Interreg Alpine Space

Co-funded by the European Union

X-RISK-CC

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Deliverable 2.1.1

# REPORT ON PAST AND FUTURE (COMPOUND) HAZARDS IN THE PILOT AREAS

## X-RISK-CC

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

LEAD PARTNER

PROJECT PARTNERS

This project is co-funded by the European Union through the Interreg Alpine Space programme. www.alpine-space.eu/project/x-risk-cc/

# 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

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|---|---|
| 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<br>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.<br><br>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. |

| | |
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| | 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.<br><br>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.<br><br>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).<br><br>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.<br><br>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.<br><br>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 2.1.1, documents the methods applied and the results obtained regarding the analysis of past and future (compound) hazards in the pilot areas of X-RISK-CC as part of Activity 2.1. The activities described here are followed by Deliverable 2.2.1, which documents the methods applied and the results obtained regarding past and future risk pathways in the pilot areas of X-RISK-CC as part of Activity 2.2. 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, and 2) establish a practice-oriented concept to generalise and translate the new knowledge into risk management and adaptation options across the Alpine Space.

The project activity documented in this report builds on information created in Work Package 1, which combines observational data with physical and data-driven models along with new weather-extreme-specific information, and provides input for Activity 2.2, which analyses key risk pathways and develops "narrative" climate storylines.

This report presents the detailed information for each pilot area, including data from impact chains, event tables and risk questionnaires, along with explanatory texts on past and future compound impacts. The methods presented in Chapter 2 were proposed by the scientific partners and applied to the pilot areas. The complete documents developed by the pilot responsible partners as part of Work Package 2 are included in the appendix to Deliverable 2.2.1. Local-scale analyses are integrated with the results of an Alpine-wide data-driven impact model exploring the key environmental drivers for mass movement events across the Alpine Space. In the conclusion in Chapter 4, we discuss challenges and limitations of the developed approaches and results. Furthermore, we outline how the results of Activity 2.1 will be applied over the course of X-RISK-CC to inform further activities in Work Package 2 and in other Work Packages.

# 2 Methodology for Hazard Analysis

The aim of Work Package 2 "Compound Impacts and Risks" is to understand past and future compound impacts and risks in pilot areas due to weather extremes under climate change and to establish a practice-oriented concept for generalising and translating this new knowledge into risk management and adaptation options across the Alpine Space. To achieve this, 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 visualize the causal relationships between climate changes and their resulting impacts. We compiled a comprehensive catalogue of event data in each pilot area, which can provide a basis for subsequent analysis of natural hazards. We then developed a structured risk questionnaire accompanied by a set of tools, enabling the pilot areas to analyse past and future hazards, compound impacts and risks triggered by weather extremes within their specific contexts (see D 2.2.1 for an in-depth description of the risk questionnaire and the results on key risk pathways). The approach allows the pilot areas to conduct qualitative or quantitative assessments, depending on the data available or the aim of the local investigation. The answers provided to the risk questionnaire in the pilot analysis form the basis for the development of the climate risk storylines (see D 2.2.1)., which represent a narrative-based approach to understand and communicate potential future climate risks

To complement the analyses conducted in the pilot areas a data-driven model was developed and applied to derive the probability of mass-movement damaging events across the Alpine Space. The modelling approach combines meteorological, morphometric, geological, hydrological, land cover data, as well as data on potentially exposed assets, to identify and infer statistical relationships between impact related to slide, flow and rockfall events and their drivers. This knowledge is expected to help to inform the design and implementation of risk reduction measures, such as impact-based forecasts and warnings. The resulting environmental drivers for each type of process are discussed in the following, while the application of the model to derive impact scenarios and aid the assessment of risk across the Alpine Scale is reported in D 2.2.1.

## 2.1 Sequential Impact Chains

The first step involved creating a conceptual description of selected compound and cascading hazard events in the pilot areas. To understand the risk drivers and impacts resulting from potential cascading effects in these areas, we developed impact chains. These impact chains are grounded in the Intergovernmental Panel on Climate Change (IPCC) risk concept, which states that 'risks result from dynamic interactions between climate-related hazards and the exposure and vulnerability of the affected human or ecological system to these hazards' (Reisinger et al., 2020). To conceptualize specific risks, impact chains provide a structured approach to understanding and visualizing the causal relationships between climate changes and their resulting impacts (Zebisch et al., 2023).
In the X-RISK-CC project, we designed **'sequential'** impact chains to represent the chronological progression of events. These impact chains illustrate a sequence of meteorological conditions,

subsequent hazards, key predisposing and preparatory factors, and their impacts on the socio-economic system (Figure 1).

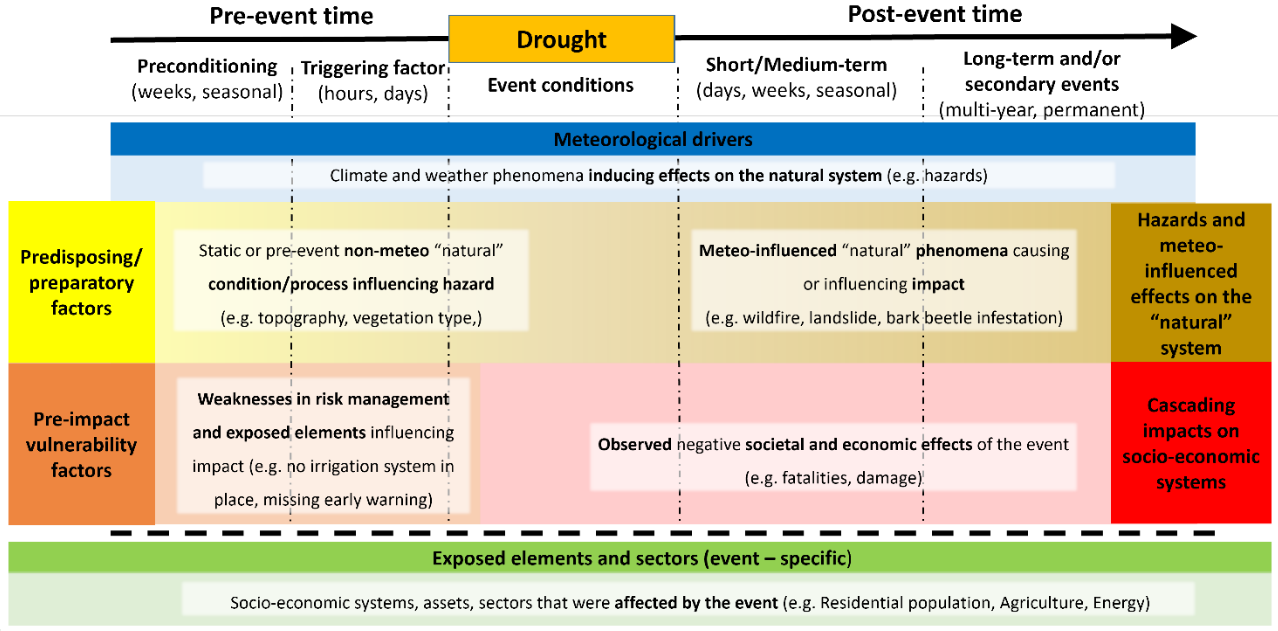


**Figure 1: Structure of the sequential impact chain.**

Having these impact chains for each pilot area enabled us to identify the meteorological conditions (WP1), as well as the hazards and exposure/vulnerability factors (WP2), for analysis. (Figure 2). The sequential impact chains created by each pilot area responsible project partner were presented at a pilot area stakeholder meeting and, if necessary, revised based on expert knowledge.

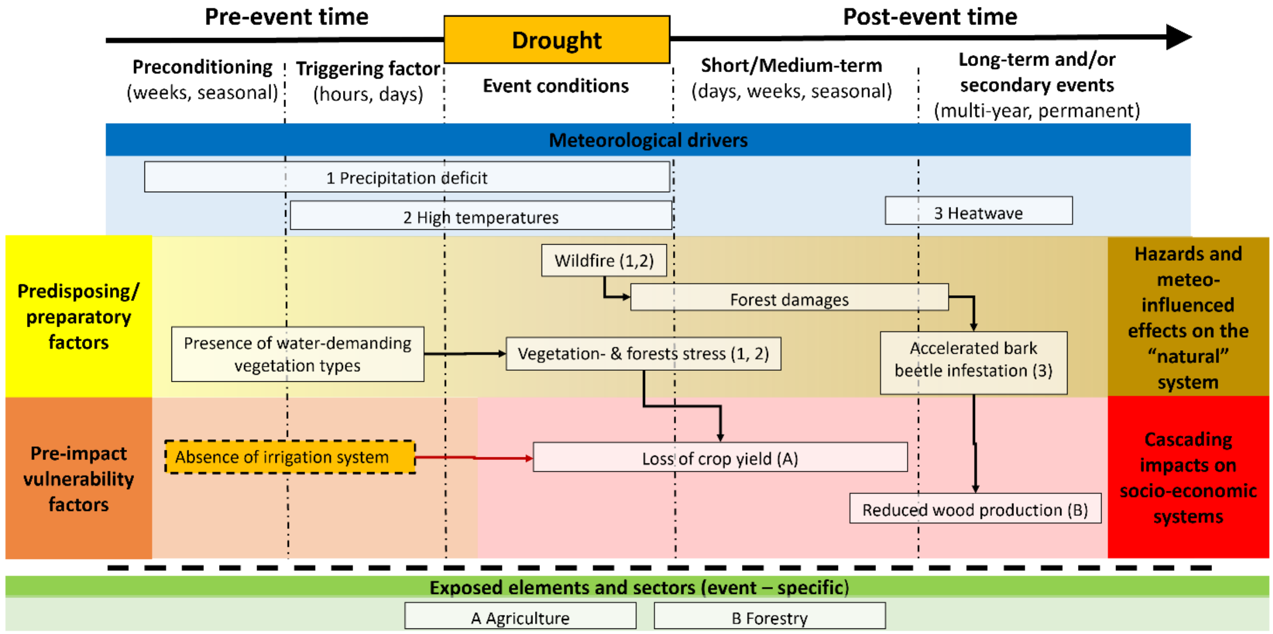


**Figure 2: Generic example of the sequential impact chain for a drought event.**

## 2.2 Past and future hazard trends at pilot scale

### 2.2.1 Modular approach for hazard assessment

The development of the hazard framework is based on the systematic collection of data of past hazardous events. The comprehensive compilation of event data covers 1) the recorded meteorological drivers of the respective event, 2) the type, magnitude and characteristics of the hazard event, and 3) the extent and costs of damages caused by the event. This information can be obtained e.g. from automated stations like weather stations or gauging stations, national/local event databases or event reports. The inventory of past hazards serves as the basis for the hazard analysis as part of the risk questionnaire (Section 2.2.2) in each pilot region.

A variety of different hazard types that has shown to be relevant in the pilot regions, is considered throughout the course of X-RISK-CC. Available event data is collected for of the following hazard types:

**Table 1: List of hazard types considered in the pilot area analysis of X-RISK-CC. *Storms, extreme heat and droughts are considered as weather extreme and natural hazard, likewise.**

| Hazard type | Hazard Group |
|---|---|
| Storm* | Atmospheric |
| Extreme heat* | |
| Wildfire | Biophysical |
| Rockfall, rock slope failure | Geological |
| Landslide | |
| Debris flow | |
| Hyperconcentrated flow | |
| Flash flood | Hydrological |
| River flood | |
| Snow avalanche | |
| Drought* | |

### 2.2.2 Risk Questionnaire

In X-RISK-CC, we encourage risk managers to take a holistic view at 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 near to mid future (up to 2040).

For that purpose, we developed, in the form of a questionnaire, some guiding questions that give an overview of these contributing factors and to improve the understanding of overall risk and its' drivers. Risk managers and researchers provide answers to these questions based on the collective expertise available in their organisations and other important stakeholders in their region of interest. They 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 and researchers in the pilot areas.

The questionnaire follows the structure presented in Table 2 covering the perspective of current risk and risk in the near to mid future (up to 2040). This report focusses on the first part of the risk questionnaire, i.e. the assessment of the general climate and (multi-)hazard situation. We want to refer to the report of Activity 2.2 (D 2.2.1) for a description of the risk questionnaire and its' tools and methods applied for answering questions IV-VII on key risk pathways.
*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. We suggest a variety of optional tools, methods and concepts that can be applied by risk managers to help answer the questions of the risk questionnaire.

**Table 2: 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)<br>- event tables,<br>- impact chain,<br>- hazard-interaction-matrix<br>- frequency-magnitude relation,<br>- 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,<br>- impact chain,<br>- exposure checklist,<br>- system impacts table<br>- vulnerability models<br>- quantitative risk analysis<br>- 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? | | | |

In the following subchapters, the tools and methods proposed to support answering *Part 1: General Climate and (multi-) hazard situation* (Question I – III) of the risk questionnaire are introduced.

### 2.2.3 Hazard interaction matrix

A hazard interaction matrix offers a structured approach that helps identify, analyse and visualise interactions between multiple hazards. We used the concept presented in (Gill and Malamud, 2014) and adapted the hazard interaction matrix to the spatially relevant natural hazards in the pilot regions. The matrix allows to examine the interactions between 9 types of natural hazards by determining which of these hazards could trigger or increase the probability of other hazards (Figure 3).

