive policies for recovery.

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X-RISK-CC Climate Risk Storyline – Gorenjska, Sora catchment (SI) - Flooding

In the year 2040…

Scope	Geographical setting: Sora river catchment in Gorenjska (municipalities of Škofja Loka, Gorenja vas-Poljane, Žiri and Železniki) Temporal setting: August 2040 Intended purpose: Stress testing and appraisal of risk management for extreme flooding events and compound impacts.
General climate situation (normal conditions in year 2040)	Gorenjska is in a warmer climate with an average temperature increase of 1 °C compared to the early 21st century. New temperature records of up to 40 °C have been recorded in lowland areas. Mountain regions are still relatively cool, even though winter and summer temperatures are higher than in the past. Winters are getting mild and wet throughout the region with more rain and less snow. Precipitation regime is highly variable with dry periods up to several months interrupted by intense precipitation events. Extreme precipitation events in the region are more intense and frequent than in the past, especially in spring and winter with accumulated daily amounts exceeding 220 mm/day. Precipitation in summer shows a greater variability with dry periods, often in combination with heatwave conditions, interrupted by intense short-duration precipitation events. Precipitation in late summer and autumn can be occasionally very intense and persist for several days, mainly driven by warm and moist southerly flows. During these events, 3-day precipitation totals can locally exceed 300 mm in Gorenjska.
General effects of climate change	Shorter but more intense rainfall periods cause more frequent flooding (particularly flash floods), erosion, and landslides. Stronger winds lead to more frequent windthrow events, exacerbating erosion on slopes where forest protection functions are already weakened by other factors. Climate change reduces snow cover and overall precipitation, worsening aquifer recharge and river and lake flows, threatening drinking water supplies. Prolonged drought and heatwaves accelerate soil erosion and degradation, destabilizing ecosystems, especially in arid areas. Forests are particularly vulnerable to heat, drought, and pests, increasing the risk of erosion, landslides, and wildfires. Changes in temperature and precipitation disrupt ecosystem balance, causing species extinctions, the spread of invasive species (e.g., bark beetles), and negatively affecting agriculture and health.
General non-climatic situation / non-climatic risk drivers	The population in the region has not significantly increased in the last 15 years, but the demographic structure in higher-altitude villages has shifted. Most residents there are aged 80 or older, making evacuation challenging due to reduced mobility. There are fewer active volunteers in Civil Protection and firefighting organizations. Škofja Loka has seen the most significant population growth. By 2040, it has become more urbanized, serving as an important centre for the Sora River catchment area with higher number of educational institutions and services. A larger urban area has more impermeable surfaces than before, increasing the water runoff and the

	potential for urban flooding. Some drainage systems are outdated and poorly maintained. Tourism is one of the main economic activities in the Sora River catchment area, especially in higher-altitudes. Winter tourism has declined due to lack of snow, while other tourism offerings in other seasons have expanded. Some of the new touristic infrastructure has been built in the landslide-prone areas. The number of farms has not decreased significantly, and the agricultural area has remained stable. However, the total area of agricultural and forestry land affected by extreme weather and hydrological events has increased, which has led to greater economic damage. Škofja Loka has a railway station on the Ljubljana-Kranj route. The railway connects Škofja Loka also to Jože Pučnik Airport, which is of great economic importance for the area. Flood protection in Železniki, built against 100-year floods (including the "Pod Sušo" reservoir, sediment retention measures, and regional bypass road improvements), is now about 15 years old. **Event of 2038** In November 2038, the region experienced an extreme 2-day rainfall event (270 mm/day), concentrated in the northern Sora River catchment (Železniki). Flood protection measures effectively mitigated the impact of flash floods. Some damage occurred to houses and roads upstream of Železniki due to landslides around Zali Log and Davča. Sediment retention structures prevented sediments from being transported downstream, but not all retention structures had been cleared by August 2040. Infrastructure damaged in the 2038 floods, such as roads between Zali Log, Davča, and Železniki, has been only partially repaired by 2040.
Meteorological event	After a dry and unusually warm June, July, and most of August, marked by multiple heatwaves and brief but intense rainfall events, Gorenjska was hit by a multi-day extreme rainfall event on August 27, 2040. Synoptic situation: A low-pressure system with a weather front developed over Central Europe. Warm, moist air from the heated Mediterranean flowed into the region from the south, and due to unstable air masses and orography triggered intense convective rainfall over the Alpine-Dinaric barrier. In the Poljanska Sora catchment, near Gorenja Vas, 250 mm of rain fell in the first 24 hours, starting in the early afternoon. The following day, the heaviest rain shifted to the northern basin, over the Selška Sora. Less intense rainfall continued evenly across the Sora Basin for a third day. Over three days, local precipitation totals reached 370 mm.
Event – Hazards	Due to intense rainfall, and critical underlying conditions (extremely dry soil, unemptied sediment retention structures, forest debris, urban impermeable surfaces in Škofja Loka, and landslides from 2038, which haven't been remediated), the rainfall triggers flash floods and sediment erosion. Poor infiltration leads to most rainwater immediately running off into river channels. Woody debris from forests and other floating materials jam river channels, causing flooding. First-day flash floods in Poljanska Sora deposit large amount of debris on the main road between Škofja Loka and Gorenja Vas, limiting access to some villages.

	Landslides require the evacuation of residents and because of many elderly residents with health issues, the process is delayed into the night. As rain moves northward, further evacuations are needed, including foreign tourists who are unfamiliar with local warnings. Second-day rain triggers more landslides, notably unremediated ones around Davča and Zali Log. The flood protection measures in Železniki significantly limit damage downstream of the Pod Sušo retention reservoir. However, rivers overflowed at certain sediment retention structures and dams that had not been maintained since the floods two years prior (e.g., in Češnjica). The main road between Železniki and Škofja Loka remains undamaged but requires monitoring over the next 48 hours. On the second day in Škofja Loka, flooding occurs also at the confluence of the two Sora rivers, near the Fishermen's Club in Puštal. After three days of rainfall, the overwhelmed drainage channels cause runoff water to flood the basements of buildings on Sorška Cesta, as well as facilities at the Škofja Loka Secondary School Center and High School, as well as the Poden Sports Hall.
Event – impacts	Tourists and local residents have to be evacuated from Dolenje and Gorenje Brdo, Davča, and the surrounding areas. Houses were damaged by floods and landslides. Access to drinking water is limited. A two-day power outage affects a large area around Gorenja Vas and Žiri, causing consequent problems for cooking, access to houses with “smart” doors, gates, roller blinds, cooling for food in supermarkets etc. Businesses, including shops, hotels, and restaurants, are unable to operate. Mobile networks are unstable, and emergency lines are overloaded on the first and second day of the event.
Post-event (post emergency)	The effects of this event last for months or years, requiring extensive repair of buildings, roads, and bridges throughout the Sora River catchment. Landslides cause severe erosion on already affected slopes, further destabilizing them and destroying areas of protective forests. Sediments accumulated at critical points increase the risk of future flood events. The population becomes deeply concerned about the future. The tourism sector is heavily impacted, suffering significant economic losses due to direct damage to infrastructure and the inability to resume activities until recovery. The agricultural sector is also faced with substantial damage, having already been weakened by prior droughts.

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2. Garmisch-Partenkirchen, Germany

X-RISK-CC Climate Risk Storyline – Garmisch-Partenkirchen (DE)

In the year 2040....

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: region of Garmisch-Partenkirchen in Bavarian Alps, municipality of Garmisch-Partenkirchen Temporal setting: August 2040 Intended purpose: Stress testing and appraisal of risk management for extreme (compound) hydrometeorological events.
General climate situation (normal conditions in year 2040)	The region of Bavaria is in a warmer climate with new temperature records in both summer and winter. Winters are milder and wetter than in the past with more rain and less snow. Summer temperatures frequently exceed 40°C in the city of Munich. The mountainous regions in the Bavarian Alps are still relatively cool with summer temperatures not exceeding 35°C in the side valleys. However, summer temperatures are continuously increasing and seldomly fall below 0 °C also at the highest elevations (Zugspitze) of the region. Precipitation shows high variability. Drought episodes can last up to several months and are often interrupted by intense rainfall events. In particular, short duration, extreme precipitation events in the summer- often exceeding 10mm/h[1] - occur more frequently and intense than in the past.
General effects of climate change	Due to warmer conditions, accelerated snow melt, and prolonged dry periods, (especially in summer) are more likely with negative consequences on soil and vegetation. During the drought periods, in combination with heatwaves and favorable wind conditions, wildfires are becoming an emerging hazard throughout the Bavarian Alps. Forests are progressively losing their natural protective function in the region due to a mixture of disturbances (i.e. shift of temperature optimum, burnt areas and bark beetle proliferation) with reduction of water retention and soil-stabilization capacities. More unstable slopes, as a consequence of weakened protection forests, have increased the possibility of mass movements in the region. Landslides, debris flows and flooding, also as cascading processes, are more frequent than in the past as consequence of changed preconditions and the increased frequency and intensity of triggering rainfall.
General non-climatic situation / non-climatic risk drivers	The population of Garmisch-Partenkirchen has shown a moderate increase with respect to 2025, but with a marked decrease of younger people and a significant increase of the elderly (80+) that are more vulnerable, less active and less mobile (for evacuation, voluntary organizations, ...). Overall tourism numbers in Garmisch-Partenkirchen have been increasing steadily in the summer season, since more southern holiday destinations have become too hot. The share of international visitors has also increased. As a reaction to increasing visitor numbers, admission to the Partnach Gorge has been limited.

[1] See WP1 pilot reports for Wipptal/Stubaital and Garmisch – analysis of future sub-daily precipitation considering the Global Warming Level of + 2 °C (GWL2)

	The completion of the two bypass tunnels, Kramertunnel and Wanktunnel, helped to significantly reduce transit vehicles in the urban center of Garmisch-Partenkirchen. To boost public transport, the train connections to and from Garmisch (in the direction of Munich and Innsbruck) run more frequently and are in high demand. A driftwood rake has been installed upstream of the Ferchenbach/Partnach confluence and has been effective in preventing driftwood from entering the gorge from the Ferchenbach. However, the effort for removing debris and sediment that deposits upstream of the Partnach Gorge (also to maintain the function of the rake) has increased in recent years due to instable slopes along Ferchenbach, moderate increase of debris yield in the upper Reintal, and additional debris availability after a recent wildfire.
Event – meteorological event	After a dry spring, summer 2040 is warmer than average with persistent drought conditions. During July, several convective rainfall events of moderate intensity were registered with precipitation reaching 50mm/day[2] in some locations of the Garmisch-Partenkirchen region. In the middle of August, a cutoff low system (Vb Wetterlage, synoptic situation) develops over the Alps causing a series of very intense precipitation phenomena in the area for several days with values exceeding 150mm per day[3] During the rainfall episodes, wind gusts locally up to 100 km/h are also recorded.
Event – hazards	The large-scale, intense rainfall and the critical initial conditions (high soil saturation due to previous rainfall, weakened protective forest/tree cover, large quantities of loose material) trigger moderate flooding along the rivers in the region, including Kanker, Ferchenbach, and Partnach. The bypass channel is activated to relieve the Kanker channel by diverting a share of the Kanker discharge into the Partnach. Landslides occur on steep slopes with no or damaged forest cover. The large amount of sediment and additional wood is transported into the Partnach Gorge by the Partnach and Ferchenbach streams. A blockage of approx. 8 m height occurs at the narrowest part of the southern portal of the Partnach Gorge. As a result, a temporary lake forms with a volume of approx. 100.000 m^3 reaching all the way to the Ferchenbach/Partnach confluence. The dam breaks after approx. 1 hour and the entire debris-laden water discharges through the Partnach Gorge within 30-45 minutes, while the highest discharge coincides with the first dam-break wave. Downstream of the Gorge, the wave dissipates and loses depth, however, still exceeding the HW extreme (as per official Flood maps). Over the next 2 km, flooding occurs at bridges and other transverse structures (e.g. weirs) that block or divert the flow. The transformer station Garmisch Ost is affected by the flooding.
Event – impacts	Before the floodwave: - The bypass channel is activated to relieve the Kanker channel by diverting a share of the Kanker discharge into the Partnach. Due to weather warnings by DWD and increased discharge along the Partnach, the Gorge is closed to visitors. Several people are reported to be located in Reintal on their way to Garmisch-Partenkirchen.