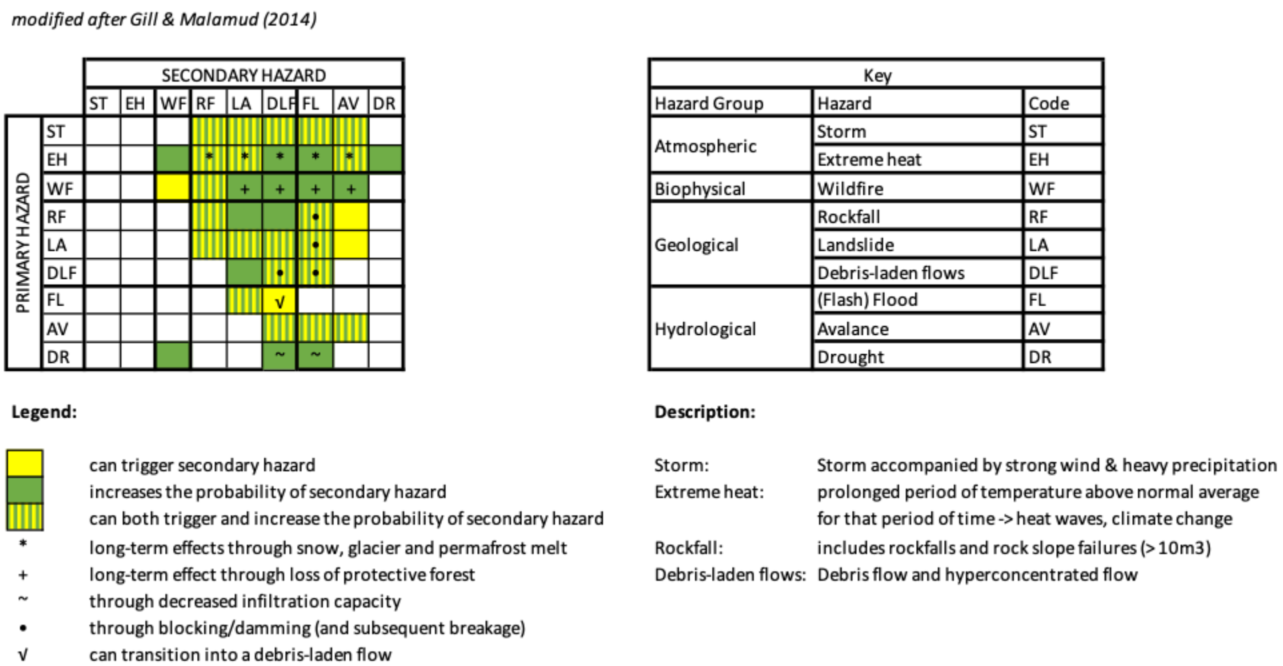


**Figure 3: A network of hazard interactions, in which a primary hazard can trigger or increase the probability of a secondary hazard. Modified after Gill & Malamud (2014).**

The Hazard-Interaction-Matrix can be applied in the pilot areas to develop sequential or compound hazard processes that can occur under current weather conditions, but also for new processes that may become relevant due to climate change (e.g., wildfire as a newly emerging hazard due to increasingly long drought periods and heatwaves), which have not yet been observed or observed to a minor degree in the pilot area but can pose a risk in the future.

### 2.2.4 Changing predisposing factors

Climate change affects many aspects of natural hazards, involving predisposition (or preconditioning), triggering and impact. Predisposing factors can be considered all physical (i.e., mechanical, thermal, and hydrological) or chemical changes that cause a transition from a stable into an unstable state (Jacquemart et al., 2024).
While changes in meteorologic triggering events, such as precipitation, wind speed, heatwaves and droughts, have been analysed in WP1, changes in geological or hydrological hazards are often more

difficult to identify: the concept of preconditioning helps to understand complex, non-linear interactions of climate change and their influence on hazard activity. We compiled a checklist that encompasses relevant predisposing factors for different hazard processes, such as debris-laden flows, floods, and wildfires. The impact of climate change on preconditioning factors can be manifold and affects debris availability, availability of driftwood, warming and thawing of permafrost and high alpine-/or glacier environments, antecedent soil moisture conditions and the state of (protective) forests and vegetation. The checklist can be applied for pilot-specific analyses, and benefits from the knowledge of local, catchment-specific conditions to estimate how possible future changes can influence the frequency and magnitude of natural hazards in the pilot area.

#### 2.2.5 Frequency-Magnitude analysis

Frequency and magnitude are particularly important variables in hazard assessment and risk analysis. Information on the frequency and magnitude of hazard processes can be obtained from a variety of sources, including instrumental records like gauging data in streams, aerial photographs and satellite images, age dating methods, numerical modelling, field reconnaissance and historical records/databases.
Inventories of hazard magnitude in a time period over which data are available can be processed and visualised in different ways, including 1) frequency-magnitude curves plotting a range of return periods (frequency) against the associated return level (magnitude) using the rank order analysis (e.g., Jakob and Nolde, 2024), 2) reconstructed time series of hazard magnitudes as individual magnitudes or magnitude classes (e.g., Lugon and Stoffel, 2010; Stoffel, 2010), and 3) statistical representation of temporal frequency of hazard events for different magnitude classes in a table (e.g., Stoffel, 2010). A classification for hazard magnitude into classes is also useful to compare the impact between affected areas (Jakob, 2005).
For the pilot analysis, different approaches can be applied depending on the type of hazard, number of data entries, and level of detail of historical records.

## 2.3 From pilot areas to the Alpine area: Exploring environmental drivers of mass movement events

To complement the detailed analyses undertaken in the X-RISK-CC pilot areas, we draw on a much larger dataset of inventoried impact events to develop a data-driven machine-learning model designed to predict the probability of past and future weather extremes that result in societal impacts due to mass movements (landslide, debris flow and rock fall) across the Alpine Space. The model is intended to better understand the relationships between the various driving factors and the conditions under which geomorphic high-impact events generally occur, thus supporting practitioners in emergency response to prepare for potential adverse consequences and know where and when critical conditions are more likely to occur.
The sequential impact chain (see Section 2.1) represents the main concept underpinning for a space-time modelling approach (Figure 4), which samples from combined landslide, debris-flow and rock-fall damage inventories across Austria and South Tyrol (Italy) spanning the period 2005-2021. Building on previous methodological developments (Steger et al., 2024), meteorological indicators, accessible at different spatial scales, were integrated with morphometric, geological, hydrological, land cover data, as well as data on potentially exposed assets, to train hierarchical generalised additive mixed models (GAMMs), one for each gravitational mass movement process, based on half-basin units. By inferring statistical relationships between impact events and their drivers, we aim to evaluate how this knowledge can be used to inform the design and implementation of risk reduction

measures, such as impact-based forecasts and warnings. The sample used for training the model is built from combined landslide, debris-flow and rock-fall damage inventories across Austria and South Tyrol (Italy) spanning the period 2005-2021.
A full description of method is provided in the supplementary appendix to Deliverable 2.2.1. The results in Section 3.2 focus on the environmental drivers and triggering conditions of mass movement impact events observed across Austria and South Tyrol (Italy), between 2005 and 2021. While the models were trained using mass movement events from Austria and South Tyrol, data was processed for the entire Alpine Space to allow spatial transferability of the models to the entire Alpine Region.

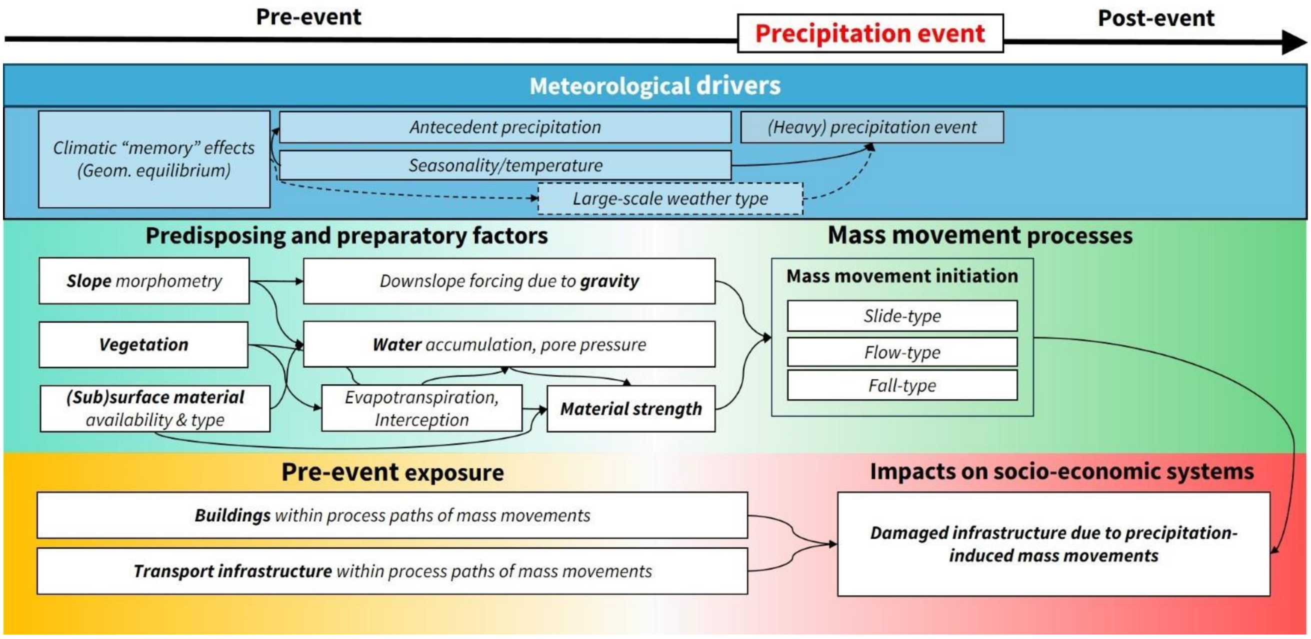


**Figure 4: A sequential impact chain for mass movement impact events provides the conceptual underpinning of the mass movement models, describing the meteorological drivers that interact with key predisposing and preparatory factors to trigger mass movement processes causing impacts on society when affecting exposed infrastructure.**

# 3 Results on past and future (compound) hazards

## 3.1 Past and future (compound) hazards in the pilot areas

Relevant past and future hazards caused by various weather extremes were analysed for five pilot areas, and their sub-regions, across the Alps (Figure 5 and Figure 6). In the following subchapters, we summarised the elaborated results in each pilot area, including with the sequential impact chains (see Section 2.1) and the analysis on the climate and (multi-)hazard situation in the pilot areas within the framework of the risk questionnaire (see Section 2.2). The full risk questionnaires with detailed answers by each pilot area are provided in the supplementary appendix to Deliverable 2.2.1.

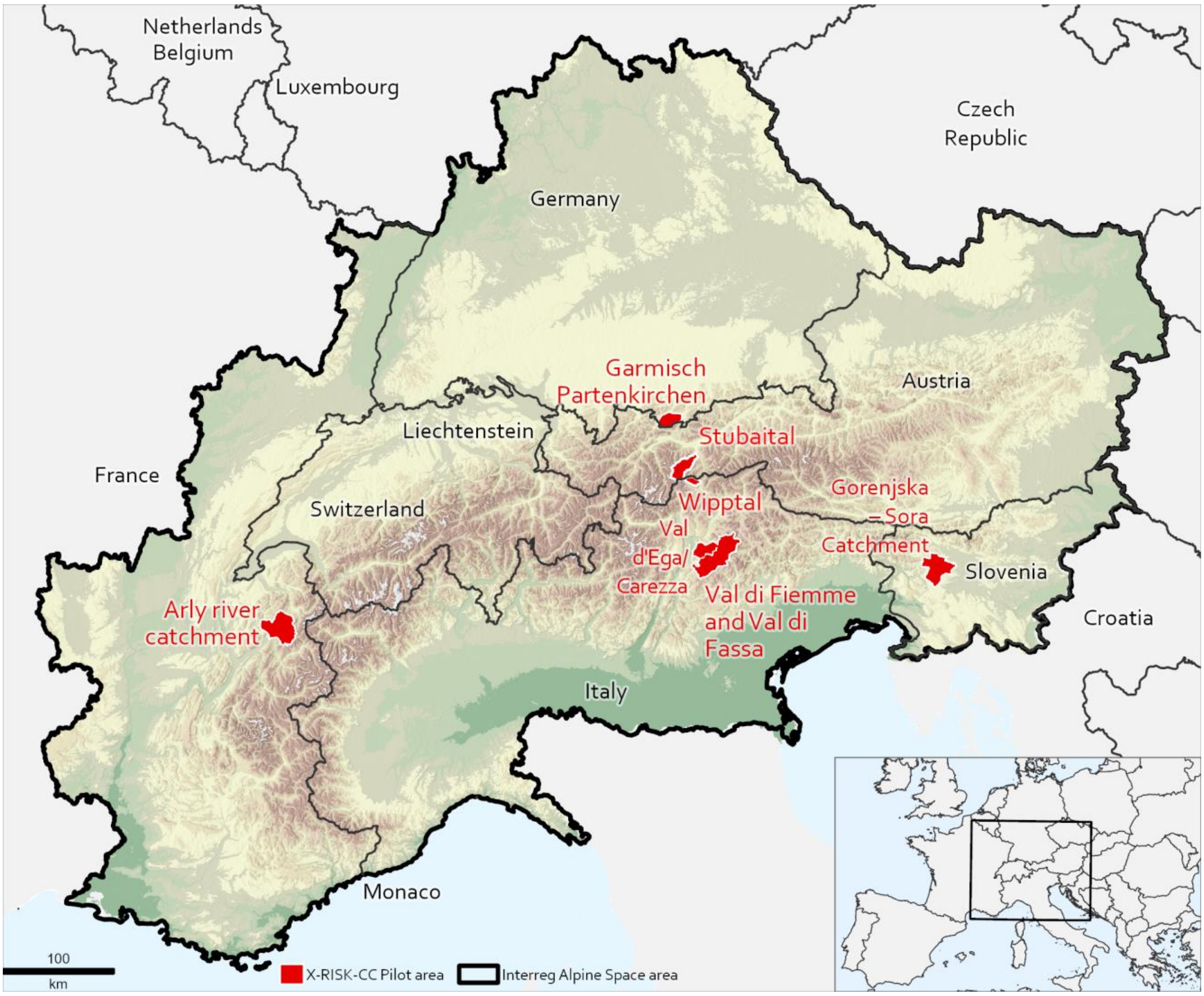


Figure 5: Map showing the location of the X-RISK-CC pilot areas and sub-regions.

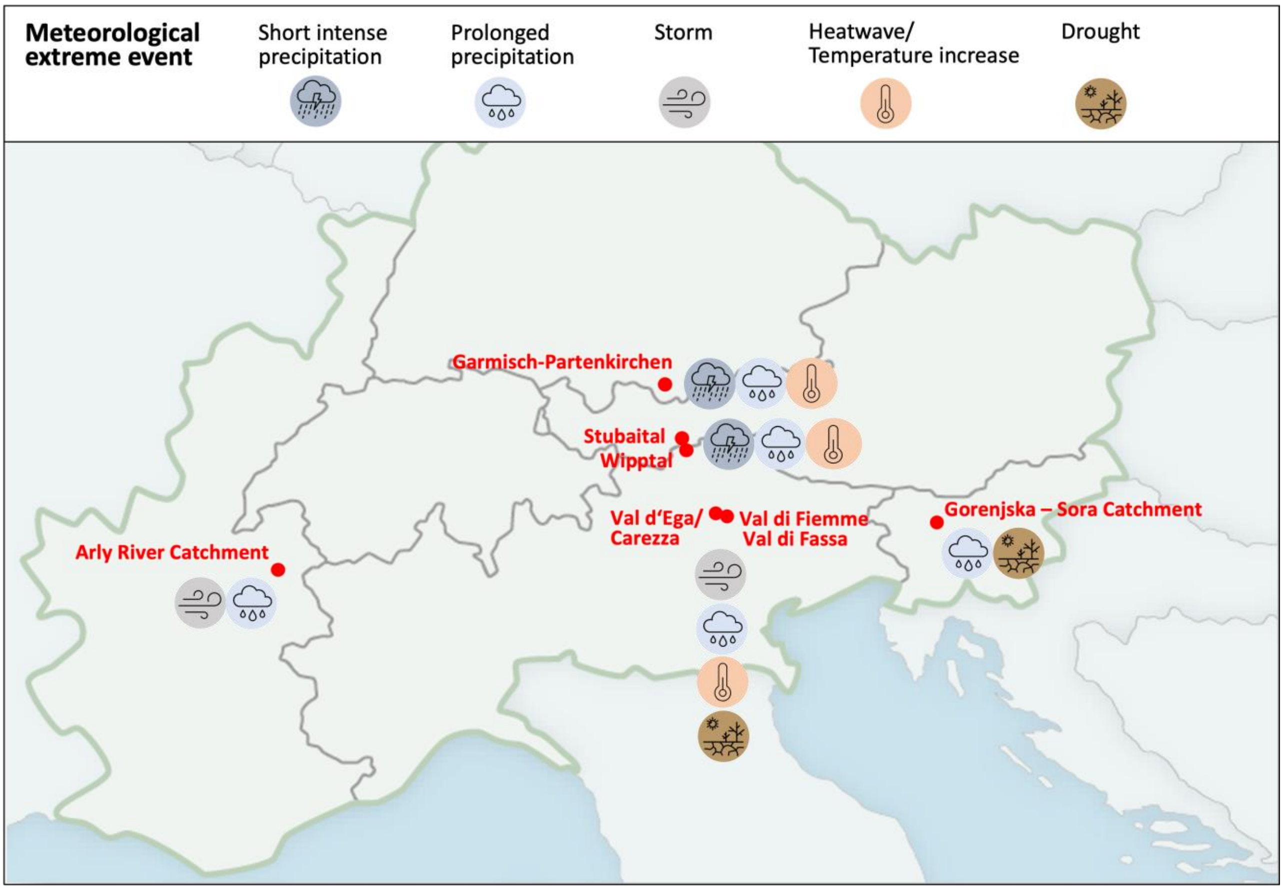


**Figure 6: Map showing the weather extremes in the pilot areas and sub-regions leading to natural hazard events.**

### 3.1.1 Gorenjska, Slovenia

#### 3.1.1.1 Pilot area introduction and impact chain

The pilot area of Gorenjska is located in northwestern Slovenia, in the eastern Alps. The Gorenjska – Sora catchment covers an area of approximately 512 km$^2$ with elevation ranging from about 320 m to 1,600m above mean sea level (a.m.s.l.). The main rivers in the catchment are Selška Sora in the north and Poljanska Sora in the south of the pilot area (Figure 7).

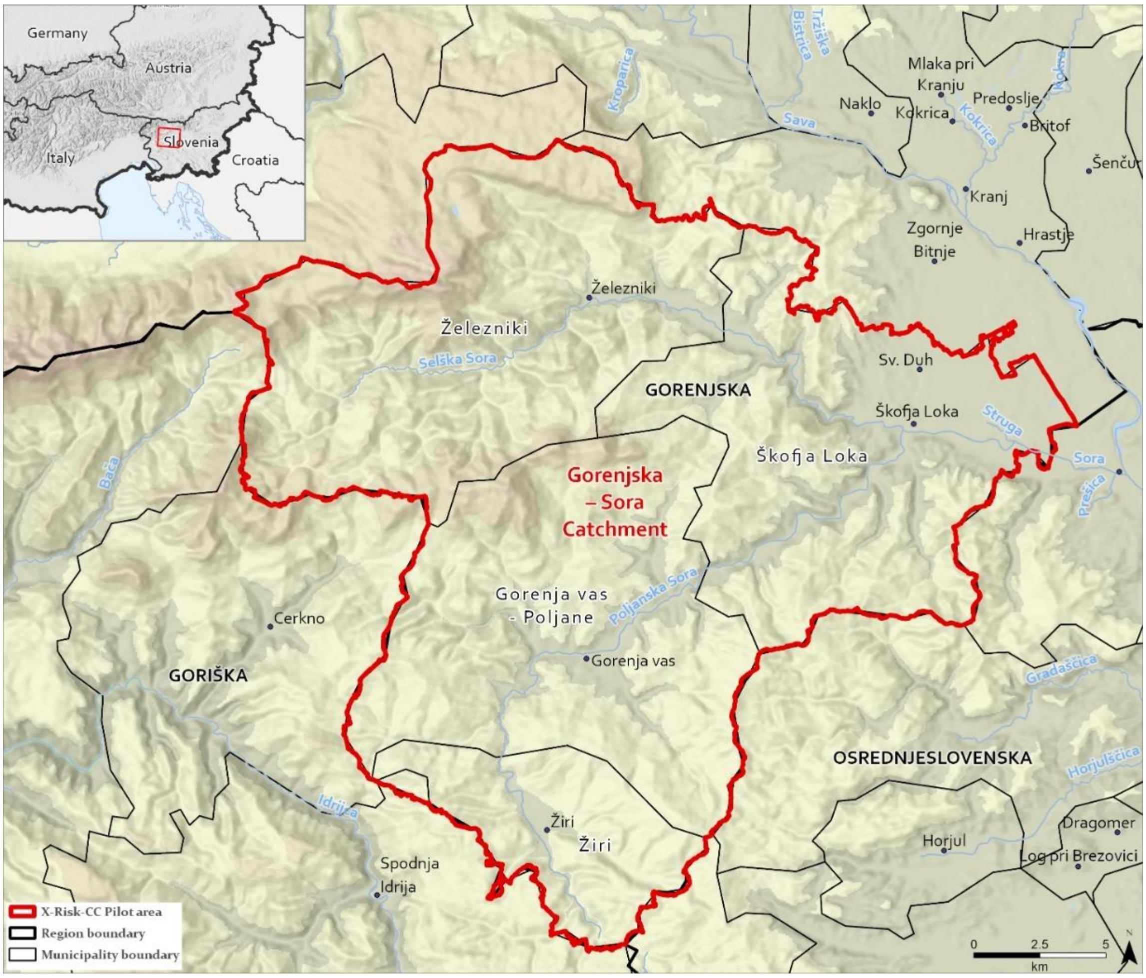


**Figure 7: Map showing the extent of the pilot area Gorenjska – Sora catchment.**

In the Gorenjska pilot area, two hazard types – droughts and flash floods – were analysed. In order to identify, understand and visualise cause-effect relationships three respective impact chains were created (Figure 8, Figure 9 and Figure 10).