[2] Based on the projected changes in summer maxima of 1-day precipitation in the station sites in Garmisch-Partenkirchen under GWL2.
[3] A 100-year event in the year 2040 based on the projected changes in the station sites in Garmisch-Partenkirchen under GWL2.

	After the floodwave: - The rain event as well as the temporary lake cause damages to slopes and paths upstream of the Partnach Gorge. - Inside the Gorge, the debris-laden flow demonstrates enough force to move boulders up to 5 m in the Gorge and erode the rock wall (locally up to 10 cm). The railings and paths are damaged and blocked with driftwood. - Downstream of the Gorge, the wooden bridge is completely washed away, cutting of access to the Gorge. Flooding at the Bridge “Wildenauer Str.” at crossing “Hohen Weg/Partnach Alm” impacts the transformer station, leading to power-outage in Garmisch-Partenkirchen. Wildernauer Str. is closed due to debris blocking the road. - Large amount of debris are deposited immediately upstream of the train line impacting the outlet of the Kanker bypass. The train line cannot be operated. Downstream flooding occurs mainly to the right between Silberackersteg and Kanker confluence. There is little time to evacuate. Basements and ground floors are damaged by debris-laden water. Up to the Loisach confluence bank protections are damaged and some transverse structures completely destroyed. In some areas, the Partnach bed was deepened by up to 1 m, in other areas bed load deposits up to 2 m high were formed.
Post-event (post emergency)	Upstream of Gorge: - Reconstruction of slopes and paths takes several months. Partnach Gorge: - The structural integrity of some of the paths inside the gorge need to be evaluated. Removing of debris and wood, and the reconstruction of wooden bridge, slopes and paths inside the gorge take several months. The gorge remains closed for this time. The lack of accessibility severely impacts businesses around the gorge (huts, restaurants, Graseckbahn). Garmisch Partenkirchen: - Direct damages mainly affect private properties, the transformer station, the sawmill and businesses along the Wildenau. Cleaning up after the flood takes multiple weeks/months. - The train line cannot be operated until the debris deposition is removed. The transformer station needs to be repaired as soon as possible. - Flood protection standards along the Partnach cannot be ensured as long as damages along bank protection and transverse structures remain.

3. Stubaital, Austria

X-RISK-CC Climate Risk Storyline – Stubaital (AT)

In the year 2040….

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Vorderes Wipptal/Stubaital in Tyrol and its side valleys (especially the municipalities of Mieders, Fulpmes and Neustift). Temporal setting: from July 2040 (event) to December 2045 (long-term consequences/recovery phase). Intended purpose: Stress testing and appraisal of risk management for extreme (compound) hydrometeorological events.
General climate situation (normal conditions in year 2040)	In 2040, Tyrol will find itself in a warmer climate. New temperature records of over 40°C are measured in Innsbruck, while the mountain regions such as the Stubaital still remain relatively cool. In the side valleys, summer temperatures do not rise above 35°C. Winters are increasingly mild and wet, with more rain and less snow. Summers become warmer and temperatures at altitudes above 3000 m often no longer fall below 0°C. Precipitation is highly variable: dry periods lasting several months alternate with intense rainfall events. Thunderstorms in summer occur frequently and with intense rainfall (over 10 mm/hour[1]). Autumn regularly brings stormy and rainy weather, which increasingly overcomes the main Alpine ridge in short intervals in frequency and duration due to the warm Mediterranean ("Genoa low").
General effects of climate change	Glacier retreat and melting of permafrost above 2500m lead to higher mobilizability of material and to decreasing slope stability at these altitudes. Due to the increasing intensity and frequency of thunderstorms, some alpine catchments are more active than in 2025, which also increases the occurrence of flash floods and debris flows.
General non-climatic situation / non-climatic risk drivers	Since 2025, tourism in Tyrol has been steadily increasing, especially summer tourism and summer retreats from the Inn Valley, as classic summer destinations (such as the Mediterranean) have become too hot and more distant destinations appear too expensive and unsafe. Despite plans to limit soil sealing, the tourist infrastructure (hotels, parking lots, new campsites) has expanded considerably and roads have been widened to cope with the high volume of traffic. Some of the new buildings are located in areas previously classified as yellow zones or near red zones. Forests continue to be affected by climate-related problems (drought, bark beetles) and the protective forest function in Tyrol has declined by around 20 %. Forest fires are seen as an increasing risk, which is exacerbated by the succession of dry years. The number of inhabitants has increased only moderately compared to 2025, but there is a marked decrease in the younger population and a significant increase in the older population (80+), who are more vulnerable, less active and less mobile (for evacuations, voluntary organizations, etc.). The number of volunteers in aid organizations is also decreasing. As both tourists and the local population are becoming increasingly international, risk communication and the exchange of a common risk culture is becoming more and more of a challenge.

[1] See WP1 pilot reports for Wipptal/Stubaital and Garmisch – analysis of future sub-daily precipitation considering the Global Warming Level of + 2 °C (GWL2)

Event – meteorological event	After a dry spring and a warmer than average beginning of summer, July was hot and humid. A low pressure system developed over Central Europe and led to a series of rainfalls with local precipitation of up to 50 mm per day[2], in the middle of July. Geosphere Austria has issued an orange warning for western Austria due to an impending Vb-like weather situation. The heaviest precipitation is expected in the central Tyrolean region. On 20st July, the warning is changed to red for the Wipptal, Stubaital and Sellrain areas during the course of the day. Precipitation totals in the region of 300 mm in 48 hours are expected. On July 21th it will start to rain intensively in the northern Wipptal, Stubaital and Sellrain areas. Convective showers will occur locally, with very high intensities of over 30 mm/h in small areas, up to 150 mm per day[3] and a total of 400 mm in three days[4]. In addition, strong winds with gusts of up to 100 km/h will affect the region.
Event – hazards	The intensive precipitation and the critical initial conditions (high soil saturation due to previous precipitation, weakened protective forest, high quantities of mobilizable material) not only trigger debris flows in torrents, but also landslides on steep slopes without or with damaged protective forest. The large amount of material (sediment, debris, soil) and wood (trees toppled by strong gusts of wind) is transported by the torrents into the main valley (sometimes also into the receiving waters). The Brenner highway and the Brenner federal highway are closed in both directions due to several landslides and mudslides. The Stubaital is therefore inaccessible (except via the streetcar that runs to Telfes). In Mieders, the municipal road is blocked due to a mudslide on the Klaushofbach. A bridge on the Zrikenbach stream is destroyed and therefore the municipal road is also closed. The Stubaitalstraße is blocked due to a mudslide on the Griesbach. The center of Fulpmes is only passable with difficulty due to flood and debris deposits. The Stubaitalstraße is also closed due to erosion damage caused by the Ruetz. In the industrial zone, all 3 bridges are closed due to a debris flow on the Margarethenbach. There was also a debris flow at the Höhlebach and therefore the Stubaitalstraße is also blocked in this area. In the Kampl area, the bridge over the Ruetz is impassable due to high water, and further into the valley, a debris flow in the Pinnisbach is shifting the Ruetz and flooding is occurring. In Neustift, the traffic circle at the Bachertalbach stream is closed due to flooding. In Milders, the bridge was destroyed due to fluvial sediment transport on the Oberbergbach. Due to lateral erosion of the Oberbergbach, the connecting road into the Oberbergtal valley is interrupted. A debris flow on the Steinbichelebach causes the bridge to be closed. Further into the valley, the Stubai Valley road is interrupted several times by debris flows from the Grobentalbach, Mischbach and Grawanockbach streams.
Event –impacts	Tourists and local residents are unable to leave the valleys and have to be evacuated. Due to the high season, more than 2000 tourists are affected. Damage to transformers leads to power cuts, which paralyzes the region for

[2] Adaption of WP1 result considering recent heavy precipitation events in Austria, e.g. June 2024 (Bregenz) and September 2024 (Lower Austria).
[3] Adaption of WP1 result (see above)
[4] As happened in Slovenia in August 2023 (Porocilo_visoke_vode_in_poplave_avg2023.pdf (gov.si)) or in Austria in September 2024 (Zahlreiche neue Höchstwerte bei Regenmengen — ZAMG). Period shortened due to reaction time of specific Stubaital torrent catchments.

	two days and causes problems with cooking, access to houses with “smart” doors, gates and blinds, refrigeration in supermarkets, hotels and restaurants. Some buildings and infrastructure outside the hazard zones are also affected. The mobile phone network becomes unstable and emergency call lines are sometimes overloaded. Not all those affected are able to report their emergency situation. Due to the damage to water pipes, the supply of drinking water is not guaranteed in some mountain huts.
Post-event (post emergency)	The effects of this event will last for months and years, as buildings, roads and bridges in the Vordere Wipptal and Stubaital have been damaged. Landslides and erosion have further reduced the stability of some slopes and the remaining debris deposits at critical points increase the risk of future events. The protective forests have also been partially affected. The inaccessibility of the valley and the damage to the infrastructure also resulted in severe economic losses in tourism. Now that the main roads have been cleared and cleaned up, the secondary and forest roads must also be cleared. Destroyed bridges also need to be repaired. The water supply for the mountain huts must also be restored for the winter season. In general, the mood among the population after the event is one of concern/tension, as more events of this kind are to be expected in the future.

4. Wipptal, Italy

X-RISK-CC Climate Risk Storyline – Wipptal (IT)

In the year 2040….