## Gorenjska – Drought / Flash drought (Y. 2022)

*(focus municipalities: Škofja Loka, Gorenja vas – Poljane, Železniki, Žiri)*

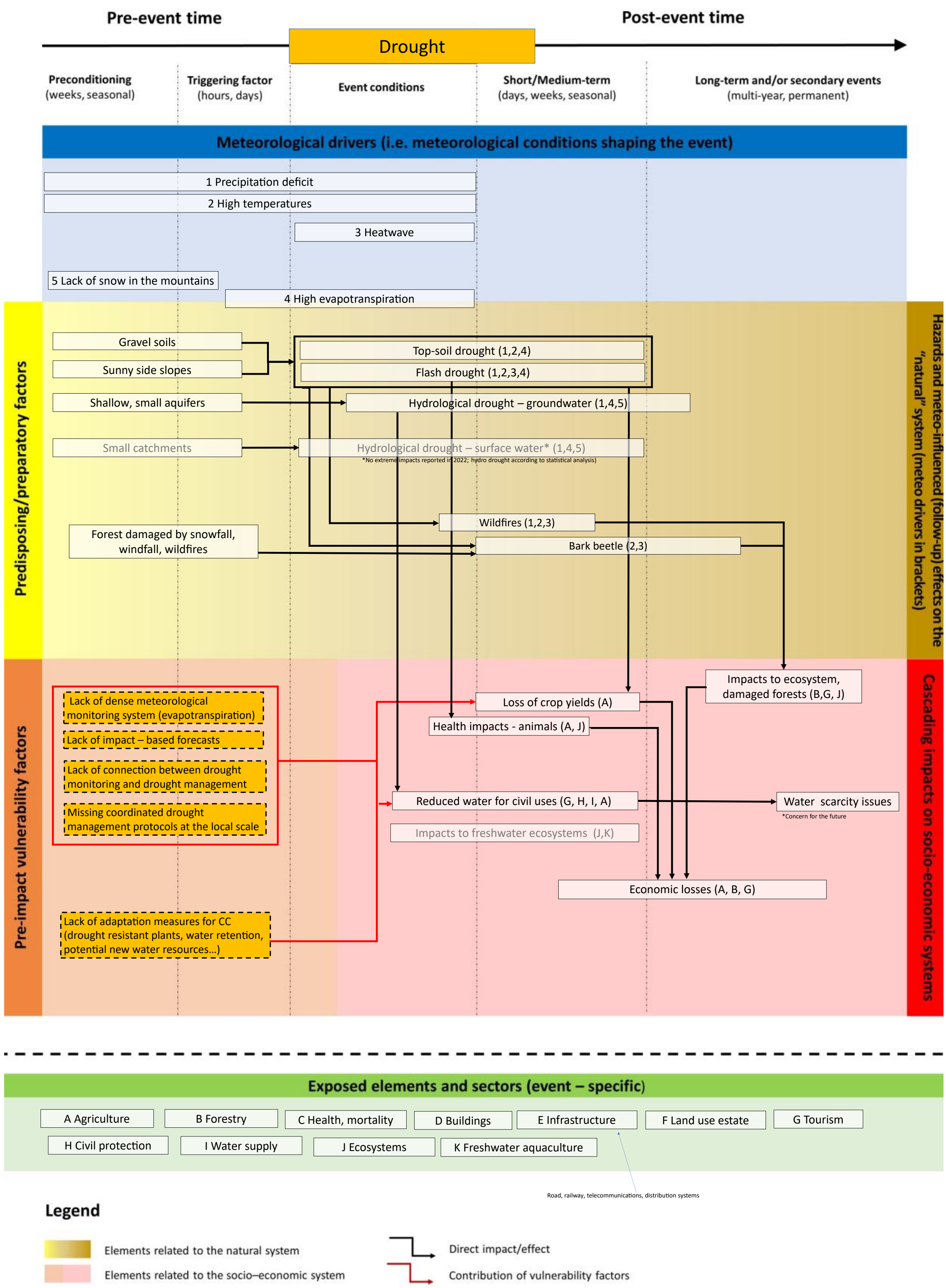


**Figure 8: Impact chain of the risk of drought in Gorenjska.**

## Gorenjska – Flash Floods (Floods) – (Y. 2007)

*(focus area: Gorenjska – Sora watershed)*

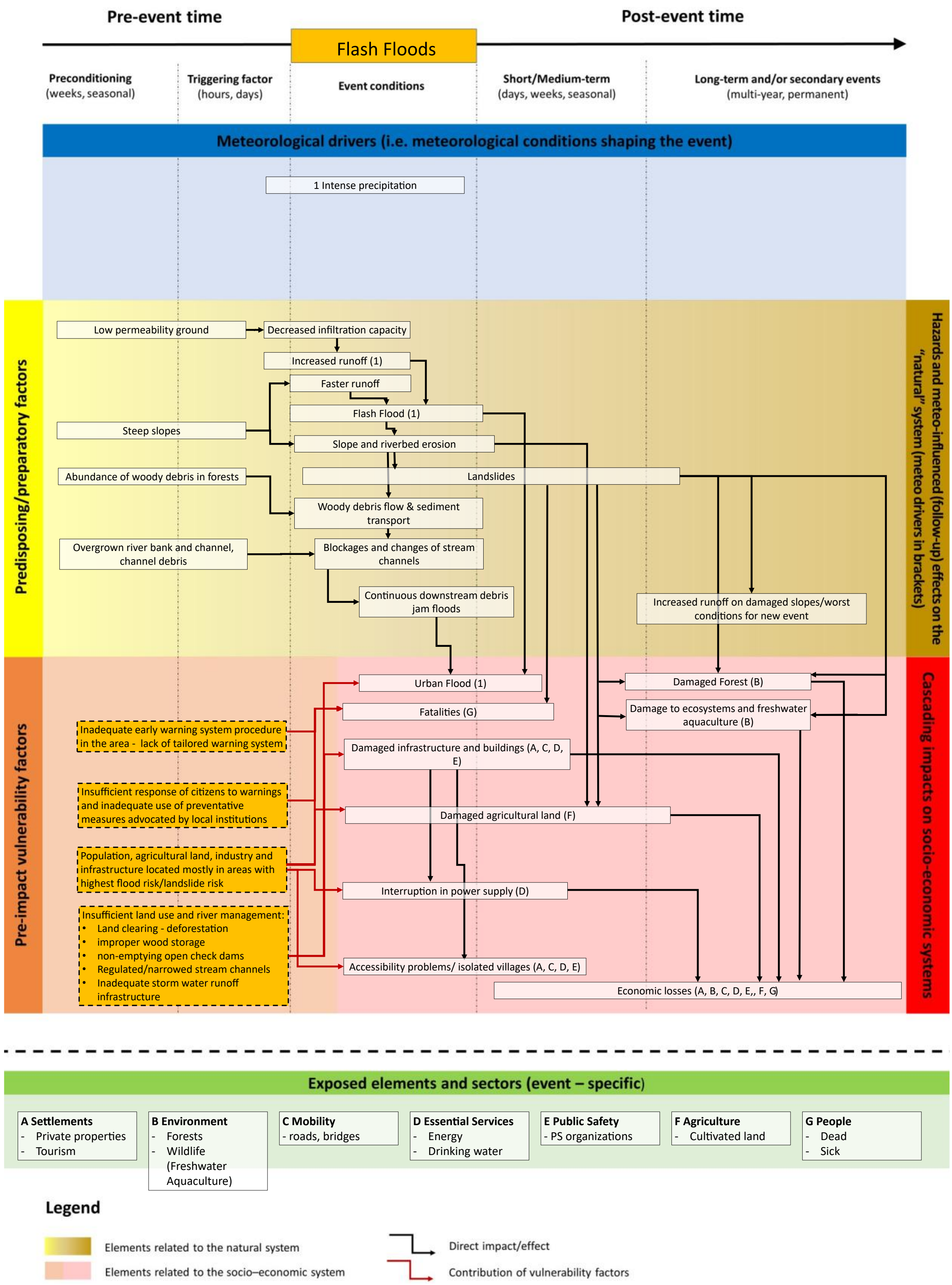


**Figure 9: Impact chain of the risk of floods in 2007 in Gorenjska.**

## Gorenjska – Flash Floods (Floods) – Y. 2023

*(focus area: Gorenjska – Sora watershed)*

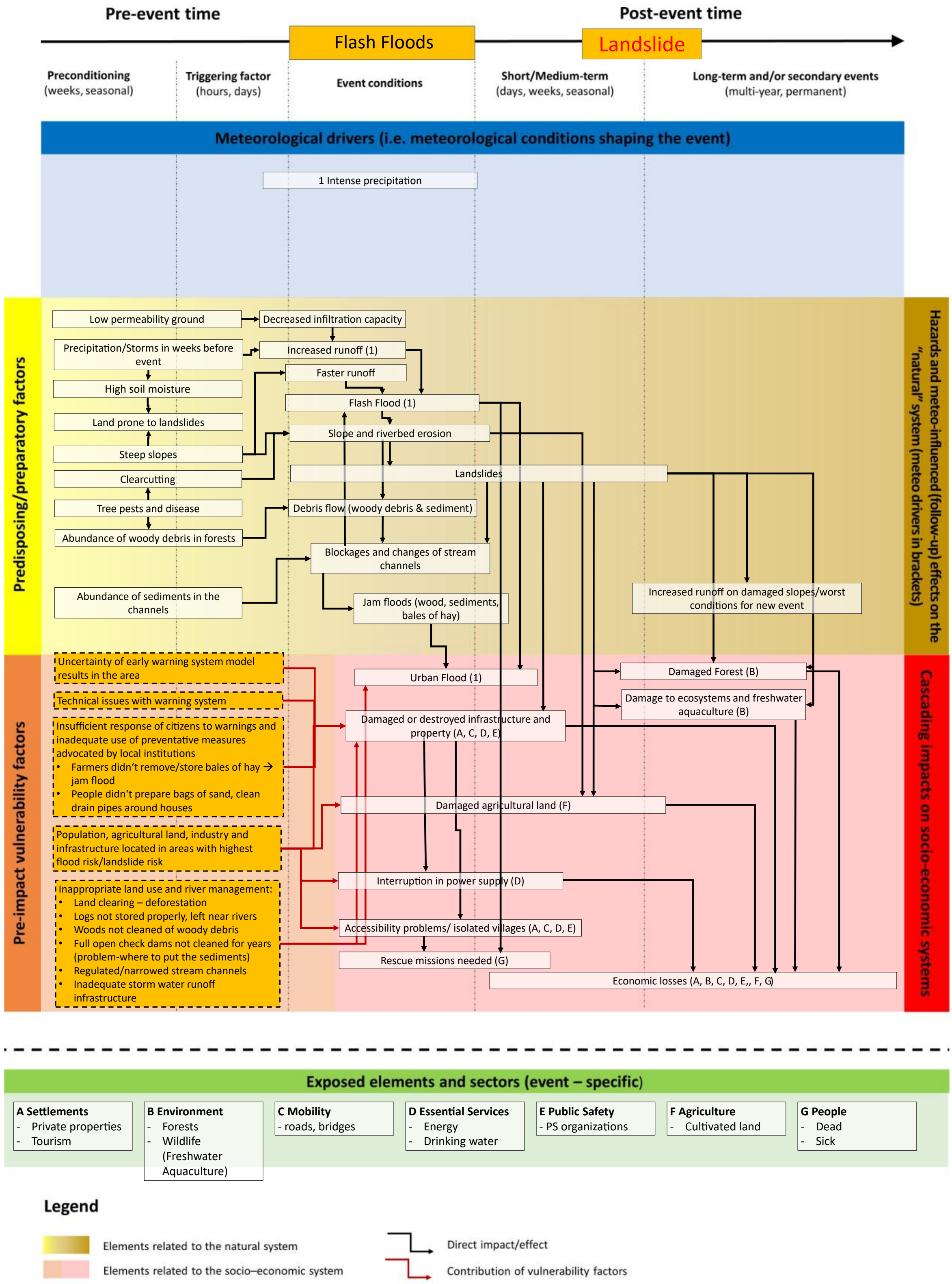


**Figure 10: Impact chain of the risk of floods in 2023 in Gorenjska.**

#### 3.1.1.2 Weather extremes in the past and in the future

**Drought** is considered as weather extreme and hazard, likewise. In the pilot area Gorenjska, top-soil drought, heatwaves, compound events of drought and heatwave events, and groundwater drought were studied.
Past weather extremes:
Historical data shows an increase in frequency of occurrence of circulation patterns that reinforce top-soil drought. Comparing two consecutive 30-year periods, the number of dry and severely dry months shows an increase, with the three most severe drought events happening in 2003, 2013 and 2022. 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. 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. With regard to groundwater drought, it is found that in the period 1971–2023, according to the data of groundwater recharge, there were severe droughts between March and August in the years 1993 and 2022, while in 1997, 2003, 2011, 2012, 2015, and 2017 moderate droughts were recorded.
Future weather extremes:
In the future, both top-soil 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 %. For groundwater drought, net groundwater recharge 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. The situation could be different for dry summer periods, but the future scenarios for summer months are disperse.

Floods
Past weather extremes:
The two most pronounced events in the Sora Catchment were floods in September 2007 and in August 2023, resulting from 1- to 3-day extreme precipitation with return periods of at least 200 years (locally exceeding 500 years). 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.
Future weather extremes:
For 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 97$^{th}$ 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).

See the WP1 pilot report of Gorenjska for further information on the climate projections.

#### 3.1.1.3 Hazard events due to weather extremes in the past

**Drought**
As drought is considered as weather extreme and hazard, likewise, past and future trends of drought events have been described in the previous Section 3.1.1.2. However, drought in combination with heatwaves can also trigger cascading effects in the pilot area like wildfires, as well as animal and plant diseases (e.g., bark beetle infestation). Droughts can also increase the probability of negative effects of subsequent heavy rain and flood events, due to changed infiltration capacity, damaged vegetation and related more rapid surface runoff. In the recent past, cascading events of drought and subsequent floods happened in 2007 and 2022.

**Floods**
In the Sora River Catchment, extreme precipitation can lead to several hazard processes, including river floods, flash floods, debris flows and landslides. The most relevant natural hazards are flash floods (triggered by short, intense precipitation) and river floods (after prolonged rainfall). Debris flows are occurring in smaller scale in the tributaries relative to the Sora River activating alluvial fans. Since the beginning of the 20th century, 16 flood events have been recorded, with the most severe floods happening in 1923, 1926, 1990, 2007 and 2023.

#### 3.1.1.4 Hazard events due to weather extremes in the future

**Drought**
See Section 3.1.1.2, paragraph future weather extremes.

**Floods**
Due to an increase in expected precipitation intensity, all observed phenomena related to floods, erosion processes, mass movements and debris flows are expected to intensify as well. Extreme events, like those observed in 1924, 1926, 2007 and 2023 are likely to occur on an even more frequent basis.

#### 3.1.1.5 Past/present hazard frequencies and magnitudes

**Drought**
See Section 3.1.1.2, paragraph past weather extremes.

**Floods**
Six gauging stations distributed across the catchment are recording water level and river discharge. We used the series of available discharge data and evaluate the return period (2 year- up to a 1000-year flood) of a particular discharge. Hazard maps for 10-, 100-, and 500-year floods exist for the Sora Catchment, but climate change impacts are not included yet.

#### 3.1.1.6 Potential future hazard frequencies and magnitudes

**Drought**
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 (see Section 3.1.1.2). In relation to that, there is high likelihood of increase of other related cascading hazards in the future, like wildfires and 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.

**Floods**

The expected increase in frequency and intensity of 1-hour and 1-day precipitation can affect the geo-hydrosystem of the Sora Catchment in the following way:
Enhanced sediment availability due to accelerated landslides, increased hillslope-channel coupling, also leading to higher probability of debris-laden flows
More intense and more frequent flooding events due to high saturation of the soil during prolonged rainfall, inhibiting infiltration of water and leading to enhanced surface runoff
more frequent flash floods triggered by short-duration rainstorms
Considering forest stands and their retention capacity in the Sora Catchment, we estimate that disruptions can become more likely in the future due to windbreaks (caused by storms) and replacement/adaption of spruce trees with more resilient species.

According to a recent study at the University of Ljubljana about (multi-) hazard analysis of the Sora Catchment, it is estimated that there will be a shift in return periods of the river discharges resulting in floods. With a high degree of uncertainty, an estimate is given for the expected return periods and corresponding future discharges. The current 100-year return period flood corresponds to the flood with the 10-year return period in 2100, the current 500-year flood to 100-year flood in 2100, and current 500-year flood discharge increased for 20 % to the 500-year flood in 2100.

### 3.1.2 Garmisch-Partenkirchen, Germany

#### 3.1.2.1 Pilot area introduction and impact chain

The pilot area of Garmisch-Partenkirchen is located in southern Germany, within the central Alps, north of the alpine ridge. It spans approximately 223 km², with elevations ranging from about 680 to 2,900 m a.m.s.l.. The main river in the pilot area is the Partnach (Figure 11).

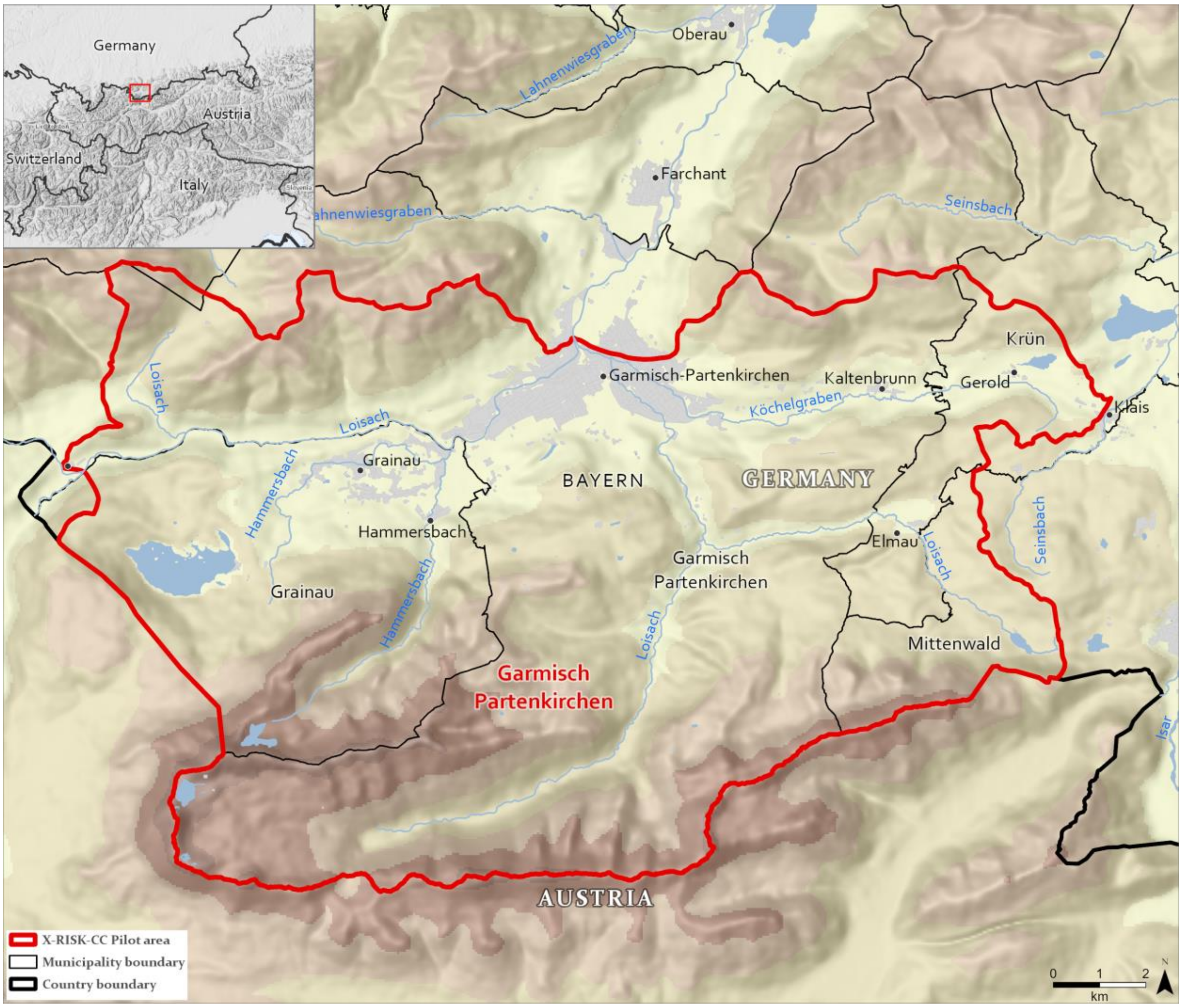


Figure 11: Map showing the extent of the pilot area Garmisch-Partenkirchen

In the pilot area Garmisch-Partenkirchen floods and flash floods as well as cascading gravitational mass movements and floods were analysed. A respective impact chain was created (Figure 12).