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Upper Eisack / Isarco valley (Wipptal) with its side valleys (Pflersch / Fleres, Ridnaun / Ridanna, Pfitsch / Vizze). Temporal setting: from August 2040 (event) to December 2045 (long-term consequences / recovery phase) Intended purpose: Stress testing and appraisal of risk management for extreme (compound) hydrometeorological events.
General climate situation (normal conditions in year 2040)	South Tyrol is in a warmer climate with new temperature records in the city of Bolzano exceeding 40°C. The mountainous regions such as Wipptal are still relatively cool with summer temperatures not exceeding 35°C in the side valleys. Winters are getting mild and wet with more rain and less snow. Summers are getting warmer and temperatures at high altitudes above 3000m are frequently not falling below 0°C. Precipitation shows high variability with dry periods up to several months interrupted by intense precipitation events. Thunderstorms in summer can get very frequent and intense with precipitation above 10mm/hour[1]. In addition, autumn brings frequently stormy and rainy weather with higher intensity and a longer duration over several days in short sequence, mainly driven by the warm Mediterranean Sea ("Genua-Tief"). [2]
General effects of climate change	Glacier retreat and melting permafrost above 2500m lead to higher amounts of material that can be mobilized and to decreasing slope stability at these altitudes. Due to the increased intensity and frequency of storm events, some mountain basins are more active than the past (2025), thus also the occurrence of flash floods and debris flow has increased.
General non-climatic situation / non-climatic risk drivers	Tourism in South Tyrol has been steadily rising since 2025. Summer tourism in the area has particularly expanded, since the classical summer destinations (e.g. the Mediterranean Sea) have become too hot and remote destinations too expensive and insecure. Despite plans to limit soil sealing, touristic infrastructure (hotels, parking lots, new campsites) has expanded and upgraded with high investments, and the roads have been extended to adapt to the heavy traffic load. Some of the new buildings are in zones classified as blue in the hazard maps or close to red ones. Forest is still strongly affected by climate-related problems (drought, bark-beetle) and the capacity of protection forest decreased by approximately 20% over South Tyrol. Partly, technical measures (rock fences) had to be installed to compensate for a lost protection function. Forest fires are considered an emergent risk, further enhanced by the sequence of dry years. The resident population has shown only a moderate increase in size with respect to 2025, but with a marked decrease of younger people and a significant increase of the elderly (80+) that are more vulnerable, less active and less mobile (for evacuation, voluntary organizations, …). The number of volunteers in response organizations is also decreasing. The fact that tourists and local population are getting more and

[1] See WP1 pilot reports for Wipptal/Stubaital and Garmisch – analysis of future sub-daily precipitation
[2] See WP1 pilot report for Vaia – more frequent GWT 7 gross weather type (Vaia type)

	more international, the language used for risk communication and the sharing of a common risk culture is becoming a challenge.
Event – meteorological event	After a dry spring and warmer than average June and July, August has been rather humid and hot. A low-pressure system developed and persisted over Central Europe leading to a series of rain events, locally up to 50mm per day[3], in the beginning of August. An orange warning is issued by the Civil Protection Agency. On 16th August, a series of intense rain events of convective type, develops and affects also the Wipptal area with very intense phenomena of up to 120mm per day[4] and a total amount of 300mm in three days[5]. In addition, heavy wind with gusts up to 100 km/h is affecting the region.
Event – hazards	Due to the intense rainfall (trigger) and the critical preparatory conditions (high saturation of soils from pre-events) and pre-conditions (poor health of protection forest, high amount of material that can be mobilized) the rainfall triggers not only flash floods in rivers, but also landslides on steep slopes with missing or disturbed protection forest. The high amount of material (sediment, debris, soil) and additional load of wood, partly triggered by falling trees due the heavy wind gusts, is transported by the rivers to the main valley. Specifically, the Kogbach/ rio Covolo produces a debris flow affecting the Pflerscherstrasse and thus isolating part of the fraction of San Antonio and two hotels upstream, which are fully booked, since we are in the high touristic season. Unexpectedly, the Allrissbach / rio Alberes also produces a big debris flow, depositing in the main valley the sediments produced by the glacier retreat and by the complete destruction of the first wooden bridge encountered in its downstream flow. The deposited material causes the blockage of the main road and of the confluence with the Fernerbach / rio Ferner. Consequently, the Fernerbach floods in its left orographic side. The main road and the forestry road (used in winter as sledge track) are damaged and the water intake of the mountain huts upstream is compromised. Downstream, the Toverino river produces a debris-flow event with a 100-year recurrence interval: part of the material is captured by the new protection structures realized after the 2021 debris flow. However, the retention basin cannot contain all the material, which partially floods the main road (Pflerscher strasse). The main road remains closed for two hours for the cleaning operations. At the same time, in Pfitschtal / val di Vizze the Riederbach / rio di Novale produces a debris flow causing the further flooding of the Pfitschbach towards the biotope located on the orographic left. The bridge and the main road are not affected for now, but they must be set under control for the next 24 hours.
Event –impacts	Tourists and local inhabitants cannot leave the valleys and must be evacuated. Due to high season, more than 2000 tourists are affected.

[3] Considering the projected increase of 1-day precipitation maxima under GWL2 with respect to observed average values in 1991-2020 in Wipptal station sites.
[4] A 100-year event in the year 2040, about 10-15% more intense than a 100-year event today at the Fleres station, according to WP1 pilot report for Wipptal/Stubaital.
[5] As happened in Slovenia in August 2023 (Porocilo_visoke_vode_in_poplave_avg2023.pdf (gov.si)) or during Vaia event 2018 in South Tyrol (Pubblicazioni | Meteo | Provincia autonoma di Bolzano - Alto Adige)

	Damages to a transformer house close to the river causes an electric black-out that is affecting the region for two days with consequent problems for cooking, access to houses with “smart” doors, gates, roller blinds, cooling in supermarkets, hotels and restaurants. Some buildings and infrastructure outside hazard zones are also affected. Cell phone network is getting unstable, and the emergency lines are partly overloaded. Not all affected people are able to indicate their emergency. Due to the damage to the water intake, few huts remain without drinkable water.
Post-event (post emergency)	Effects of this event last over the next months and years, with buildings, roads and bridges damaged in three side valleys in the Wipptal region. Furthermore, landslides have led to heavy erosion on already affected slopes and further reduced the slope stability and destroyed further parcels of protection forest. Sediment is accumulated at critical locations that could increase the risk of future flood situations. The population is very concerned about the future. The tourism sector has been heavily affected and had a high economic damage from direct damage to infrastructure but also by the fact that they could not continue with their touristic activities until recovery. After the cleaning operations of the main roads, the secondary and forestry roads remain to clean and new bridges are necessary. Some mountain huts are still without water and cannot open for the winter touristic season.

5. Val d'Ega/Carezza, Italy

X-RISK-CC Climate Risk Storyline – Carezza/Ega Valleys (South Tyrol, IT)

In the year 2040....

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Carezza and Ega Valleys (municipalities of Aldino, Nova Ponente and Nova Levante) Temporal setting: October 2040 Intended purpose: Stress testing and appraisal of risk management for extreme storm events and compound impacts.
General climate situation (normal conditions in year 2040)	South Tyrol is in a warmer climate with new temperature records in the city of Bolzano exceeding 40°C. The mountainous regions such as Carezza and Ega Valleys are still relatively cool with summer temperatures not exceeding 35°C. Summers are getting warmer and temperatures at altitudes above 3000m are frequently not falling below 0°C. Autumns and winters are getting mild and wet with more rain and less snow. Precipitation regime is highly variable with dry periods up to several months interrupted by intense precipitation events. Summer thunderstorms lead to new 1-day rainfall records, while autumn brings frequently storms with precipitation extremes persisting for several days and mainly driven by southerly flow from a warm Mediterranean Sea ("Genua-Tief"). [1] During these events, 3-day precipitation totals usually reach 100mm[2] in the Carezza and Ega Valleys.
General effects of climate change	The evapotranspiration demands have increased favoring the occurrence of drought episodes which are weakening forest ecosystems. Rising temperatures are also altering the optimum growth areas and shifting the temperature optimum for the prevailing tree species (particularly spruce trees) upwards, leaving them more vulnerable at lower altitudes. Exposition to bark beetle outbreaks is rising due to weakened trees, a prolonged vegetation period and an earlier start of the flight season in spring, which enables the production of several bark beetle generations within one year. In winter intense and wet snowfall events frequently lead to damages of forests, especially evergreen trees, due to snow pressure. These disturbances add to the damages caused by some extreme weather events occurred over the last 20 years and still not completely recovered. This results in an overall reduction of the natural protective function in the region (a reduction of ~ 30%[3] with respect to 2018), with loss of water retention and soil-stabilization capacities. Slopes are more unstable due to less protective forests, enhanced permafrost melting and more intense precipitation events thus making mass-movement phenomena more probable than in the past throughout the area and at all altitudes.

[1] See WP1 pilot report for Vaia – more frequent GWT 7 gross weather type (Vaia type)
[2] It is based on the projected changes under Global Warming Level 2 °C (GWL2, WP1 pilot report)
[3] -14% in the region resulting from the Vaia storm and the bark-beetle outbreak (province and EURAC data) and an estimated doubling in the future up to 2040

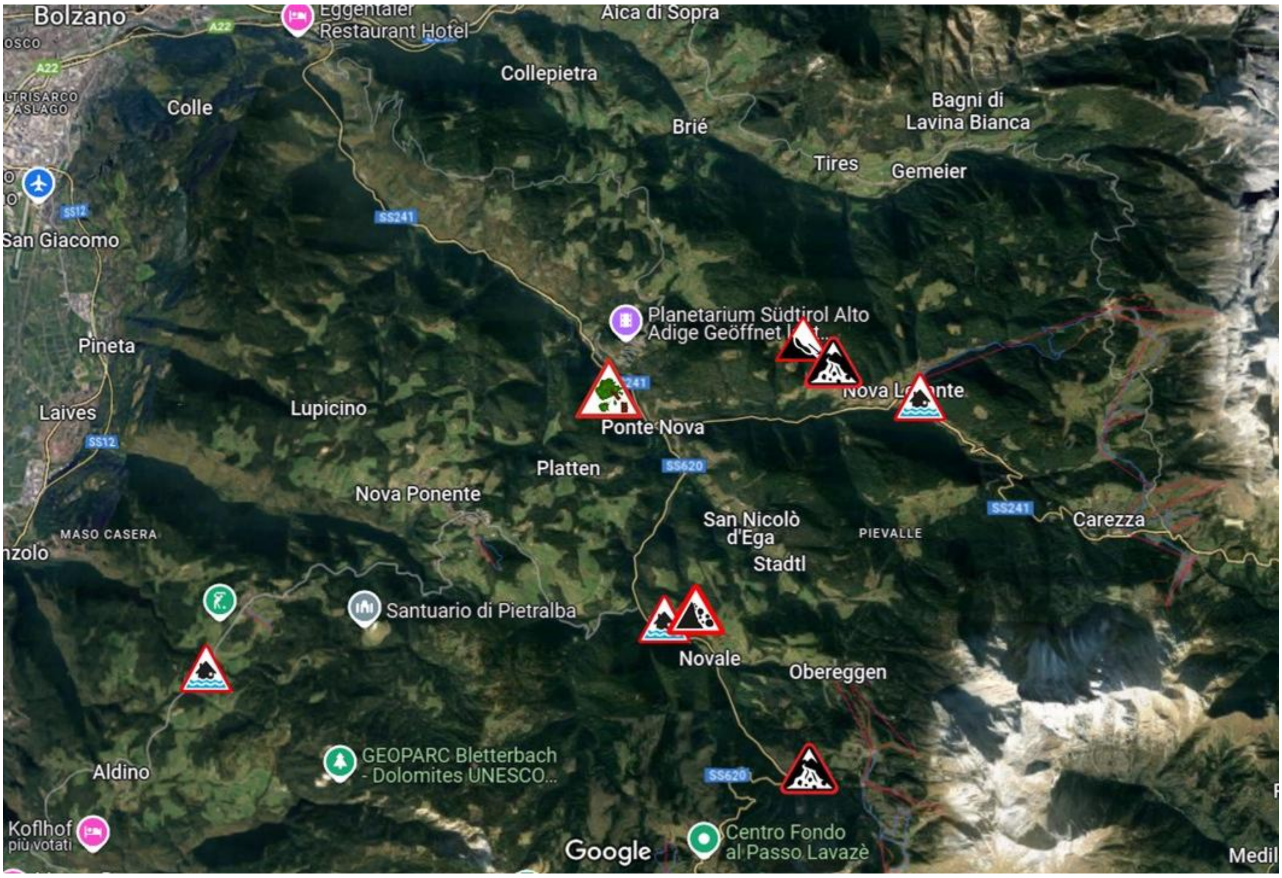
General non-climatic situation / non-climatic risk drivers	The resident population has shown only a moderate increase in size with respect to 2025[4], characterized by a marked increase of elderly (80+)[5]. Therefore, the general population is more vulnerable, less active and less mobile (for evacuation, voluntary organizations, ...). The number of volunteers in response organizations is also decreasing. Tourism in South Tyrol has been steadily rising since 2025. Summer tourism in the area has particularly expanded, since the classical summer destinations (e.g. Mediterranean Sea) have become too hot and remote destinations too expensive and insecure. Furthermore, the touristic season has been extended to include October and often November as these months are cooler and more and more appealing for international tourism. Consequently, the touristic and recreational infrastructure in the valleys remains active until late autumn. Moreover, due to population increase and the continuous touristic expansion, the settlement and infrastructure areas have expanded in the last decades with an increase of the sealed surface. Moreover, due to a lack of alternatives, new buildings and infrastructure have been expanded also in areas previously classified as blue zones in the hazard zone map or in areas close to red zones. Also, the recreational aspect (e.g. cable cars bringing people to otherwise hardly accessible mountain areas) was a driver for these developments. As a very important part of the appeal for leisure activities, the forests are under anthropogenic stress further aggravated by the fact that they are largely private (up to 64%[6])by owners who do not actively invest in resilient forest management, due to a lack of awareness and economic profitability. Reforestation actions, especially after the Vaia event in 2018, have been performed, leading to a mixed age forest. To compensate for the overall reduction of forest protection capacity, new technical measures (e.g. avalanche fences, rock nets) have been installed over large portions of the area. Forest fires are considered an emergent risk, further enhanced by the sequence of dry years, and most municipalities have included them in their hazard zone plans as well as Civil protection plans. The touristic expansion has also given rise to conflicts in land and water use (e.g., agricultural areas vs touristic areas), especially during drought episodes. The fact that tourists and local population are getting more and more international, the language used for risk communication and the sharing of a common risk culture is becoming a challenge.
Event – meteorological event	After a hot and dry summer frequently interrupted by intense thunderstorms, often accompanied by hail episodes, October recorded mild conditions and the persistence of the dry period. In the last days of the month, a low-pressure system develops over Western Europe and causes southerlies from the still warm Mediterranean Sea. This condition leads on 27th October to precipitation totals of exceptional intensity in the southern side of the Alps. Due to the atmospheric blocking caused by the high-pressure system on Eastern Europe,