## Garmisch – Compound cascading gravitational mass movements and floods

*(focus area: Hammersbach, Ferchenbach & Partnach catchments, especially Reintal, Höllental, Partnachklamm & Höllentalklamm)*

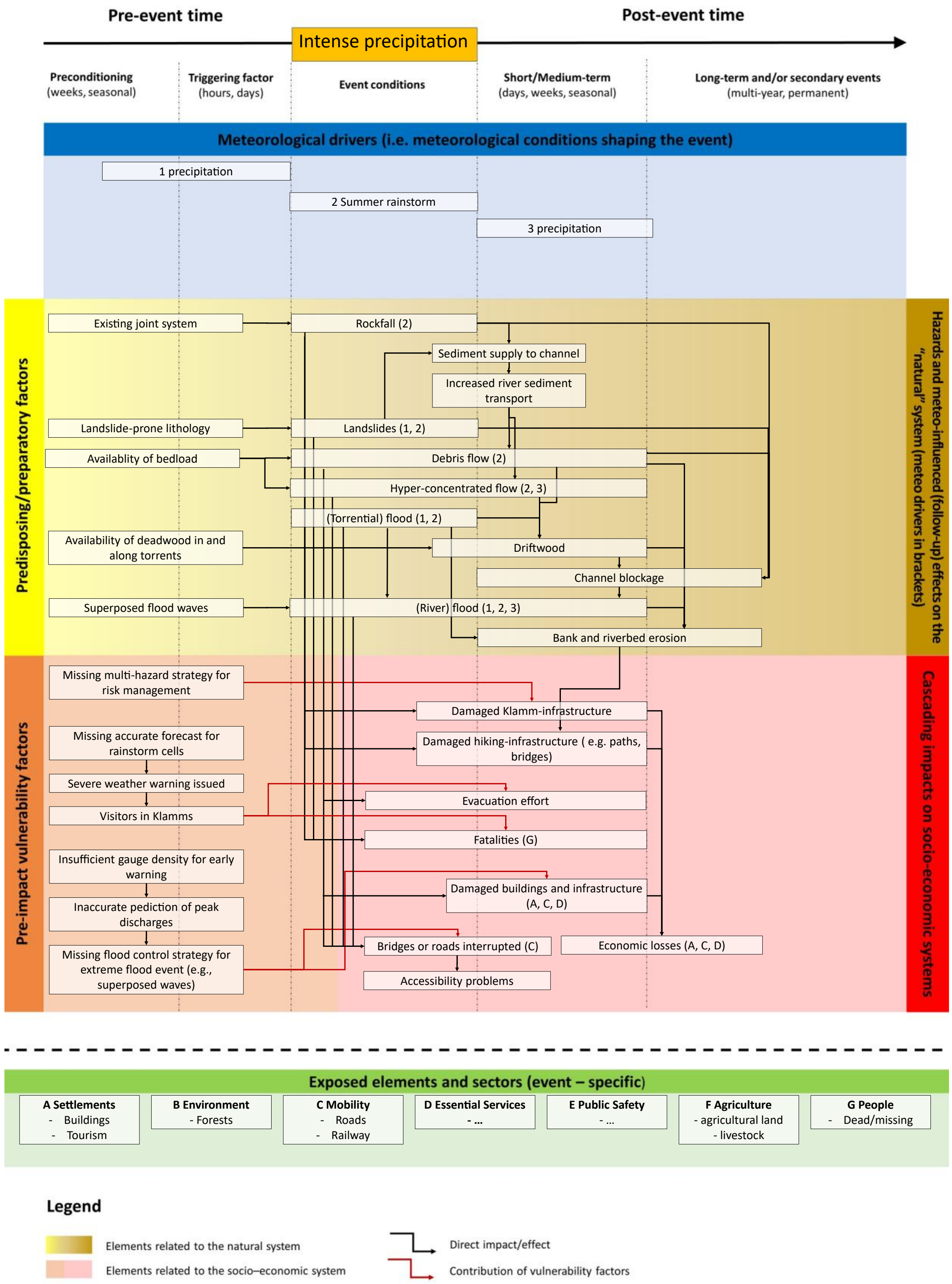


**Figure 12: Impact chain of gravitational mass movement and floods in Garmisch-Partenkirchen.**

#### 3.1.2.2 Weather extremes in the past and in the future

The main weather extremes considered in the Garmisch-Partenkirchen pilot area are heavy precipitation events, especially 1-day and sub-daily (1-hour) rainfall. Analysis of weather station data (conducted by WP1) show that 1-day precipitation maxima have increased up to + 2.5 %/decade (station Zugspitze). Short-duration (1-hour) precipitation above the 99$^{th}$ percentile increased over the period 2000-2023 by + 4.3 events/decade (station Garmisch-Partenkirchen), while half of the annual trend can be attributed to summer events. Analysis of climate trends (period 1951-2015) show an increase in mean annual temperature of +1.5 °C and approximately + 7 days of dry conditions without rain from April until June (reported by Bavarian Environment Agency).

Future projections anticipate an increase in the annual number of days with daily precipitation above the 97$^{th}$ percentile, reaching between 12 to 25 more extreme precipitation days under GWL 4 with respect to 1991-2020. The intensity of 1-day precipitation extremes is projected to increase by 7 % (station Garmisch-Partenkirchen) under GWL 4. Estimations for future sub-daily (1h) precipitation, based on the Clausius-Clapeyron relation (7.6 % ± 1.1 % per °C of warming), indicate an increase in intensity: using 1991-2020 as reference period, it yields increases for the current 99$^{th}$ percentile from 8.2 mm/h to 11.0 mm/h under GWL 1.5 and reaching 32.4 mm/h under GWL 5. In addition, drier conditions in summer months are expected due to rising temperatures and a deficit in summer precipitation of up to -24 %.

#### 3.1.2.3 Hazard events due to weather extremes in the past

The region of Garmisch-Partenkirchen is exposed to multiple hazards such as debris-laden flows, river floods, flash floods, rock slope failures and landslides. 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 Partnach Gorge and Höllental Gorge, as well as the town of Garmisch-Partenkirchen.
The Partnach Gorge is frequently hit by flooding events with relatively low sediment concentration, but driftwood log jams are a major issue. Landslides and debris flows are occurring further upstream in the tributary catchments of the gorge, leading to a generally high sediment availability. In 2020, a hyperconcentrated flow rushed through the neighbouring Höllental gorge, revealing the potential for such types of flow in the pilot area.

#### 3.1.2.4 Hazard events due to weather extremes in the future

The projected increase in frequency and intensity of extreme 1-day precipitation can also increase the likelihood of flooding and compound flooding events at the Kankerbach, Partnach and Ferchenbach. It is also expected to enhance mass-wasting processes (large landslides and debris flows), acting as sediment source of debris-laden flows in the lower Partnach Catchment. The projected warmer climate and prolonged drought periods in summer can also increase the potential for wildfires and cascading debris-laden flow hazards in subsequent years.

#### 3.1.2.5 Past/present hazard frequencies and magnitudes

We have analysed discharges of past flood and flash flood events at the gauging station Partenkirchen/Partnach for the period 1920-2020, which shows a clear trend of flood events happening more frequently since the 1980s. Sediment yield characteristic of the lower Partnach Catchment approximates 1000 $m^3$/year. Debris flows in the upper Reintal in 2005 have reached volumes up to 50,000-100,000 $m^3$ and the hyperconcentrated flow in the Höllental gorge in 2020 reached about 60,000 $m^3$.

### 3.1.2.6 Potential future hazard frequencies and magnitudes

The projected increase in frequency and intensity of extreme 1-day and 1-hour precipitation is expected to lead to sediment overloading of the Partnach and Ferchenbach by landslides and debris flows, increasing the likelihood of debris-laden flows, that also reach the Partnach Gorge. After wildfires, which can get more relevant in the projected warmer climate and with prolonged drought in the summer, debris flow activity is expected to intensify. Studies from burnt slopes north of Innsbruck have shown that erosion rates remained ten times higher even decades after the wildfire. Potential future volumes of debris-laden flows are estimated to reach > 10,000 $m^3$. Flash floods in the gorge are also expected to occur more frequently with projected changes in convective (1-hour) rainfall.

### 3.1.3 Stubaital, Austria

#### 3.1.3.1 Pilot area introduction and impact chain

Stubaital is the Austrian part of the Wipptal/Stubaital pilot area. It is located in western Austria, in the centre of the Alps and spans approximately 282 km², with elevations ranging from about 780 m in the northeast to 3,500 m a.m.s.l. at the southwestern edges. The main river is called Ruetz (Figure 13).

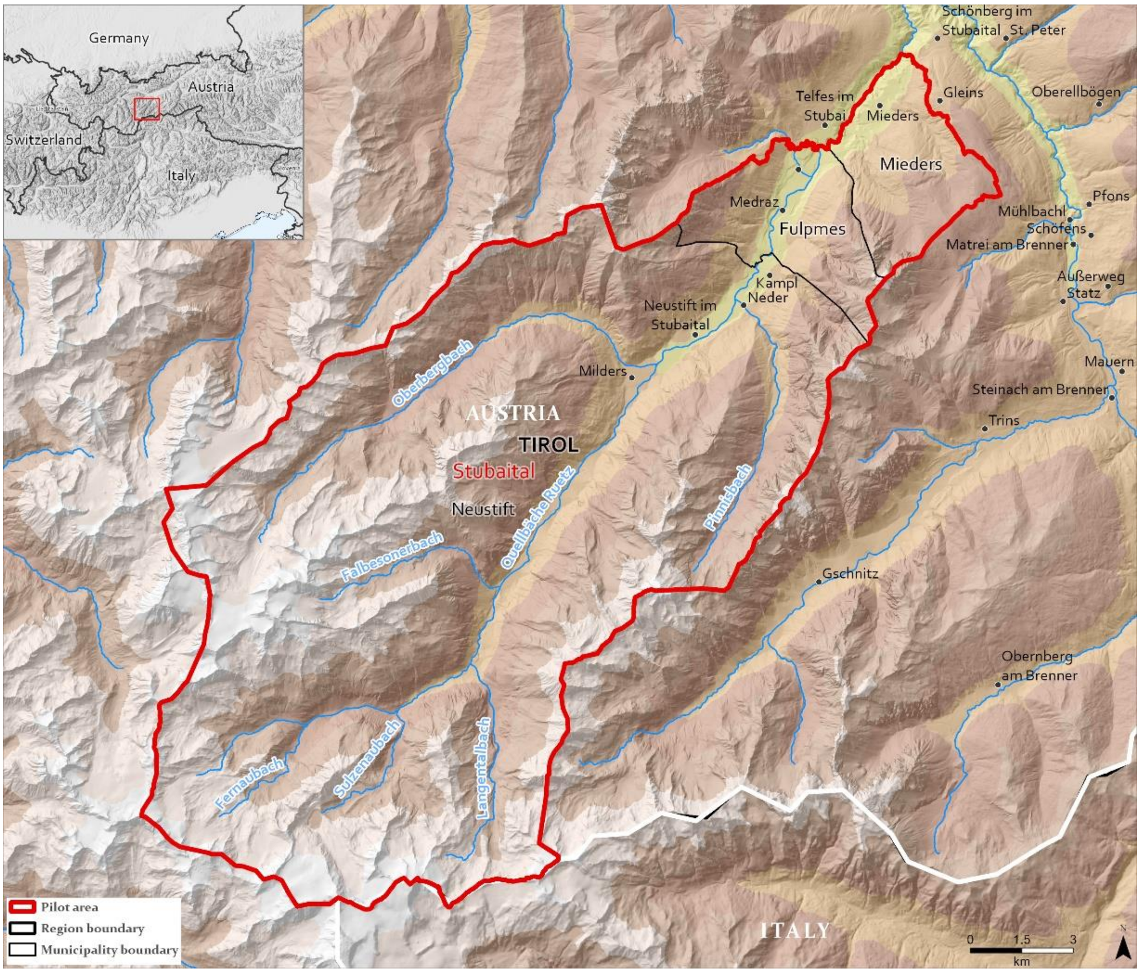


Figure 13: Map showing the extent of Stubaital.

In Stubaital, debris flows and hyperconcentrated flows in five catchments (Mutterbergbach, Grawanockbach, Oberbergbach, Margaretenbach, Mühltalbach) were analysed. The impact chain for Stubaital was developed in conjunction with the Italian portion of the pilot area in Wipptal (Section 0, Figure 14).

## Wipptal - Stubaital – Debris flows + river flooding

*(focus area: Wipptal Stubaital)*

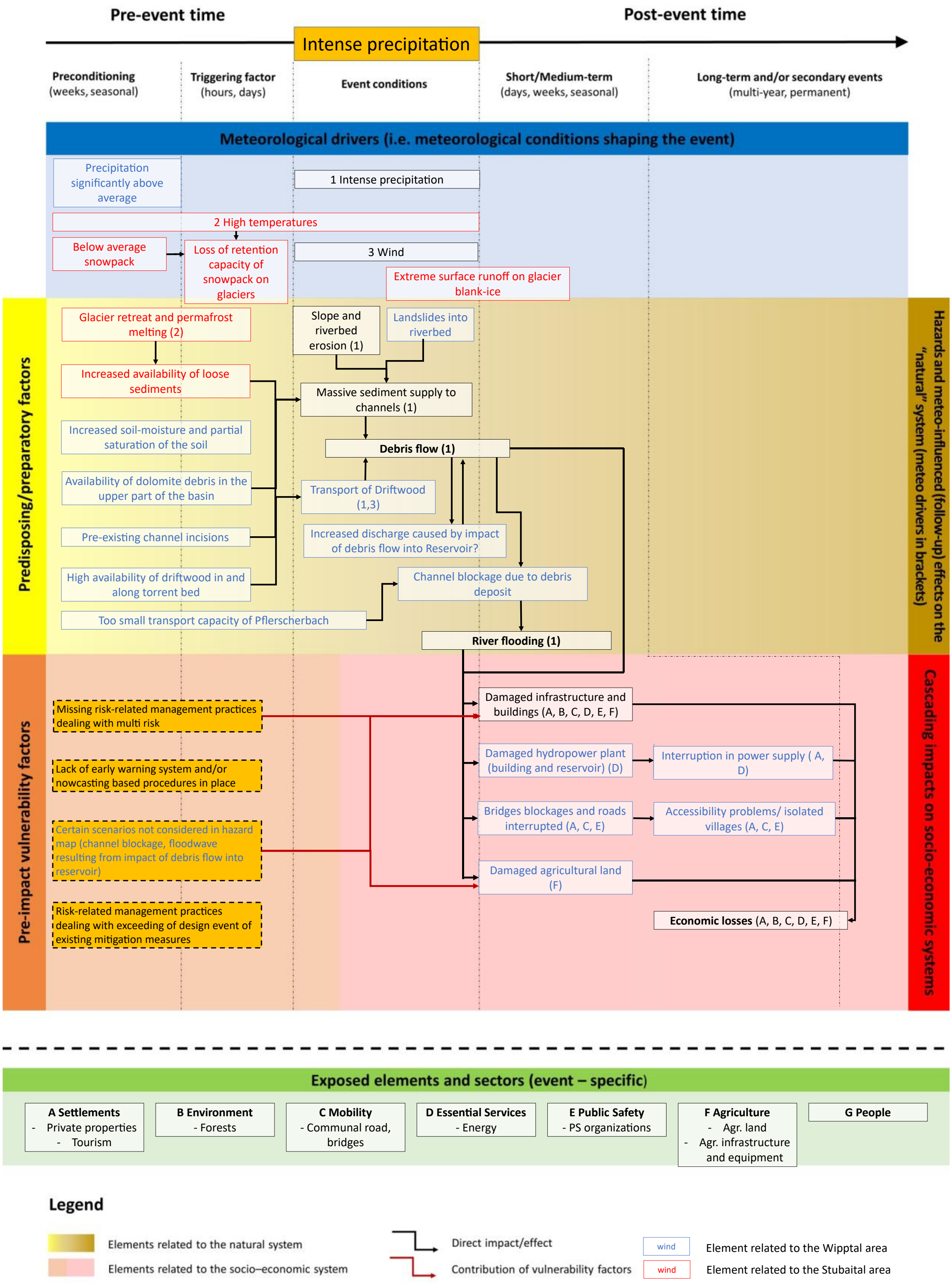


**Figure 14: Impact chain of the risk of intense precipitation and debris flows in Wipptal-Stubaital.**

#### 3.1.3.2 Weather extremes in the past and in the future

WP1 analysis show positive trends of past 1-day precipitation extremes with an increase of up to +14 % per decade with respect to long-term averages.
In the future, the frequency of heavy 1-day precipitation is projected to increase by +3 % under best-case scenarios (global warming limited to +1.5 °C or +2 °C) and by up to +23 % under worst-case scenarios (global warming reaching +3 °C or +4 °C).
Projected changes in the intensity of 1-day precipitation extremes relative to the current values (1971–2000) indicate increases all return periods across all global warming scenarios. For a 20-year recurrence event, the spatial average of projected increases in precipitation intensity ranges from +5 % to +15 %, depending on the global warming level.
Additionally, the frequency of heavy, short-term precipitation events (sub-daily precipitation) is projected to rise between +6 % to +46 % compared to the current period (1991–2020), depending on the level of global warming.