[4] Statistikatlas (provinz.bz.it)
[5] Statistikatlas (provinz.bz.it)
[6] calculated from Q GIS available provincial data (internally)

	the conditions persist over several days leading to 3-day precipitation totals exceeding 200mm[7] in many parts of South Tyrol. The snow line remains above 3000 m, and precipitation in mid-elevation locations was accompanied by extreme wind gusts with peaks up to 100-150 km/h in the Ega and Carezza Valleys. A similar meteorological event occurred two years before, in autumn 2038, causing relevant damages in the area. Heavy snowfall episodes during winter and the bark-beetle outbreaks in the following summers further affected the forests and slopes in Carezza and Ega Valleys. The Civil Protection Agency preventively declares the civil protection status Alfa (Attention).
Event – hazards	The strong wind gusts cause the windthrown of different forested areas (across all municipalities, as shown in the map). One of the biggest windthrown areas is located along the SS241, north of the village of Birchnabruck/Ponte Nuova. The road is therefore closed for the partial removing of the fallen trees isolating the village from the city of Bozen/Bolzano. Several mass movements, flash floods and debris flow occur simultaneously in a broad area across Bolzano and Trento Provinces and including the municipalities of Ega and Carezza Valleys. One of the most critical situations regards the Zanggenbach /Rio della Pala producing a debris flow on the SS620, south of the village of Novale, causing the road to be closed for hours for the cleaning operations. At the same time, a rockfall occurred north of Novale brings lots of sediments into the Zanggenbach /Rio della Pala making it flood on the SS620, effectively isolating Novale. A landslide also occurs into the Michaelerbach in the village of Welschnofen / Nova Levante producing a debris flow and several rivers reach the limits of the protection structures, therefore requiring special attention e.g., Welschnofnerbach and its tributaries and Petersbergerbach on SP72.
Event –impacts	The blocking of the SS241 and SS620 makes risk management actions and connections outside of the municipalities more difficult. The SS241 remains closed for 4 hours necessary for the cleaning operations, and the village of Novale remains completely isolated for 12 hours. Due to the damages to the water intake, few structures and huts remain without drinkable water. Tourists and local inhabitants cannot leave the valleys and must be evacuated, in some cases with a helicopter. In addition to the local population, due to the still active touristic season, more than 3000 tourists are affected. Due to wind damages as well as overload, the cellphone network is partially out of service, meaning that many impacted people cannot communicate their emergencies. All cable cars were closed due to high winds and some structures and mountain huts remained isolated. Several buildings and infrastructure are damaged by landslides, rockfall and debris flows, specifically the hotel Oberlehenhof in Eggen (LS 76), located in a blue zone, the main roads (SS620, SS241, SP72) in several points and some protection structures reaching their structural capacity limits. The hotel has contacted the emergency services and communicated that there are 30

[7] It corresponds to a 3-day precipitation event with a 100-year return period under GWL2

	people in need of evacuation, of which 2 in need of urgent evacuation and medical assistance. The windthrown area located above the SS241 was a protection forest against rockfall, therefore the existing protection structures, damaged by the fallen trees, have to be repaired immediately and some further measures are needed in the areas without trees. Furthermore, in the 7 hours after the main event, 5 international tourists are reported missing from the regions of Eggen/Ega along the Samweg and Aldino/Aldein direction Schmiederalm. The municipalities declare their civil protection status to Beta 3 hours in and then up to Charlie after 5 hours.
Post-event (post emergency)	The extreme event led to long-lasting consequences across the affected region. Buildings, roads and bridges were damaged and require long restoration times, the occurred landslides have led to heavy erosion on already affected slopes and further reduced the slope stability and sediment is accumulated at critical locations that could increase the risk of future flood situations. The post-event management of the forest areas was characterized by heterogeneous approaches. On former protection areas which are crucial for shielding e.g. settlements, the timely construction of artificial protection structures was necessary in order to guarantee the immediate protection of the most exposed and most frequently visited areas. In other, less immediately important protection areas, not directly relevant for settlement areas, the affected slopes have been left partly unmanaged, following a more nature-based approach which made use of the partly protective function of left-behind trees and tree stumps, combined with increased artificial reforestation efforts to boost the recovery function of the forest and punctually integrate climate-adapted tree species. However, the complex, fragmented ownership structures with small forest parcels in all municipalities complicated respective actions. The visible stumps, felled trees, and undergrowth left behind at the same time contribute to a landscape that is visibly scarred, with significant impacts on the aesthetic value of this touristic region, especially in Nove Ponente and Nova Levante; some tourists show hesitancy in returning to the area, also due to an increased risk perception. The touristic winter season was heavily impaired and could not start as scheduled, as critical ski infrastructure and access roads could not have been fully restored or remain even partly inaccessible, resulting in economic losses for tourism operators and the associated local value chain. The overall risk perception of the local population is heightened, with recurring storms and ongoing landslide risks, combined with the visible lack of protective functions of the forests, amplify the perception of vulnerability. Some locals express growing fears about the long-term safety of living in such hazard-prone areas.


Bolzano
Eggentaler Restaurant Hotel
Aica di Sopra
Collepietra
Colle
Brié
Bagni di Lavina Bianca
Tires
Gemeier
San Giacomo
SS241
SS12
A22
Planetarium Südtirol Alto Adige Geöffnet
Pineta
Laives
Lupicino
Ponte Nova
Platten
SS620
Nova Ponente
San Nicolò d'Ega
Stadtl
PIEVALLE
Carezza
MASO CASERA
Santuario di Pietralba
Novale
Obereggen
Aldino
GEOPARC Bletterbach - Dolomites UNESCO...
Koflhof
più votati
Google
Centro Fondo al Passo Lavazè

6. Val di Fiemme and Val di Fassa, Italy

X-RISK-CC Climate Risk Storyline –Fiemme/Fassa Valleys (Trentino, IT)

In the year 2040….

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Fassa and Fiemme Valleys (municipalities of …) Temporal setting: October 2040 Intended purpose: Stress testing and appraisal of risk management for extreme storm events and compound impacts.
General climate situation (normal conditions in year 2040)	Trentino is in a warmer climate with new temperature records in the city of Trento exceeding 40°C. The mountainous regions such as Fassa and Fiemme Valleys are still relatively cool with summer temperatures not exceeding 35°C. Summers are getting warmer and temperatures at altitudes above 3000m are frequently not falling below 0°C. Autumns and winters are getting mild and wet with more rain and less snow. Precipitation regime is highly variable with dry periods up to several months interrupted by intense precipitation events. Summer thunderstorms lead to new 1-day rainfall records, while autumn brings frequently storms with precipitation extremes persisting for several days and mainly driven by southerly flow from a warm Mediterranean Sea (“Genua-Tief”). [1] During these events, 3-day precipitation totals usually exceed 100mm[2] in the Fassa and Fiemme Valleys.
General effects of climate change	Regarding the distribution and composition of forests, a shift of tree species such as spruce, larch, and beech towards higher altitudes has been observed. The increase in temperatures and more frequent drought episodes are leading to a decline in the health of forest ecosystems and an increase in their vulnerability to bark beetle infestations. In late winter, intense and wetter snowfalls compared to the past often cause damage to forests, particularly to evergreen trees, due to the weight of wet snow. These disturbances add to the damage caused by extreme weather events over the past 20 years, from which forests have not yet fully recovered. A general reduction in the protective functions provided by forests in the region has been observed, including a loss of water retention capacity, soil stabilization, and protection against rockfalls and avalanches. Mass movement phenomena are therefore more likely than in the past across the entire area and at all altitudes, due to reduced slope stability (caused by decreased forest cover), more intense precipitation events, and an increased availability of sediments in mid- and high-altitude areas, partly due to the progressive degradation of permafrost.