See the WP1 pilot report for Wipptal/Stubaital for further information on the climate projections.

#### 3.1.3.3 Hazard events due to weather extremes in the past

55 torrential events (mostly debris flows and hyperconcentrated flows, few river floods) have been documented in the five torrent catchments (Mutterbergbach, Grawanockbach, Oberbergbach, Margaretenbach, Mühltalbach). Short duration precipitation events with high intensities are most relevant, however also long-duration precipitation events caused torrential processes.

#### 3.1.3.4 Hazard events due to weather extremes in the future

For the Stubaital, climate change 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. The reduction in the movement speed of thunderstorms is expected to promote the occurrence of quasi-stationary events, longer lasting convective events might be underestimated.
The projected temperature rise in the Alps implies a rising snow line of several 100 m, less solid precipitation and less snow cover during events, which can retard parts of the precipitation.

#### 3.1.3.5 Past/present hazard frequencies and magnitudes

Based on the extensive event documentation by the WLV, which can be regarded systematic since the 1970s, the number of debris-laden flow events have strongly increased since 2010, and especially in the most recent decade (2020-2024), although covering only 4 years.
Analysis of changes in debris flow volumes per decade have shown a strong rise in mobilised material per event since in the period 2010-2019 and most remarkably in 2020-2024.

#### 3.1.3.6 Potential future hazard frequencies and magnitudes

Sediment availability is identified as a crucial factor for future debris flow activity in the pilot area (sediment limited vs. transport limited catchments). In each of the five catchments, characteristic

predisposing factors are evaluated for potential future changes, their influence on debris-flow activity, and capabilities of existing mitigation measures.
For example, the high-alpine Oberbergbach Catchment is expected to be capable of producing larger debris-flow magnitudes due to increased availability of loose sediment due to permafrost degradation and the rise of the snow line. For transport limited catchments (high sediment availability), it is deducted from a semi-quantitative approach, that proven hazard zones will be affected three times more often by 2050 compared to the current situation.

### 3.1.4 Wipptal, Italy

#### 3.1.4.1 Pilot area introduction and impact chain

Wipptal is the Italian part of the Wipptal/Stubaital pilot area. It is located in northern Italy, in central-eastern Alps. Wipptal covers the Pflersch Valley, an area of approximately 75 km$^2$ with elevation ranging from about 1,000 m in the centre of the valley to 3,200 m a.m.s.l. at the northern, western and southern edge. The main river in the valley is called Pflerscherbach/Rio di Fleres (Figure 15).

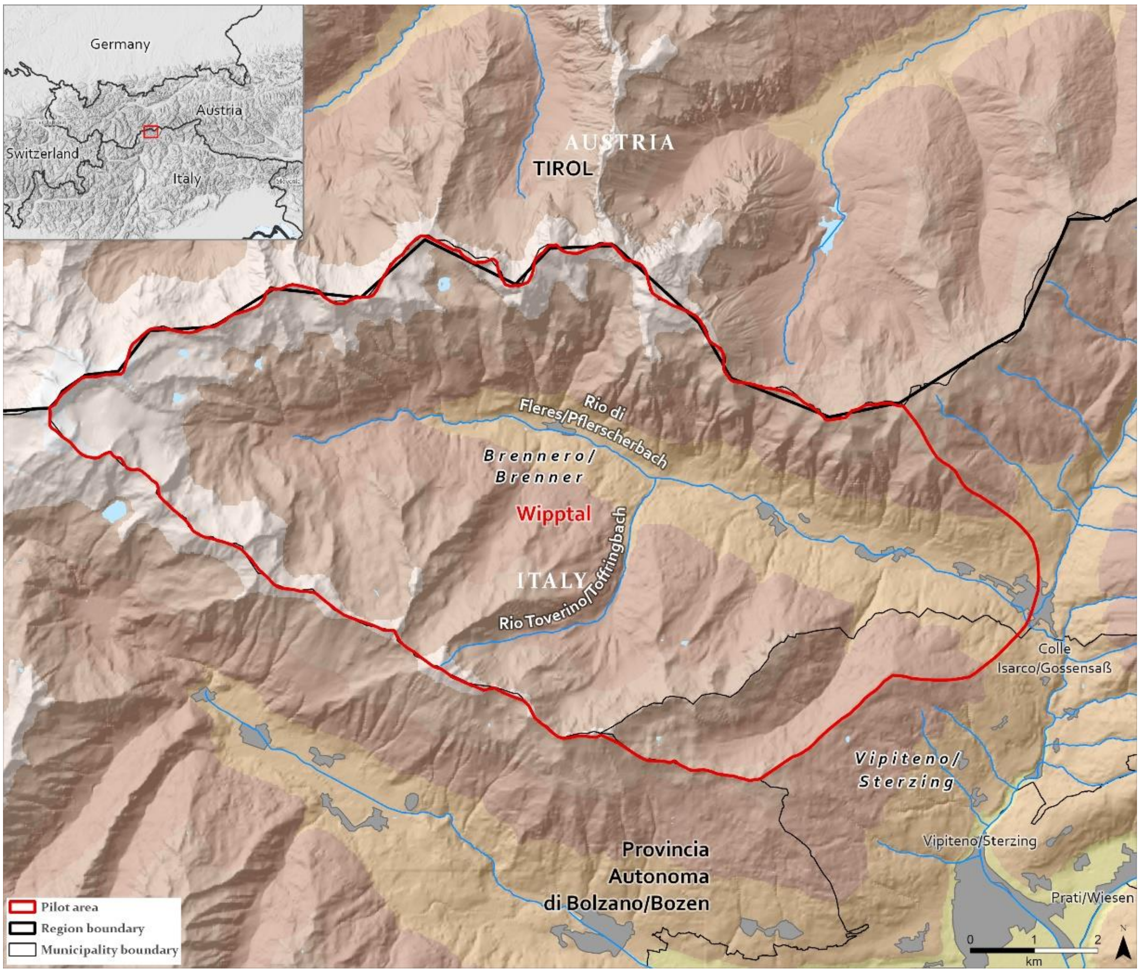


**Figure 15: Map showing the extent of Wipptal (actual extent of Pflersch Valley).**

The compound events considered in Wipptal include debris flows and river flooding. The impact chain was developed in conjunction with the Austrian part of the pilot area in Stubaital and illustrates the cause-effect relationships between hazard-triggering factors (Figure 14).

#### 3.1.4.2 Weather extremes in the past and in the future

In WP1, we calculated that in Wipptal, compared to the current period (1991–2020), the intensity of 1-day precipitation maxima is projected to increase by +4 % under best-case scenarios (global warming limited to +1.5 °C or +2 °C) and by up to +16 % under worst-case scenarios (global warming reaching +3 °C or +4 °C).

Additionally, the frequency of heavy precipitation events is projected to rise in the next decades, ranging from +6 % to +46 % compared to the current period (1991–2020), depending on the level of global warming.
Projected changes in the return levels of 1-day precipitation extremes relative to the current values (1971–2000) indicate increases for 10-, 20-, 50-, and 100-year return periods across all global warming scenarios. For a 20-year recurrence event, the spatial average of projected increases in precipitation intensity ranges from +4 % to +18 % under the worst-case scenario of +4 °C global warming.

See the WP1 pilot report for Wipptal/Stubaital for further information on the climate projections.

#### 3.1.4.3 Hazard events due to weather extremes in the past

We analysed a debris flow followed by a flooding event that occurred on August 16, 2021. This cascading event was triggered by heavy rainfall exceeding 80 mm in a single day, causing damage to buildings and infrastructure.
The Wipptal area, with steep catchments feeding into the Fleres valley, is prone to debris flows due to intense summer rainfall and steep slopes. On August 16, 2021, a heavy storm triggered a debris flow in the Toverino river, mobilising 25,000–35,000 m³ of material and causing severe erosion downstream.
Debris deposited at the Fleres confluence led to flooding, damaging buildings, farmland, roads, and a hydroelectric plant. This cascading event highlights the complex interactions between hazards triggered by heavy rainfall. Heavy rainfall triggered and increased the likelihood of debris flows on the Toverino river. In turn, the debris flow caused flooding on the Fleres river by blocking and damming its flow.

#### 3.1.4.4 Hazard events due to weather extremes in the future

An increase in the intensity and frequency of extreme precipitation, coupled with permafrost thaw, may raise the likelihood and magnitude of debris flows and landslides in the future. The future hazard interaction matrix mirrors the past but reflects potential intensification of summer storms, likely triggering more debris flows, landslides, and flooding on the main river.

#### 3.1.4.5 Past/present hazard frequencies and magnitudes

Between 2000 and 2023, 66 events occurred in the Wipptal area, the majority of which were debris flows, mainly happening during the summer season.

#### 3.1.4.6 Potential future hazard frequencies and magnitudes

For this analysis we temporally downscaled projected precipitation, based on 11 EURO-CORDEX simulations and adjusted them for the Fleres station. We examined the impact of RCP 8.5 (worst-case scenario) precipitation projections for 2021–2070 and 2051-2100 on Toverino river debris flows.
Intensity Duration Frequency (IDF) curves for observed (1995–2020) and projected (2021–2070 and 2051–2100) data report increased intensity and frequency of sub-daily maximum precipitation.

For instance, a 300-year recurrence event today could become a 100-year event by the end of the century.

Hydrographs, modelled with Peakflow, indicate amplified peak discharge and runoff volumes, potentially increasing debris flow runout areas and intensity. Simulations with the WEEZARD model show greater deposition heights and expanded runout areas, especially for 300-year recurrence events, with less pronounced changes for 100- and 30-year intervals.

### 3.1.5 Val d'Ega/Carezza, Italy

#### 3.1.5.1 Pilot area introduction and impact chain

The 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). It covers an area of approximately 226 km$^2$ with elevation ranging from about 450 m in the west of the valley to 2,750 m a.m.s.l. in the east (Figure 16).

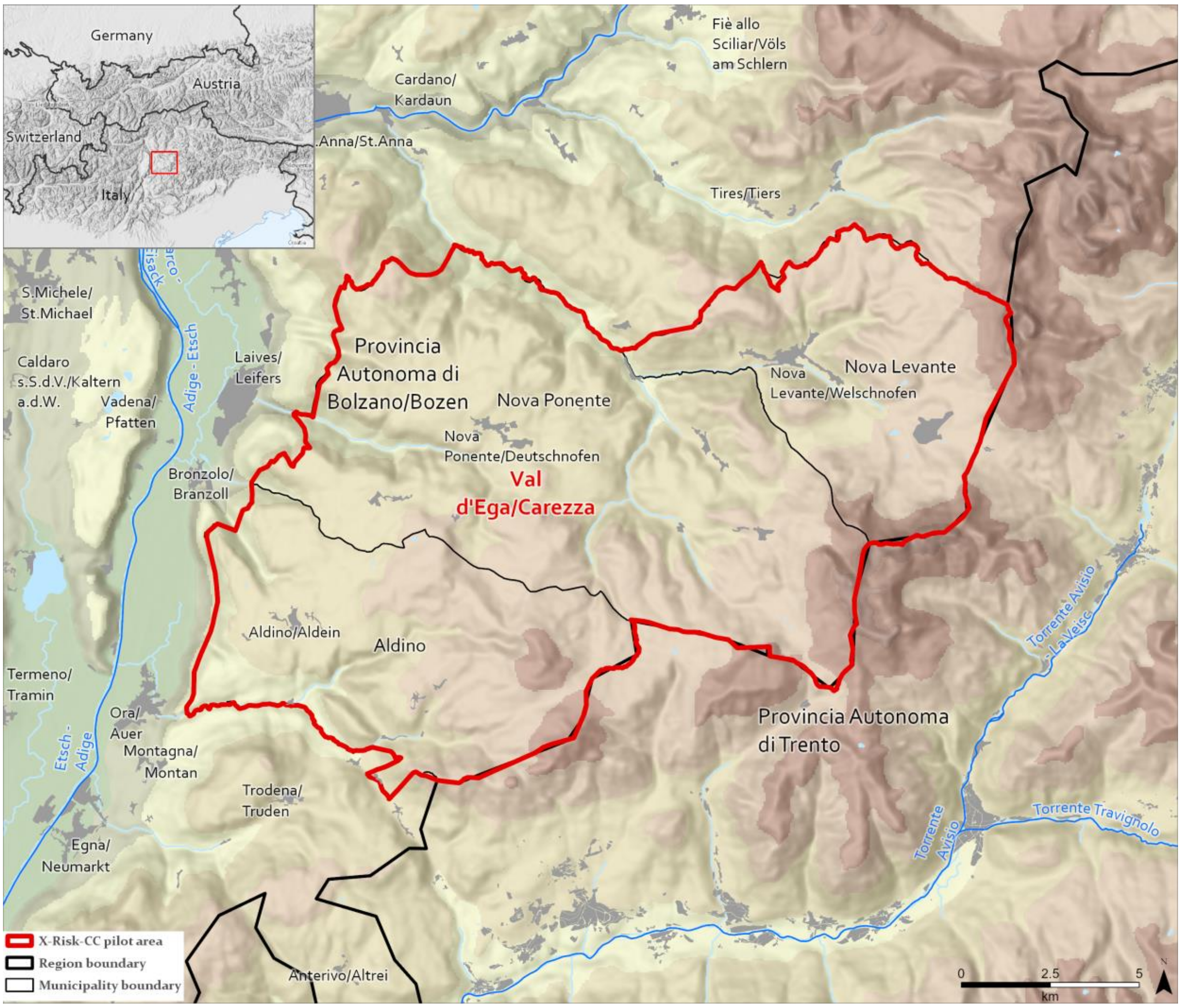


Figure 16: Map showing the extent of Val d'Ega/Carezza.

In Val d'Ega/Carezza we analysed storm events, as the storm Vaia occurred in October 2018.
The impact chain (Figure 17) was developed in conjunction with the adjacent portion of the pilot area (Val di Fiemme/Fassa) located in the Autonomous Province of Trento. It illustrates the strong wind causing falling trees, river flooding, and debris flows leading directly to damages of infrastructure and interruptions of power supply and roads. The fallen trees in connection with a warm and dry period lead to a bark beetle infestation causing additional damages to the forest which subsequently reduced the forest protection function, as well as economic losses due to a reduced wood production. The extreme climatic conditions were affecting a variety of exposed elements and sectors.

## Val d'Ega/Carezza and Val di Fiemme/Fassa - Storm

*(focus area: Val di Fiemme (Autonomous Province of Trento) Carezza and Latemar (Autonomous Province of Bolzano))*

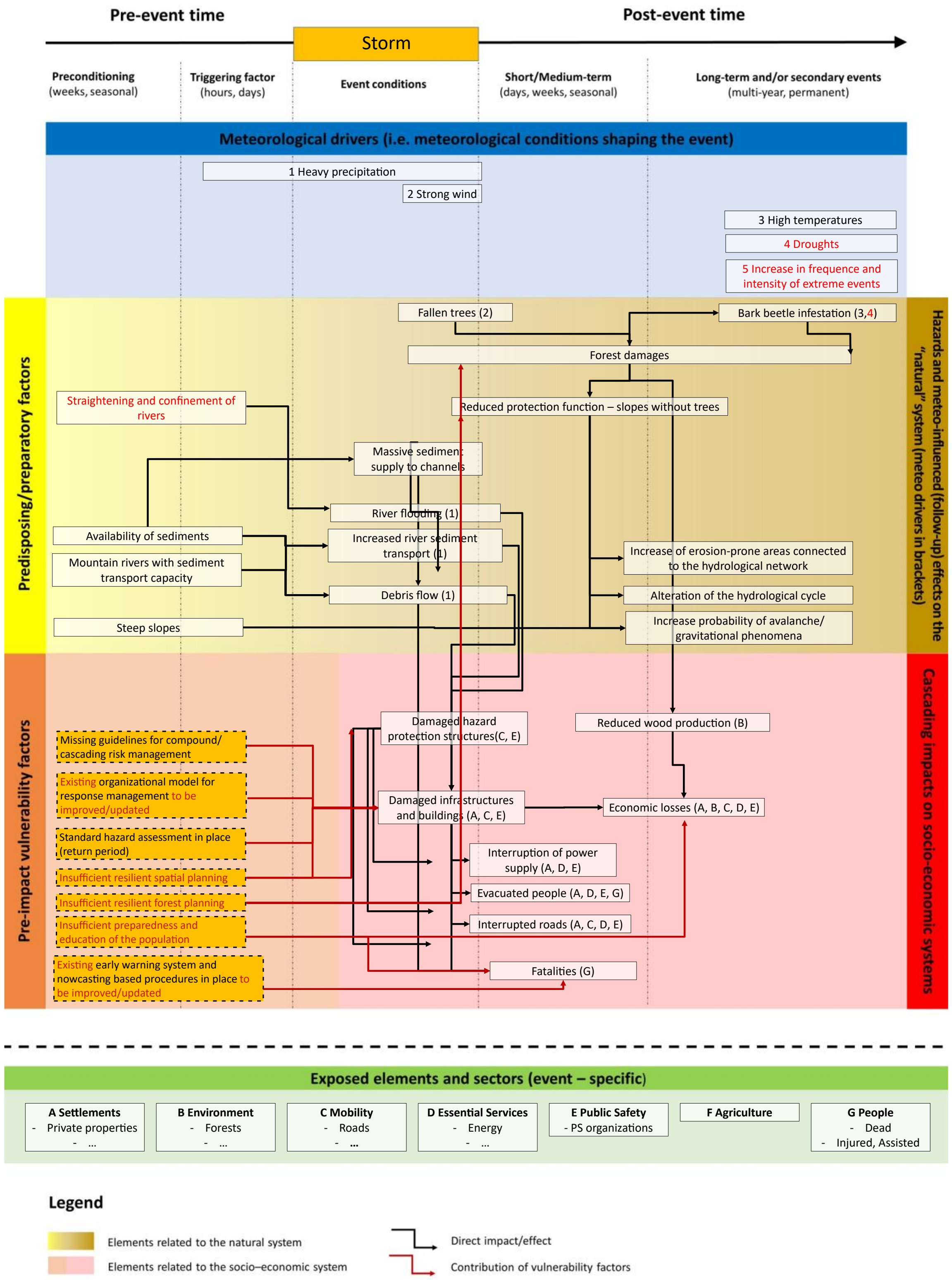


**Figure 17: Impact chain in the pilot area of storm Vaia (Italy).**

#### 3.1.5.2 Weather extremes in the past and in the future

Current weather extremes

The primary weather extremes in the pilot area are precipitation and storm, which together can trigger hazards such as fallen trees, flooding, and debris flows. Over time, cascading effects like slope instability and increased forest damage (e.g., due to increased parasite outbreaks during prolonged heat and drought conditions) may occur.

Heavy precipitation in Trentino–South Tyrol varies in intensity and seasonality. Trentino experiences annual maxima in autumn, influenced by moist Mediterranean air masses, while South Tyrol sees maxima in summer due to convective processes and orographic effects. Heavy precipitation intensity has risen across the region, with South Tyrol showing a +5 % per decade increase since 1991, particularly in summer and autumn. Less robust intense precipitation trends have been observed in Trentino until present.

Potential future weather extremes

Future projections indicate an increase in the intensity and frequency of extreme precipitation in Trentino–South Tyrol. In the pilot area, 1-day precipitation extremes may rise by +3 % to +18 % compared to 1991–2020, depending on global warming levels. Such events could also become more frequent, with Vaia-like events halving their return period under worst-case scenarios (+3 °C to +4 °C warming).

No significant changes in wind speed extremes are projected, but the likelihood of compound events combining heavy precipitation and high wind speeds may increase.

In Trentino interannual variability of snow totals can be expected to increase, despite a long-term trend of rapid snow decline at lower elevations. Years with exceptionally high snowfall may intensify the occurrence of liquid precipitation events.

See the WP1 pilot report of Vaia for further information on the climate projections.

#### 3.1.5.3 Hazard events due to weather extremes in the past and presence

The Vaia storm (27–30 October 2018) occurred in two phases, bringing exceptional precipitation and strong winds across the provinces. A major impact was the extensive windthrow in forested areas, which triggered both immediate and long-term hazards. The storm increased the likelihood of secondary hazards such as landslides, debris flows, floods, and rockfall, some occurring during or shortly after the event due to heavy rainfall. Long-term effects include reduced forest protection, decreased infiltration, and bark beetle infestations spurred by subsequent heatwaves.

#### 3.1.5.4 Hazard events due to weather extremes in the future

An increase in the intensity and frequency of extreme precipitation may elevate hazard risks in coming decades, though limited wind data makes forecasting uncertain. Vaia-like events are expected to become more frequent.

In the next 10–20 years, before forest regrowth, secondary hazard risks are likely to rise, while windthrow risks will be minimal. As forests recover, their protective function will reduce the probability of secondary hazards over time.

#### 3.1.5.5 Past/present hazard frequencies and magnitudes

In South Tyrol the Vaia pilot area has experienced various hazards since the 18th century, though systematic records began in 2000. From 2000 to 2023, over 400 events were recorded, with Nova Ponente/Deutschnofen, the largest municipality, experiencing the most. No data exists for windthrow areas before 2018, emphasizing the unprecedented impact of the Vaia storm, which caused extensive forest windthrow. During the storm (27–30 October 2018), the South Tyrolean area experienced eleven flash floods, one debris flow, ten landslides/fast flows, and six rockfalls/topples. While these caused significant damage, their magnitude was minor compared to other regional events in the last 20 years. Flash floods in South Tyrol during Vaia were analysed using the event database, which estimates debris volumes deposited in retention basins. Events were grouped into four magnitude classes based on deposited volumes. Vaia's flash floods belonged to the smallest volumetric class (<1000 $m^3$), highlighting their relatively low intensity.

#### 3.1.5.6 Potential future hazard frequencies and magnitudes

No significant changes are expected in wind speed extremes in the region. However, with increased precipitation extremes, the likelihood of simultaneous high wind and precipitation events may rise, potentially intensifying hydraulic and mass movement hazards, particularly in areas where protective forests have been lost. Additionally, soil saturation in late autumn, expected to increase due to higher precipitation during the season, may weaken tree root anchorage, making forests more vulnerable, particularly spruce forests, which have a shallower root system.
A cascading hazard triggered by the Vaia storm, the bark beetle, caused more damage to forests in the pilot area than the storm itself. This small beetle, native to Alpine spruce forests, spread due to multiple factors, including decaying material from windfalls caused by Vaia, as well as favourable conditions from extreme weather events like the summer 2022 drought and rising temperatures. The abundance of damaged trees allowed bark beetle populations to shift from endemic to epidemic levels, expected to last for years.

### 3.1.6 Val di Fiemme and Val di Fassa, Italy

#### 3.1.6.1 Pilot area introduction and impact chain

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). It covers an area of approximately 733 $km^2$ with elevation ranging from about 660 m in the centre of the valley to 3,270 m a.m.s.l. at the edges (**Error! Reference source not found.**Figure 18).

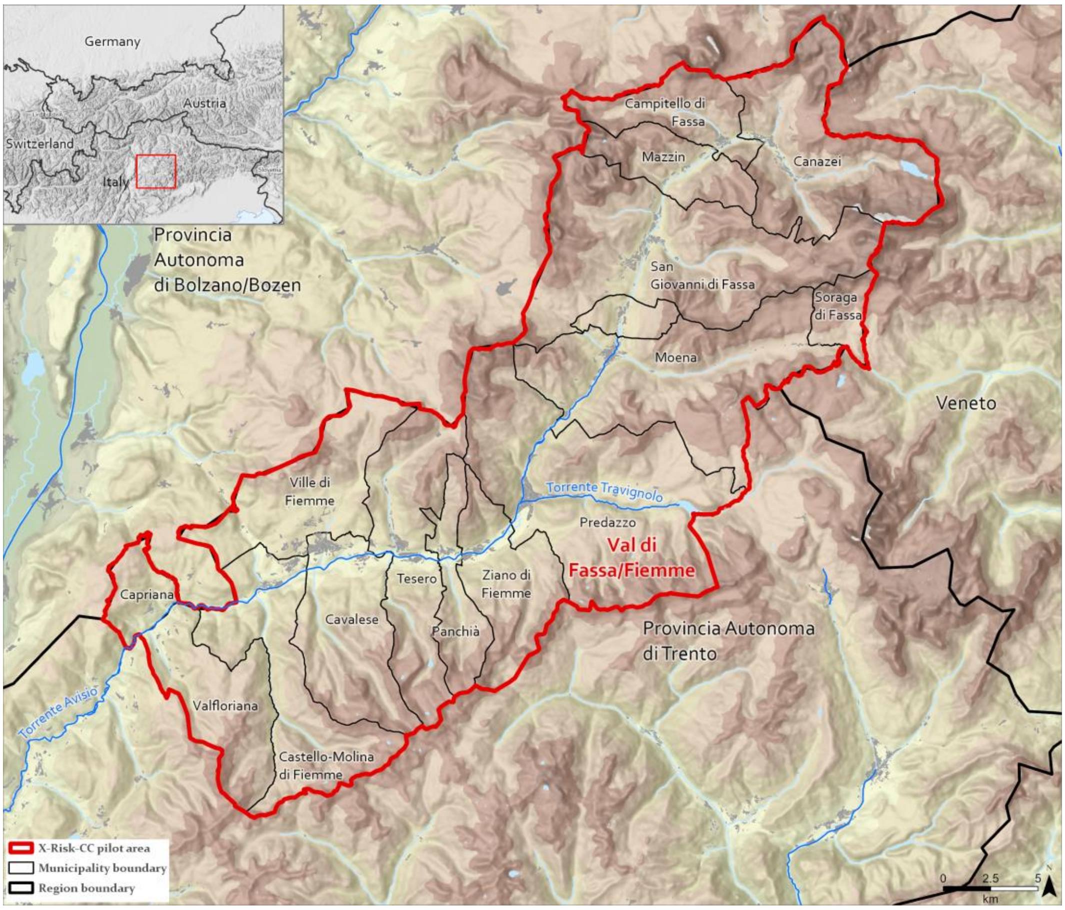


**Figure 18: Map showing the extent of Val di Fassa and Val di Fiemme.**

In Val di Fassa and Val di Fiemme, we analysed storm events, as the storm Vaia occurred in October 2018.

The impact chain (Figure 17) was developed in conjunction with the adjacent portion of the pilot area (Val d'Ega/Carezza) located in the Autonomous Province of Bolzano/Bozen. It illustrates the strong wind causing falling trees, river flooding, and debris flows leading directly to damages of infrastructure and interruptions of power supply and roads. The fallen trees in connection with a warm and dry period lead to a bark beetle infestation causing additional damages to the forest in a period spanning multiple years, which subsequently reduced the forest protection function, as well as economic losses due to a reduced wood production. The extreme climatic conditions were affecting a variety of exposed elements and sectors.

#### 3.1.6.2 Weather extremes in the past and in the future

Current weather extremes

In the pilot area, WP1 analysis focuses on weather extremes, particularly precipitation and wind, both separately and in combination (compound extremes). These can cause hazards, especially in mountainous regions with dense forests. Short-term impacts include fallen trees, flooding, and debris flows, while long-term effects may include increased slope instability, higher avalanche risk, and forest damage due to pests. Additionally, temperature increases impact the Alpine environment in various ways, from public health to glaciers and water resources. Snowfall, hail, and droughts are also important considerations.

Future climate change scenarios for Trentino, developed with the University of Trento include extreme event projections.

Precipitation in Trentino – South Tyrol shows distinct patterns, with Trentino experiencing autumn maxima and South Tyrol seeing summer peaks. Heavy precipitation intensity has increased, particularly in South Tyrol, by about +5 % per decade. Trends in frequency are less pronounced, though some areas show a +10 % increase in heavy precipitation days. Sub-daily extreme events (1-2 hours) have also become more intense, linked to more convective thunderstorms in summer.

The Cavalese station recorded 193.6 mm of precipitation during the Vaia storm, corresponding to a 317-year return period under current climate conditions. With +4 °C global warming, this return period would decrease to 61 years by 2100.

Wind data is limited due to short observation periods (10-20 years), but some wind speeds during the Vaia event were near the highest recorded.

A recent APPA analysis (1961-2020) shows an increase in extreme high temperatures and a decrease in extreme lows, with more hot days and nights and fewer cold ones. For example, between 1961-1990 and 1991-2020, the number of summer days in Trento Laste increased by 7.7 days, and tropical nights by 2.3, while frost days decreased by 12.8 days.

The overall warming trend from 1961 to 2020 has averaged 0.3-0.4 °C per decade, with a faster increase in the last few decades. By 2023, annual temperature in Trento had risen about 3.0 °C compared to the pre-industrial era, double the global average.