[1] See WP1 pilot report for Vaia – more frequent GWT 7 gross weather type (Vaia type)
[2] It is based on the projected changes under Global Warming Level 2 °C (GWL2, WP1 pilot report)

General non-climatic situation / non-climatic risk drivers	The population of Trentino continues to age progressively, albeit with some variations across different areas and valleys. The average age in 2040, slightly higher than in previous years, is 50.5 years, compared to the national average of 52.4 years. The projected percentage of the population over 65 years has increased, reaching approximately 28% of the total provincial population. The resident population in Val di Fassa and Val di Fiemme has grown by about 10% since 2024, bringing the population to approximately 11,000 inhabitants in Val di Fiemme and around 22,000 inhabitants in Val di Fassa. Tourist presence has increased in all seasons compared to 2024, particularly in the autumn months. This is due to the extension of the climatically favorable season and significant promotional efforts by Trentino Marketing and the local tourist boards (APTs) overseeing the two valleys. Tourists are generally more exposed to the risks of the mountain environment and are more vulnerable than residents due to their limited knowledge of the territory and associated risks, as well as greater difficulty accessing local information (especially foreign tourists due to language barriers). Certain measures have been implemented to limit overcrowding in some valleys, such as Val San Nicolò, but these have not significantly affected the overall numbers, which remain very high. Furthermore, due to both population growth and the expansion of tourism demand, settlement and infrastructure areas have increased in recent decades, leading to a rise in impervious surfaces. Despite periodic updates, the Hazard Summary Map is still unable to fully account for the effects of extreme events with compound and cascading impacts, such as the well-known Vaia storm that occurred more than twenty years ago. For example, this tool does not consider the potential effects of strong winds on forests and the resulting risks for buildings, mobility, infrastructure, and more. As a key component of recreational activities' appeal, forests are under significant anthropogenic pressure due to the multitude of tourists cycling and hiking along trails, even during the mild autumn season. This has had repercussions on both fauna and flora, altering the balance of forest ecosystems. A general decrease in forest biodiversity is being observed across the territory, exacerbated by the negative effects of climate change on the health and functionality of ecosystems. In the two decades following Vaia, reforestation efforts have been carried out, leading to mixed and uneven-aged forests. However, these interventions have been implemented only partially and in select areas of the territory. Many slopes still lack adequate forest cover. In the years following Vaia, protective measures against rockfalls and avalanche barriers were constructed in these areas. There are still many areas where trees grow very close to communication routes, creating potentially high-risk contexts for traffic disruptions due to possible windthrow incidents.

Event – meteorological event	After a hot and dry summer interrupted by a few intense thunderstorms, often accompanied by hail events, October 2040 experienced mild conditions and persistent dryness. In the final days of the month, a low-pressure system developed over Western Europe, causing southerly currents from the still-warm Mediterranean. This situation led to exceptionally intense precipitation on the southern slopes of the Alps on October 27. Due to the atmospheric blocking caused by high pressure over Eastern Europe, these conditions persisted for several days, resulting in three-day precipitation totals locally exceeding 500 mm in many parts of Trentino. On October 26, a red alert was issued for October 27, 28, and 29 for the Val di Fiemme, Val di Fassa, and the entire provincial territory. However, there was uncertainty among the local population and especially tourists about what behavioral practices to adopt based on the issued alert. The snow line remained above 3000 m, and precipitation in mid-altitude areas was accompanied by extreme wind gusts, with peaks reaching 150-200 km/h in the Fassa and Fiemme valleys.
Event – hazards	The intense wind gusts have caused widespread treefalls in various forested areas (across all municipalities, as shown on the map). One of the most extensive areas of treefalls is along the SS48 and SS50 roads, north of the municipality of Predazzo, in the area between Forno and Predazzo. Numerous treefalls have also occurred along the SS50 road between Lake Paneveggio and Passo Rolle. Both roads are therefore closed to allow for the removal of fallen trees, making access to the Fassa Valley and Passo Rolle difficult. Treefalls have also occurred along the new Moena bypass and in Val San Pellegrino, affecting the SS346. Mobility is blocked both north and south of Moena, and Passo San Pellegrino is also closed due to the treefalls. The fallen trees have caused widespread damage to power lines throughout the province, particularly in Val di Fassa and Val di Fiemme. The power grid operator is struggling to shut off electricity, and rescue teams are unable to reach various affected areas for evacuations. Some motorists are stranded on Passo San Pellegrino. Numerous landslides, debris flows, and flash floods occurred simultaneously across a wide area of Val di Fiemme, Val di Fassa, and more generally throughout Trentino. Many check dams and sediment basins were activated, but in many cases, they failed to fully contain the events. In particular, the flooding of the Gardonè stream caused the closure of the SS48 road in the Al Fol area. The San Pellegrino stream also overflowed, flooding parts of the center of Moena: 12 buildings were directly affected, leading to the evacuation of around 50 people. Additionally, the old road towards Val di Fassa is blocked. Other debris flows impacted roads and buildings, particularly along the Castelir, Sadole, Barbide, Soial, and Sarcine streams. Despite preventive regulation maneuvers at the Forte Buso dam, the reservoir reached its

	maximum retention capacity, and the Travignolo stream overflowed, albeit with limited flow, near the SS48 bridge in the center of Predazzo. The flow of the Avisio River exceeded the third alert threshold, causing significant bank erosion near meanders and flooding between Predazzo and Ziano, as well as near the Cermis ski lift facilities. At the same time, the Fiemme Community road (SS48) is also blocked near Predazzo, in front of the Felicetti factory, due to a large amount of sediment from a rockfall north of Predazzo. Some of the debris has reached the edge of the Avisio River. This has led to the closure of the last access point to Val di Fassa. A rockfall also occurred along the SS50 in an area known for high collapse risk. A landslide has isolated the road leading to the village of Medil. A landslide occurred on the SS50 near the Zaluna Hotel, leaving the hotel isolated and without road access. Approximately 45 people, including staff and guests, are inside the hotel. There are currently no reports of injuries or missing persons. Municipalities have activated procedures outlined in civil protection plans, but these do not account for all the compound and cascading events that occurred during the incident. Furthermore, the guidelines included in civil protection plans are not well-known by the entire population. As a result, some individuals, especially foreign tourists, are either not complying with or are unaware of the local authorities' instructions. Some are found in high-risk areas where they should not be, exposing themselves to elevated danger levels.
Event –impacts	The closure of the SS48, SS50, and SS346 roads complicates risk management actions and connections outside the municipality of Predazzo. The SS48 remains closed in both north and south directions for an entire day to allow for cleanup operations, leaving Predazzo partially isolated for the duration of the intervention. Due to damage to water supply infrastructure and contamination caused by landslides and floods, some buildings and households are left without drinking water. Several sections of the Val di Fiemme and Fassa cycle path are also interrupted due to debris flows. Significant damage is reported near the Castellir, Sadole, and Soial streams. The Barbide stream caused substantial damage to the SS48 and some adjacent houses in the municipality of Soraga. The San Pellegrino stream interrupted the road near the Negritella restaurant. The Castellir stream overflowed on the left bank of the Avisio River above the municipality of Ziano, impacting the fire station. Numerous buildings and infrastructure have been damaged by landslides, rockfalls, and debris flows. The main roads (SS48, SS50, and SS346) have been damaged in multiple locations, and some protective structures have reached or exceeded their functional and structural capacity.

	All cable cars have been closed due to strong winds, and some tourist facilities and mountain huts remain isolated due to widespread treefalls along many forest roads. There is significant uncertainty and confusion among both the local population and tourists about the appropriate actions to take following the red alert issued on October 26. Local residents are not well-acquainted with municipal civil protection plans, while tourists have no familiarity with the provincial alert system and, in some cases, are unaware of it altogether, partly due to language barriers. As a result, many people exhibit inappropriate behaviors. Both tourists and residents are facing great difficulties in mobility. The local population is voluntarily taking independent initiatives to restore essential services. Many tourist accommodations hosting guests remain isolated and without services. Due to wind damage and system overload, the cellular network is partially out of service, making it difficult for many people to report emergency situations, especially in more isolated areas. In this context, the spread of inaccurate, false, and contradictory information is proliferating, particularly on social media and through instant messaging apps. In the hours following the main event, approximately 10 Italian and foreign tourists were reported missing, particularly in mountainous areas.
Post-event (post emergency)	The extreme event caused significant impacts throughout the provincial territory, with particularly severe damage recorded in Val di Fassa and Val di Fiemme. Many road infrastructures, as well as several cycle paths running along the Avisio River, were damaged. Numerous SAT trails have become impassable. This is partly due to the widespread treefalls and partly to hydrogeological instability phenomena, including numerous landslides and debris flow events. Sediment has accumulated in critical points along the Avisio and Travignolo rivers, as well as in the following streams: Castelir, Sadole, Barbide, Soial, Sarcine, and San Pellegrino. Buildings, roads, and bridges have been damaged and will require extended restoration times. The landslides have caused severe erosion on slopes already affected in the past, further reducing their stability. Post-event management of forest areas has been characterized by varied approaches. In critical protection areas, essential for safeguarding residential centers and valuable assets, the timely construction of artificial protective structures was necessary to ensure the immediate protection of the most exposed and frequently visited areas. Rockfall barriers were installed along roads, and avalanche barriers were constructed on some slopes above sensitive areas.

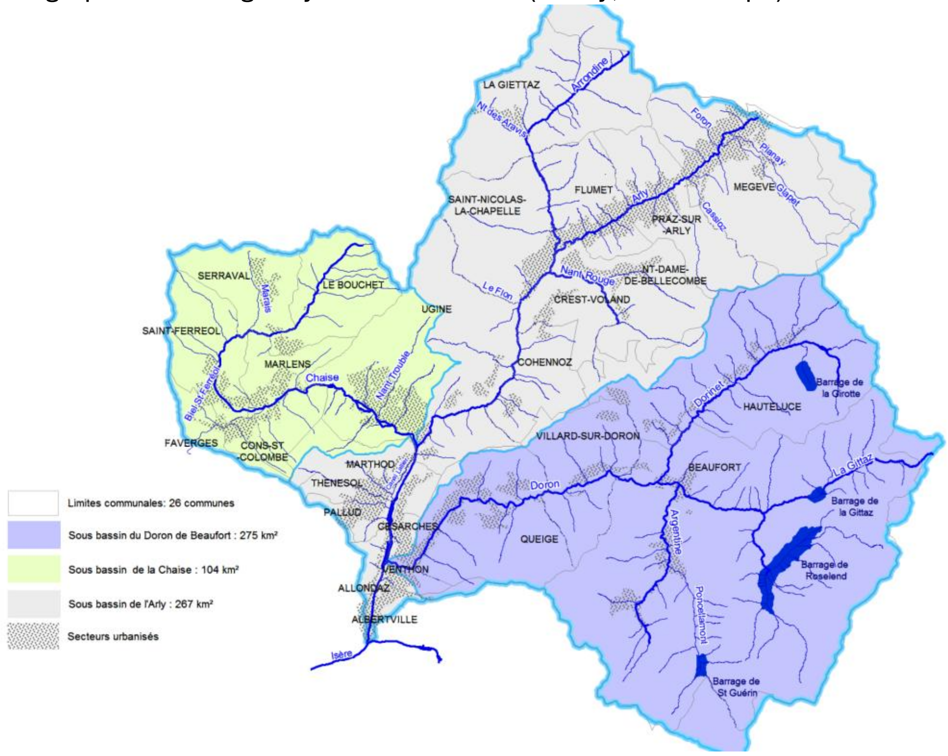
	In other less critical protection areas, particularly those not directly safeguarding settlements, affected slopes were partially left unmanaged. A more nature-based approach was adopted, leveraging the partial protective function of fallen trees left on the ground and stumps left standing at least one meter high. This approach aimed to exploit the surface roughness created by the fallen trees and cut stumps. However, this type of forest management is not feasible in all contexts due to the risk these logs might pose to exposed assets along potential fall paths. Over time, such logs and stumps could decay, increasing the risk of falling. Efforts are being made to encourage the establishment of forest species that contribute to creating mixed and uneven-aged forests. The fallen trees and stumps contribute to a visibly altered landscape, significantly impacting the cultural and aesthetic value of the region, including its tourist appeal. This has affected how tourists perceive the area, with a tendency to prefer other destinations in the future that are considered safer. The 2040-2041 winter tourist season has been severely compromised and could not open as scheduled. Some critical ski infrastructures and access roads have not been fully restored or remain partially inaccessible. This has resulted in significant economic losses for the tourism and ski sectors, with cascading negative effects on the entire valley's economy. The overall risk perception among the local population has increased. The rising frequency of storms characterized by extreme precipitation and ongoing landslide risks, combined with the tangible weakening of the protective functions of surrounding forests, amplifies the perception of vulnerability to extreme weather events. Some locals, deeply affected by the event, report reliving memories of the Vaia storm and express growing concerns about the long-term safety of living in high-risk areas.

7. Arly River Catchment, France

X-RISK-CC Climate Risk Storyline – Arly river catchment (FR)

In the year 2040....

[knowledge sources are indicated by footnotes]

<table>
<tr><td>Scope</td><td>Geographical setting: Arly river catchment (Savoy, French Alps)


Temporal setting: January 2040
Intended purpose: Stress testing and appraisal of risk management for extreme winter storm events and compound impacts.</td></tr>
<tr><td>General climate situation (normal conditions in year 2040)</td><td>The Savoy Alps are in a warmer climate with new temperature records in the main cities along the Rhone valley exceeding 40 °C. The mountainous regions in the Savoy Alps are still relatively cool with summer temperatures not exceeding 35 °C in the side valleys. Summers are warmer and drier than in the past, with more frequent drought conditions and temperature not falling below 0 °C also at the highest elevations. Winters are milder and wetter than in the past with more rain and less snow. Rain-on-snow episodes in winter are more frequent than in the past and often associated to precipitation extremes. The heavy rainfall events on 1 day or cumulated over several days in winter are also more intense and frequent than in the past, often exceeding 60 mm/day[1].</td></tr>
<tr><td>General effects of</td><td>Accelerated snow melt and more frequent rain-on-snow episodes have increased the occurrence of flooding events in the region. Milder winter and spring seasons also enhanced the occurrence of avalanches. Moreover,</td></tr>
</table>

[1] Based on the projected changes in 1-day precipitation maxima in winter under the Global Warming Level +2 °C (GWL2) with respect to 1991-2020 for the station locations in the pilot area

climate change	permafrost melting lead to **higher amounts of material** that can be mobilized and to decreasing slope stability at higher altitudes. Due to the increased intensity and frequency of intense precipitation events in autumn and winter seasons, some mountain basins are more active than the past (2025), thus also **the occurrence of flash floods, landslides and debris flows has increased**. In addition, the **Savoyard forest, weakened** by drought, heatwaves, parasitic attacks and fires, has been in a health crisis since the 2020s. By 2040, it will no longer be playing its protective role.
General non-climatic situation / non-climatic risk drivers	**Population in 2040**: The population of the basin is fairly stable. On the scale of Arlysère (61,000 inhabitants), it is mainly the urban center of Albertville that increases, while the population of mountain villages tends to decrease. **Tourism in 2040:** The region will still be able to welcome tourists to its winter sports resorts (with a proportion of difficult winters of 1 in 5). **Urbanization and infrastructures in 2040**: Various factors (land prices, Zero Artificialisation Net law, etc.) limit development possibilities in the basin.
Event – meteorological event	After a December with above-average precipitation amounts, the beginning of January 2040, record **several days of persistent precipitation of high intensity exceeding 100 mm/day**[2], driven by a stationary low-pressure system over north-western Europe. During this period, high amount of snow accumulates in the mountain areas and wind gusts up to 200 km/h are recorded. After five days of continuous precipitation (with cumulated values locally above 300 mm[3]), **a sudden rise of temperature** occurs, due to the movement of the low-pressure system across Central Europe. Due to the warm-air advection, **an abrupt transition from snow to rainfall** is registered in the mountain areas and moderate liquid precipitation continue to fall for several days also at locations where an exceptional amount of fresh snow is accumulated on the ground during the initial phase of the storm.
Event – hazards	Saturated soils cause widespread soil instability and intense runoff throughout the watershed. In the upper parts of the basin, **avalanches** and **snow slides** impact roads. **Severe flooding** affected the Arly and its tributaries (Doron, Chaise). EDF spilled water from the La Gittaz and Roselend dams to prevent the structures from collapsing, adding a further surge of water to the flow downstream. In the Gorges de l'Arly, several **slope instabilities** on the left bank were reactivated (rockslides, landslides and mudflows), and **new landslides occurred on the right bank**, sweeping away whole swathes of forest and causing logjams in the riverbed. **The breakup of a clog** causes a sudden breakup of the river. Downstream, the flow of the Arly exceeded 1200 m3/s, causing flooding on an unprecedented scale in the alluvial plain. As a result, a dyke broke upstream of Albertville, and the main deck of a bridge across the river is breached. In the Doron basin, **debris flows** downstream of the Bersend landslide blocked the river, cutting off the access road to the dams.
Event – impacts	The Val d'Arly road has been cut off in several places by landslides, and several hundred meters have been washed away by bank erosion.

[2] Considering the projected changes in 1-day precipitation intensity of a 100-year recurring event in winter under GWL2 for the station locations in the pilot area

[3] Considering the projected changes in 5-day precipitation intensity of a 100-year recurring event under GWL2 for the station locations in the pilot area

	Flooding in the alluvial plain cut off the freeway and affected small craft areas and numerous homes. The Ugitech steel mill was flooded and 200 people were trapped on the site. They were evacuated as a matter of urgency, due to the risk of water intrusion into the molten furnace, which was fortunately avoided. Hundreds of tourists were blocked for several days in the resorts of Arêches-Beaufort, Crest-Voland and the area between Saint-Nicolas and Flumet.
Post-event (post emergency)	Villages remained isolated for several weeks to months. Following this event, the Conseil départemental decided not to reopen the Val d'Arly road, due to the exponential increase in its road maintenance budget. As a result of the damage caused to the forests in the watershed, torrential erosion and boulder falls increased still further over the following decade.

Appendix C

Method description of Alpine-wide mass movement models

Method description of Alpine-wide mass movement models

Authors: Spiekermann R., Steger S., Lehner S., Enigl K., Moreno M., Crespi A., Schlögl M.

Data and Methods

Mass movement inventories

The mass movement data used in this study comes from two inventories in Austria as well as a comprehensive landslide inventory in South Tyrol, Italy, for the period 2005-2021. The Austrian GEORIOS landslide inventory compiles detailed data on landslides using a combination of historical records, aerial photography, satellite imagery, and field surveys. The WLK inventory, compiled by the WLV Austria (Agency for Mountain Stream and Avalanche Control), includes debris flows, landslides, and torrential floods in upper catchments within Austria. Additionally, landslide data were included from the regional version of the national landslide database IFFI (Inventario dei fenomeni franosi in Italia) via the IdroGeo platform. These three inventories formed the basis of the models for the three mass movement forms of 1) slide 2) flow and 3) fall type. The records include georeferenced locations alongside occurrence dates. Most of the entries were labelled only with the occurrence day, lacking information on the exact hour. Consequently, the model was designed to operate at daily temporal scales. Typically, the data entries represent point locations where damage occurred to infrastructure and property, since this is what initiates mapping of the process types. Thus, the inventories used in this study can be referred to as mass movement *impact inventories*.

Spatial units

The spatial unit upon which the models were based was the half-basin (Figure 1). In this context, the use of half-basins presents certain advantages over pixel-based approaches. As it is unclear whether the points represent the source, run-out, deposition zone or impact location of the process, half-basins are a practical solution as they capture all three possibilities. More importantly, having the process source, run-out and deposition zones (where infrastructure is more likely to be present and impacted) within an individual half-basin ensures that all processes involved are integrated within a single model. This therefore negates the necessity for separate models to represent the triggering, run-out, and impact components within a mass movement impact event.

A further consideration is the spatial resolution of the explanatory variables employed, with the objective of increasing variability between spatial units and reducing variability within. It was hypothesised that climatic variables, such as short-term precipitation, play a significant role in determining the occurrence of mass movement impact events. However, the spatial resolution of the climate data used (CERRA) is relatively coarse (approximately 5.5 km) in comparison to the resolution of the majority of static data (land cover and topography). The dimensions of the half-basins are sufficiently large to capture this variation in resolution, while also being small enough to be relatively homogenous in terms of topography, land cover, and lithology.

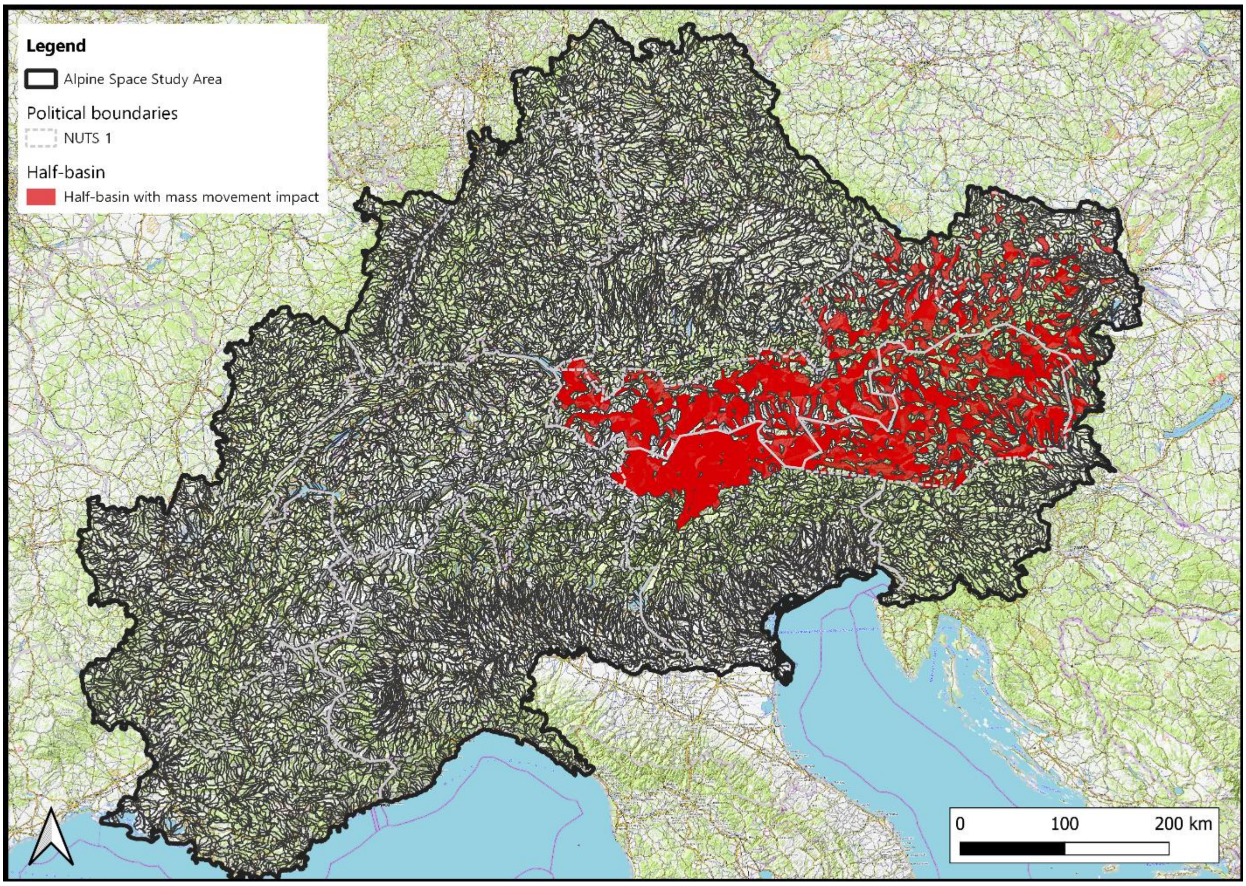


Figure 1 Half-basins across the Alpine Space generated with a 20 m DEM using r.watershed in GRASS. Half-basins within Austria and South Tyrol were used to train the model with red basins used as presence and transparent basins as absence samples.

Half-basins were derived from a 20-m LiDAR-derived digital elevation model using r.watershed in GRASS. A total of 17,872 units were generated, with a median area of 2020 ha with a minimum size of 200 ha (Figure 2). Units <200 ha in size were merged to the neighbouring polygons, first based on largest bordering length, and in a second iteration based on largest area. Of the 3698 half-basins located in Austria and South Tyrol (training area), 1014 units were affected by slide-type, 691 from flow-type, and 549 from rockfall mass movement events. While these numbers take into account the spatial extent of the affected half-basins, there were many more events in time. An equal number of unaffected half-basins were selected and several random absence days were generated and then stratified in time to ensure sampled absence days reflect the actual monthly distribution of precipitation days. An important requirement for the modelling samples was a minimum of 10 mm precipitation ($Tp\_2 > 10$ mm).

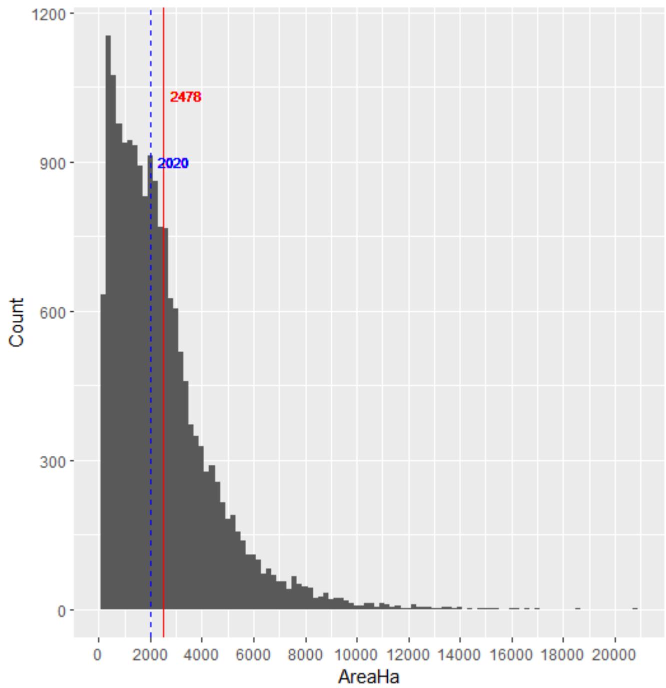


Figure 2 Size distribution (ha) of half-basins

Potential process-path areas (PPA)

Given the large size of the half-basins, we constrained the area of interest within each unit based on process-path models for slide-types, flow-types, and rockfall mass movement processes based on Wichmann (2017). The motivation behind this procedure was to spatially constrain model parameters, such as topographic conditions, land cover, geology or exposure variables, to areas potentially affected by specific processes. For example, when modelling we focus on the number of buildings within the potential reach distance of these processes (i.e. exposure proxy) rather than the number of buildings within the entire catchment. The process-path models use low estimates of initiation slope thresholds to determine potential release zones. Then, five random run-out flow paths were generated for each release pixel based on a pre-defined angle of reach to account for (some) uncertainty in the downslope mass propagation (Table 1). PPAs consist of the combined potential release areas and run-out paths (Figure 3). As areas outside of the process-path are highly to be impacted by mass movements, the respective process path areas served as a mask in the computation of static explanatory variables that are used to characterise the half-basins (Figure 3, Figure 4).

Table 1 Parameters for process-path models for slide, flow and fall mass movement types

	Slide-type	**Flow-Type**	**Fall-type**
Initiation slope threshold	>5-50	>15 (non-convex terrain)	>35
Random walk slope	30	30	60
Exponent of divergence	2.12	2.12	1.75
Persistence	1.75	1.75	1.75
Angle of reach	22	11	29
References	Steger et al., 2021; D'Amboise et al., 2021	Horton et al., 2013	Dupire et al., 2020; Menk et al., 2023

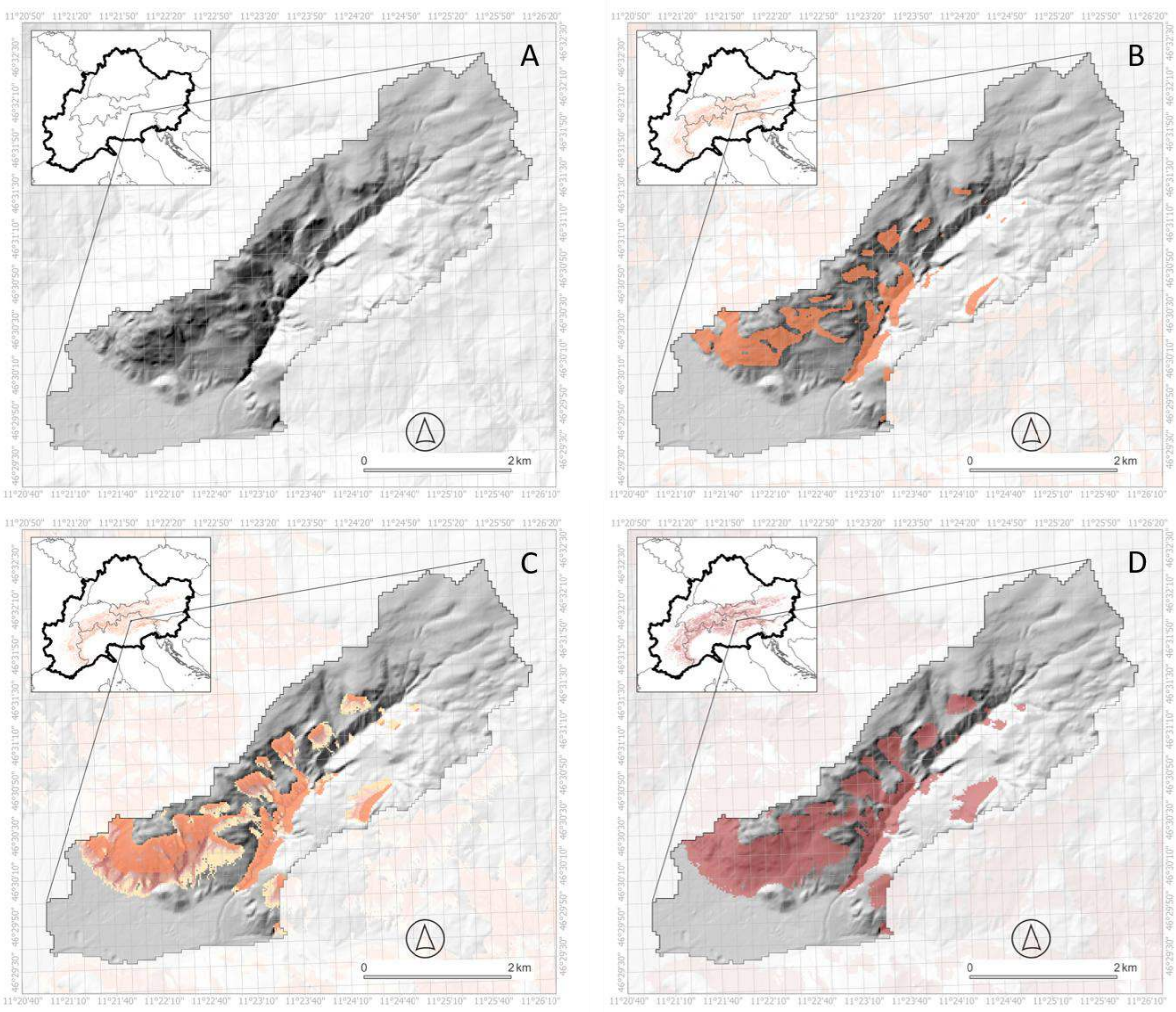


Figure 3. **Illustration of the process involved in deriving potential process path areas from the digital elevation model (the shaded relief is shown in Insert A): Beginning with the identification of potential release zones based on initiation thresholds (Insert B), run-out flow paths are determined based on pre-defined angles of reach and using 5 iterations of random walks (Insert C). The combination of release and run-out zones results in the potential process path areas (insert D), which are process-specific (see Figure 5).**

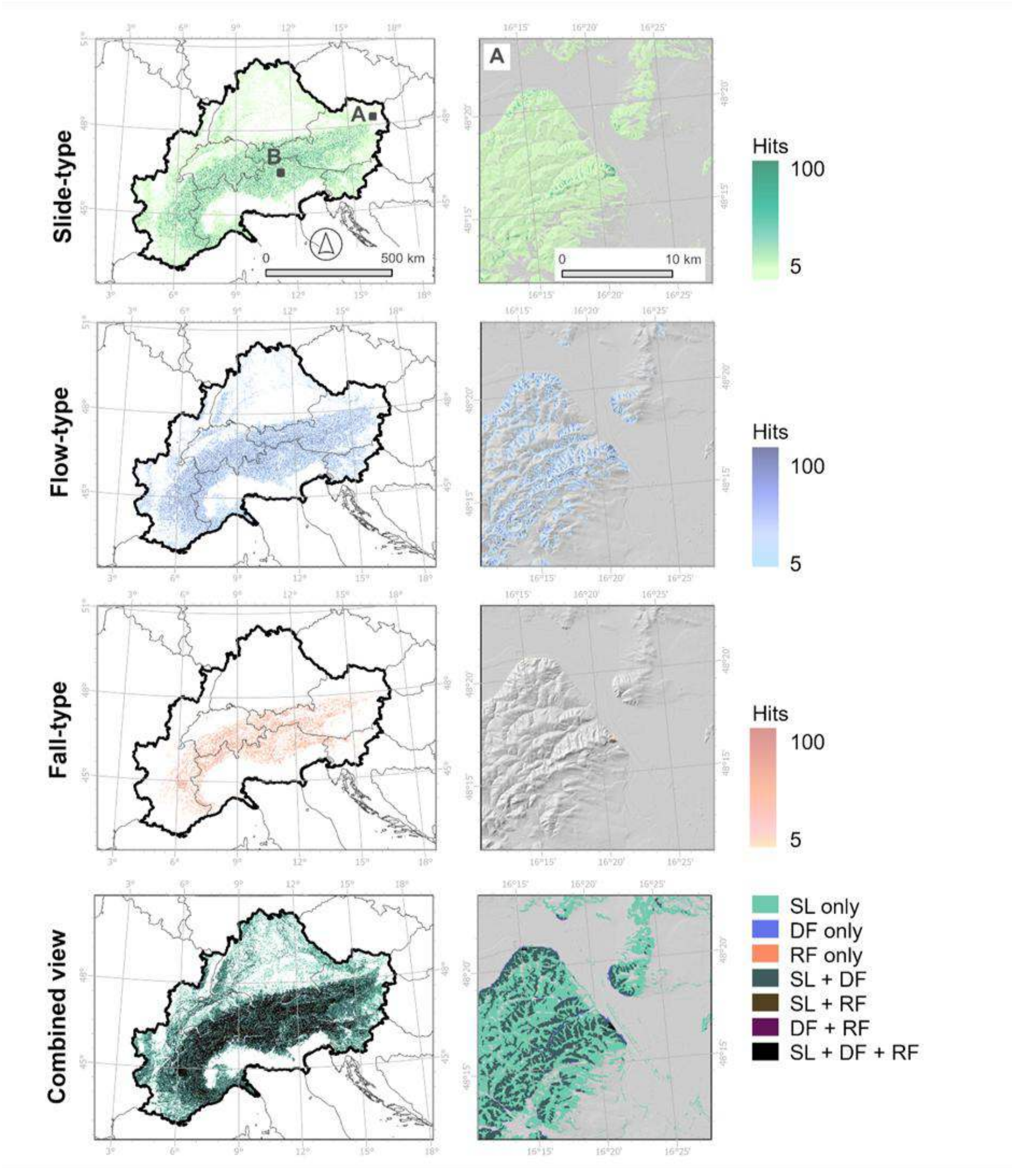


Figure 4 Potential process-path areas based on Wichmann (2017) were created for slide, flow, and fall mass movement types (shown in map). Insert A provides a localised overview. The window B refers to the maps in Figure 4.

Predictors

Dynamic predictors

Potential explanatory variables were assembled from datasets available for the entire Alpine Space (Table 2). CERRA-Land and CERRA data were used to compute climatic explanatory variables, including precipitation and temperature. The precipitation data included both a short time window of cumulative precipitation, named "triggering precipitation" and multiple antecedent precipitation variables, which sums precipitation for 7, 14, 21 and 30 days prior to the triggering precipitation. The triggering precipitation was represented using a 48-hour time window to avoid associating mass movements occurring e.g., shortly after midnight solely with rainfall occurring during that day. This 48-hour window includes the day of the event registration and the preceding day, ensuring that the short-term rainfall contributing to the mass movement is captured. The pre-event rainfall accumulation can be used as a proxy for antecedent soil moisture (Guzzetti et al., 2007). The probability of precipitation-induced slope failure is increased in situations where the soil has a higher antecedent moisture content. This is due to the fact that positive pore water pressures are more likely to occur in such conditions (Crozier, 1999). Mean annual precipitation was included as a measure of coevolution of soils and hillslopes (e.g. geomorphic equilibrium) with climate whereby landscapes adjust to repeated mass movement events (Marc et al., 2019; Crozier and Preston, 1999), which may produce contrasts in precipitation thresholds for landslide initiation (Smith et al., 2023). All climatic variables were aggregated to half-basins using the area-weighted mean.

Static predictors

Slope gradient is the most influential environmental predictor variable used in landslide susceptibility modelling (Chung and Fabbri, 2003) – particularly in combination with variables pertaining to the mechanical properties of soil and lithology (Reichenbach et al., 2018). The reason for its effective explanatory power is directly related to the physics of mass movement. The greater the slope gradient, the greater the resistance force mobilized in response to increasing driving force. Mean slope gradient was therefore calculated per half-basin. As with other all static explanatory variables, the process path areas were used as masks for the calculation, i.e. only pixels within the respective process path areas for slide, flow, and fall mass movement types were included. Thus, each half-basin had three different values of each static variable based on the varying extents of process path areas. The convergence index was a second morphometric predictor included, which is relevant because of the hydrological influences on slope stability. Convergent slopes concentrate surface runoff and subsurface groundwater flow, increasing pore water pressure. It can also be a proxy for accumulated water or variation in soil saturation.

Vegetation exerts two direct effects on slope stability: hydrological and mechanical. Vegetation affects water infiltration and soil moisture content, primarily through interception, increased soil permeability, and evapotranspiration (Sidle and Ochiai, 2006; Greenway, 1987). These functions assume greater significance when soil moisture is modified within the contributing area upstream of a potential landslide location. Hydrological mechanisms that reduce pore-water pressures in the soil are beneficial, whereas processes that increase pore pressure are adverse. The mechanical effect, which is manifested in lateral root reinforcement, basal root reinforcement, and soil stiffening, serves to enhance soil shear strength, thereby promoting slope stability in shallow soils (Schmidt et al., 2001). This is achieved through the increased strength of the composite rooted soil material produced by the integrated interaction of roots and soil under different types of solicitations (tension, compression, shearing) (Spiekermann et al., 2024). Therefore, the dominant land cover class within each of the three process path areas within each half-basin was calculated (Malinowski et al., 2020).

Lithology is commonly an important factor in determining mass movement process since the material type directly influences soil properties such as hydraulic conductivity and texture (Smith et al., 2021). It is generally unavoidable that boundary and material type errors will result from using lithological data of much lower resolution than for topographic variables. However, the inclusion of coarse resolution data nevertheless has benefits for model performance. Here, we used the Alpine-Geo-LiM Geo-lithological map (Donnini et al., 2020), which consists of a consistent classification for the entire Alpine Space, whereby we reclassified classes to simplify further.

Given that the available inventory for training the models is comprised of impact inventories, which were created as a result of damage to infrastructure, it is imperative to control for the potential for exposed elements to be damaged through mass movement events. Therefore, we used Open Street Map data to quantify the number of buildings within the three respective process path areas, as well as the fraction of rasterized roads per process path area – whereby only primary roads including forestry roads were included. Additional predictors were included to account for spatial and temporal dependencies through random effects based on sampling location, time of year and size of the process path area and half-basins.

Table 2 Overview of explanatory variables used as candidates in the mass movement impact models.

Domain	Predictor	Unit	Spatial resolution	Type	Source
Climatic	Triggering precipitation - 2 days	mm	5.5 km	daily	CERRA-LAND
Climatic	Antecedent precipitation - 7, 14, 21 and 30 days	mm	5.5 km	daily	CERRA-LAND
Climatic	Mean annual precipitation 2005-2021	mm	5.5 km	daily	CERRA-LAND
Climatic	Temperature - mean	°C	5.5 km	daily	CERRA
Climatic	Temperature - sub-zero binary*	0/1	5.5 km	daily	CERRA
Climatic	Temperature - crossing-zero binary*	0/1	5.5 km	daily	CERRA
Morphometric	Slope - mean in PPA	°	20 m	static (2015)	DEM
Morphometric	Convergence index - mean in PPA	Index	20 m	static (2015)	DEM
Land Cover	Dominant land cover in PPA	Class	10 m	Static (2017)	S2GLC
Land Cover	Frac no vegetation PPA	Class	10 m	Static (2017)	S2GLC
Lithology	Dominant lithology in PPA	Class	~ 1:5,000,000	static	Alpine-Geo-LiM
Exposure	Buildings in PPA	No. of buildings in PPA (log)	-	static	OSM
Exposure	Roading, incl. forestry roads in PPA	Fraction roads in PPA	-	static	OSM
Other	Administrative boundaries	class	-	static	NUTS
Other	Half-basin areal extent	Number	-	static	
Other	Process path areal extent	Number	-	static	
Other	Day of year	1-365(366)	-	daily	

Model development

Following Steger et al. (2024), three binomial generalized additive mixed models (GAMM) were trained using impact inventories of landslides, debris flows and rockfalls (Figure 5). The models are temporally dynamic in that they allow predictions to be made in space and time (daily scale). The advantage of the spatiotemporal GAMM model is its ability to capture complex, non-linear relationships between landslide occurrences and environmental covariates via smooth functions as well as group effects (e.g. repeated measurements within a unit; in our case year and basin ID) via random effect variables. The GAMM enhances predictive accuracy and interpretability by allowing for flexible, data-driven adjustments to both fixed and random effects, making it a suitable tool for understanding the dynamic processes influencing landslide phenomena. In principle, variable selection (cf. candidates in Table 2) used an automated selection procedure based on shrinkage (Marra and Wood, 2011) while the optimal time-window for representing antecedent precipitation was identified using random cross validation, whereby the following time windows were tested: 7, 14, 21, 30 days before triggering day T; Table 1).

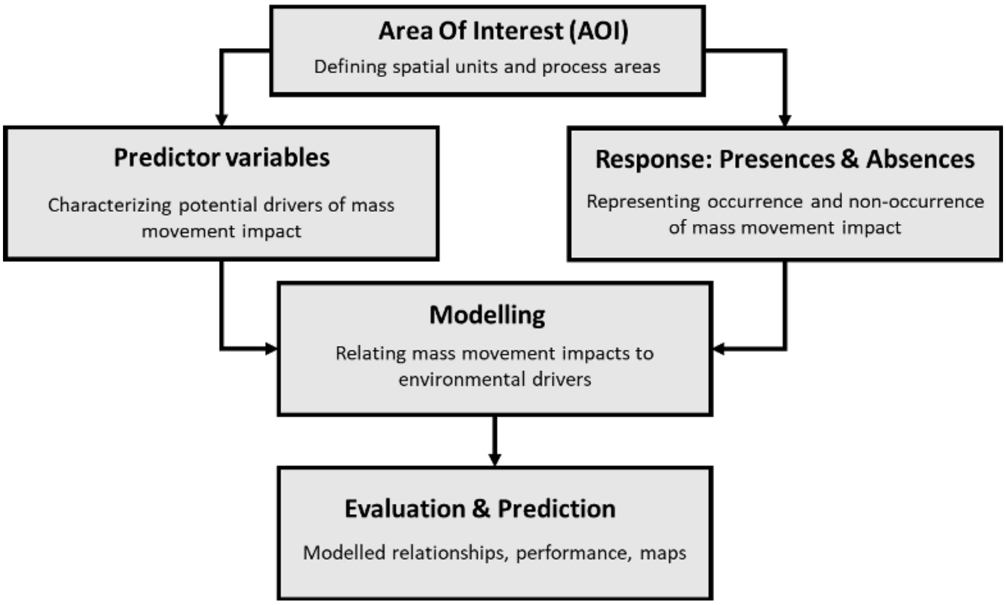


Figure 5 Workflow of mass movement impact modelling

10-fold cross-validation was used with five repetitions to assess predictive performance within the training area using the Area Under the Receiver Operating Curve (AUROC). The resulting dynamic maps represent daily probabilities for impacts resulting from slide, flow, and fall mass movement types across various precipitation scenarios. As the models address a classification issue based on a sample of presences and absences in space and time, the probabilities do not pertain to the actual probability of an impact event occurring, but rather reflect the probability that the conditions for a given day and for a given half-basin are such that a mass movement impact event could occur (i.e. higher vs. lower potential for mass movement impact) Thus, the higher the probability, the more similar the conditions are to when events were observed in the past. It should be noted that the selection of absence samples was constrained to wet days (Tp_2 > 10 mm), with the objective of reducing the influence of climatic variables and developing a model capable of distinguishing between wet days with no impact and wet days that are likely to result in impacts to infrastructure.

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