Hailstorms, which cause significant economic damage, are becoming more frequent. From 1999 to 2021, the number of hail events in the Alps and Po Valley increased, especially in Northern Italy, where hailstorms with stones over 5 cm in diameter have tripled since the 1950s. In Trentino, hailstorms have increased in intensity, though the total number and affected area have remained stable.

Snowfall trends in Trentino show a significant reduction in snow cover and depth since the 1990s, especially below 1,000 m a.m.s.l., due to rising temperatures. While variability exists at higher elevations, snowfall trends are generally negative, particularly in April.

Potential future weather extremes

Future projections indicate increases in intensity and frequency of extreme precipitation events. For the pilot area, 1-day precipitation extremes could increase by 3-16 % by century's end, with a Vaia-like event expected to occur more frequently under worst-case scenarios. Future projections also suggest a 20 % increase in maximum 5-day precipitation but no significant trends for consecutive dry days.

No significant changes in wind speed extremes are projected, but the likelihood of compound events combining heavy precipitation and high wind speeds may increase.

In Trentino interannual variability of snow totals can be expected to increase, despite a long-term trend of rapid snow decline at lower elevations. Years with exceptionally high snowfall may intensify the occurrence of liquid precipitation events.

Significant increases in both the frequency and the intensity of extreme high temperature events are expected, with increases in summer days and tropical nights.
No increase in the frequency of hail events is expected, while the intensity of hail events and the associated damages are expected to increase.

See the WP1 pilot report of Vaia Storm for further information on the climate projections.

#### 3.1.6.3 Hazard events due to weather extremes in the past and presence

Extreme weather events, such as heavy rainfall, windstorms, heatwaves, and droughts, frequently trigger natural hazards in Alpine regions, including floods, landslides, avalanches, and wildfires. Compound events and cascading effects, such as those seen during the Vaia storm, often exacerbate these impacts. While qualitative assessments are available, quantitative predictions for future hazard frequency and intensity in Trentino remain lacking.
The Hazard Synthesis Map (CSP), a regulatory component of the Trentino Provincial Urban Plan, identifies areas affected by hydrogeological, seismic, avalanche, and wildfire risks, serving as a critical planning tool.
Floods, caused by intense rainfall or rapid snowmelt, vary from slow valley-floor watercourse overflows to fast-moving debris flows in steeper areas. Notable events include the Vaia storm (2018), which caused extensive flooding and sediment transport, and the severe downpour in Val di Fassa (2022), leading to local floods and landslides. Historical floods in 1882 and 1966 revealed the region's vulnerability, compounded by land exploitation.
The Vaia storm devastated 20,000 hectares of forest, weakening protective functions and increasing risks of landslides, floods, and soil erosion.
Wildfires, although infrequent in Trentino, are linked to droughts and human activities. Despite a downward trend, hotter, drier conditions could increase fire risk, especially during summer.
Heatwaves, which have become longer and more frequent, pose risks to health, ecosystems, and energy demand. Vulnerable populations and urban areas are particularly at risk, with impacts extending to agriculture, tourism, and infrastructure.
Droughts, worsened by reduced snowmelt, altered precipitation, and higher temperatures, stress natural systems and heighten conflicts over water use. Recent severe droughts, like those in 2022, underscore growing challenges, including wildfire risks, reduced crop yields, and soil degradation.

The Vaia storm (27–30 October 2018) occurred in two phases, bringing exceptional precipitation and strong winds across the provinces. A major impact was the extensive windthrow in forested areas, which triggered both immediate and long-term hazards. The storm increased the likelihood of secondary hazards such as landslides, debris flows, floods, and rockfall, some occurring during or shortly after the event due to heavy rainfall. Long-term effects include reduced forest protection, increased risk of avalanches, decreased infiltration, and bark beetle infestations spurred by subsequent heatwaves and droughts.

#### 3.1.6.4 Hazard events due to weather extremes in the future

Future flood risks may rise due to increasing extreme precipitation and rain-on-snow events, while glacier retreat and permafrost thaw could destabilize slopes.
Future warming and increased autumn precipitation may reduce root stability, heightening vulnerability, particularly for shallow-rooted spruce forests.

Future scenarios for Trentino predict rising temperatures, more extreme heat events, slightly lower summer rainfall, and increased drought conditions, highlighting the need for adaptive land and water management strategies.
An increase in the intensity and frequency of extreme precipitation may elevate hazard risks in coming decades, though limited wind data makes forecasting uncertain. Vaia-like precipitation events are expected to become more frequent.
In the next 10–20 years, before forest regrowth, secondary hazard risks are likely to rise, while windthrow risks will be minimal. As forests recover, their protective function will reduce the probability of secondary hazards over time.

### 3.1.6.5 Past/present hazard frequencies and magnitudes

We have quantified the frequency and magnitude of past processes and projected their future changes, though this task is challenging due to limited and incomplete historical data. The scope of our analysis was constrained by the diverse impacts of the Vaia storm and anticipated climate change effects, as well as resource limitations. Despite these challenges, we incorporated insights from broader studies, including Jacquemart et al. (2024), which found measurable climate change impacts on one-third of alpine mass movement studies. However, the complexity of natural systems and data limitations continue to hinder precise quantification.
Floods and Torrential Phenomena
Efforts to standardize flood documentation in Trentino began in the early 2000s under the DIS-ALP project. Historical sources and field data collection have resulted in a GIS-based database cataloguing ~4,000 flood events over the past century. This data aids in understanding hydrogeological responses and aligns with EU Floods Directive 2007/60/EC requirements. Event classification includes liquid floods, debris flows, and solid transport, though urban areas are overrepresented due to reporting biases.
In the pilot area, ~300 flood events were recorded, with major provincial floods in 1882, 1966, and during the 2018 Vaia storm. Vaia caused widespread instability, with processes such as bed erosion, sediment deposition, and vegetation damage. Of the 34 flood phenomena recorded during Vaia, 141 stream sections were affected, predominantly by liquid floods with solid transport, though debris flows and liquid floods also occurred. Damage severity was mitigated by hydraulic structures, limiting high magnitude impacts primarily to agricultural and forestry areas.
Historical data reveal no clear trend in flood frequency, though certain areas above the tree line are experiencing increased debris flow activity due to permafrost degradation and glacier melting. It is expected that meteorological changes will increase the frequency and intensity of flood events in Trentino, particularly in autumn, while drier summers may result in fewer but higher-magnitude sediment transport events.
In Trentino the 2018 Vaia storm caused significant floods and transport phenomena, affecting about 80,000 m². Similar severe flooding events occurred in 1882 and 1966. The Vaia storm had a return period of over 100 years in some areas. Rising temperatures and altered precipitation patterns are expected to exacerbate flood risks, especially through rain-on-snow events and flash floods. The Vaia storm caused extensive wind damage, in Trentino uprooting 4 million cubic metres of trees, especially in areas with spruce forests. This damages the forests' protective functions, increasing the risk of landslides, avalanches, and flooding. Future wind damage may rise due to warming and wetter autumns, which weaken tree root systems.
The bark beetle infestation, worsened by the Vaia storm and subsequent drought, has caused significant damage to Trentino's spruce forests. The beetle population is expected to remain a threat for several years. Climate change could also support the spread of other pests, like the pine processionary caterpillar, which threatens forest health.

Wind-Induced Forest Collapses

During the Vaia storm, about 20,000 hectares of forest were damaged, with over 4 million cubic metres of timber affected province-wide, over a quarter in Val di Fiemme and Val di Fassa. Around 12,000 hectares were completely felled, while the remaining 8,000 hectares experienced scattered falls.

Damage levels were classified as severe (>70 %), medium (30–70 %), and low (10–30 %) based on satellite imagery and field data, with each area linked to cubic metre volumes. Historically, at least seven extreme weather events since 1882 have caused significant damage, including the 1966 cyclone, which destroyed over 90,000 cubic metres of timber. Recovery efforts included planting 150,000 seedlings between 1968 and 1971.

WP1 results indicate no clear trend in extreme wind event intensity but forecast a rise in composite precipitation-wind events, with halved return periods by century's end. Saturated ground from prolonged rainfall increases the likelihood of future collapses, making such events more frequent than in the past.

Avalanches

Trentino monitors avalanche risk through an inventory documenting events since the 1970s, primarily focused on wooded areas. High mountain avalanches are underrepresented, and updates ceased in the 1990s, though plans exist to resume reporting.

The Probable Avalanche Localization Map (CLPV) covers 40 % of the province, using internationally recognized methods that combine field data, archival research, aerial photo interpretation, and morphological studies. The CLPV records known avalanche sites without addressing return periods or event characteristics, serving as a historical summary rather than a predictive tool.

According to Jacquemart et al.(2024), lower to mid-elevations may experience fewer and less intense avalanches due to reduced snow conditions, with wet avalanches increasing and powder snow avalanches decreasing. Ice avalanche trends remain inconsistent despite rising ice temperatures.

Forest Fires

Summer droughts increase fire risk by reducing moisture content and increasing fuel flammability, exacerbated by factors like heatwaves, high temperatures, and strong winds. Earlier snowmelt further dries forests, extending periods of high flammability.

Wildfires also impact watersheds by destroying protective vegetation, increasing debris flow activity, and promoting sediment-laden flows for at least two years.

#### 3.1.6.6 Potential future hazard frequencies and magnitudes

At present, there is no clear trend emerging from historical observations that indicates an increase in the floods and torrential rain 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.

No significant changes are expected in wind speed extremes in the region. However, with increased precipitation extremes, the likelihood of simultaneous high wind and precipitation events may rise, potentially intensifying hydraulic and mass movement hazards, particularly in areas where protective forests have been lost. Additionally, soil saturation in late autumn, expected to increase due to higher precipitation during the season, may weaken tree root anchorage, making forests more vulnerable, particularly spruce forests, which have a shallower root system.

The combination of forest damages due to Vaia and to the bark beetle affected the protective function of the forest against future events like rockfalls and avalanches, potentially increasing the associated hazard level.
Considering avalanches 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.
Rising temperatures and the increasing frequency and severity of summer droughts could promote the ignition and spread of wildfires, leading to more frequent and severe damage. However, in Trentino, no significant increase in wildfires has been observed, thanks to the excellent maintenance of the forests.

### 3.1.7 Arly River Catchment, France

#### 3.1.7.1 Pilot area introduction and impact chain

Pilot area Arly River Catchment covers a catchment area located in southeastern France, in the western Alps. The Arly catchment in the region of Savoie covers an area of approximately 645 km$^2$ with elevation ranging from about 340 m in the centre of the valley to 2690 m a.m.s.l. at the edges (Figure 19).

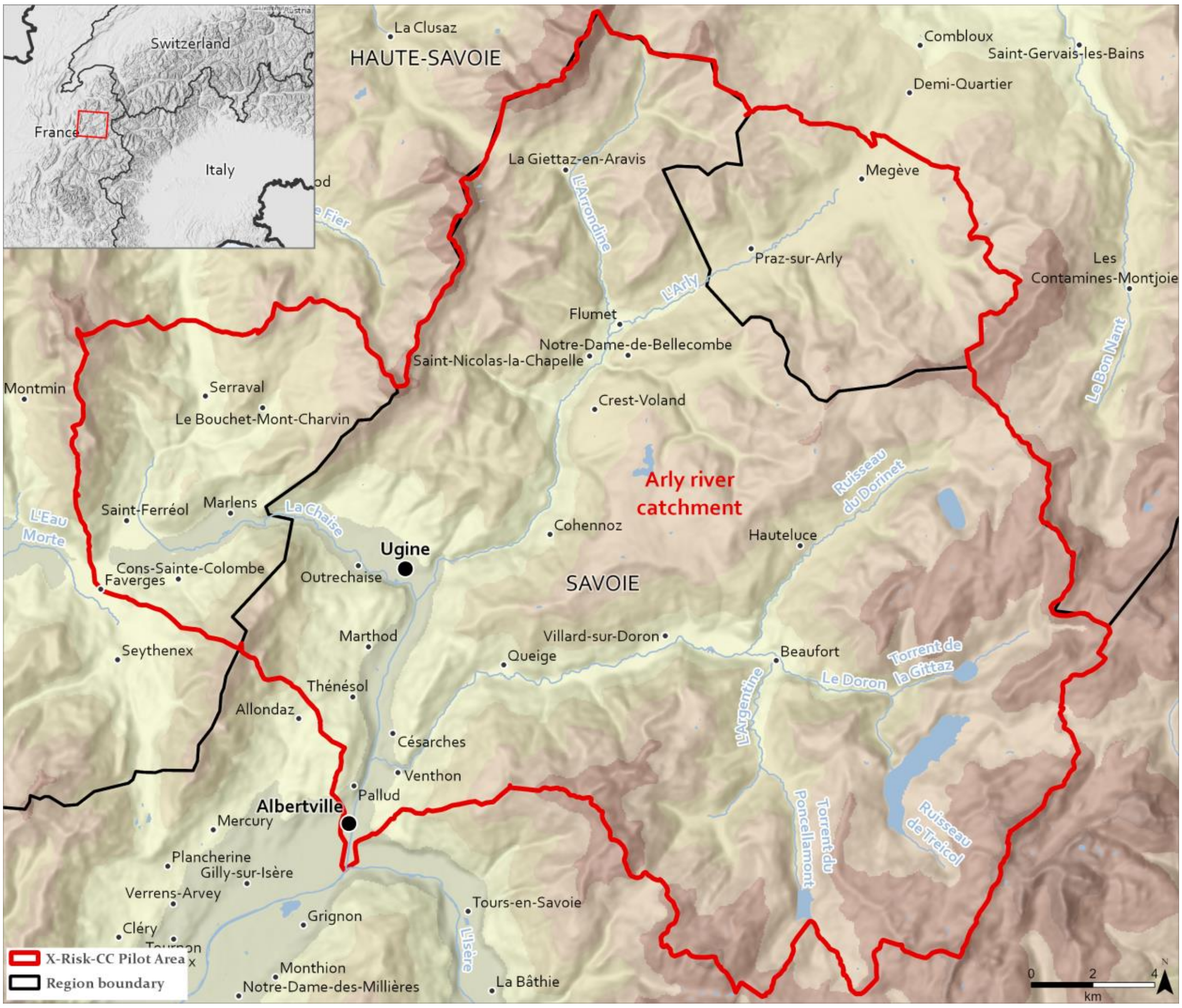


**Figure 19: Map showing the extent of the pilot area Arly River Catchment.**

In the pilot area Arly River Catchment we analysed a storm event, as the winter storm Eleanor occurred in December 2017/January 2018.

The impact chain (Figure 20) illustrates the strong wind in combination with intense precipitation. 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, causing flooding and different types of mass movements, including wet snow avalanches, landslides, debris-laden flows and rockfalls. The extreme storm event and triggered hazards lead to damages of infrastructure and interruptions of power supply and roads.

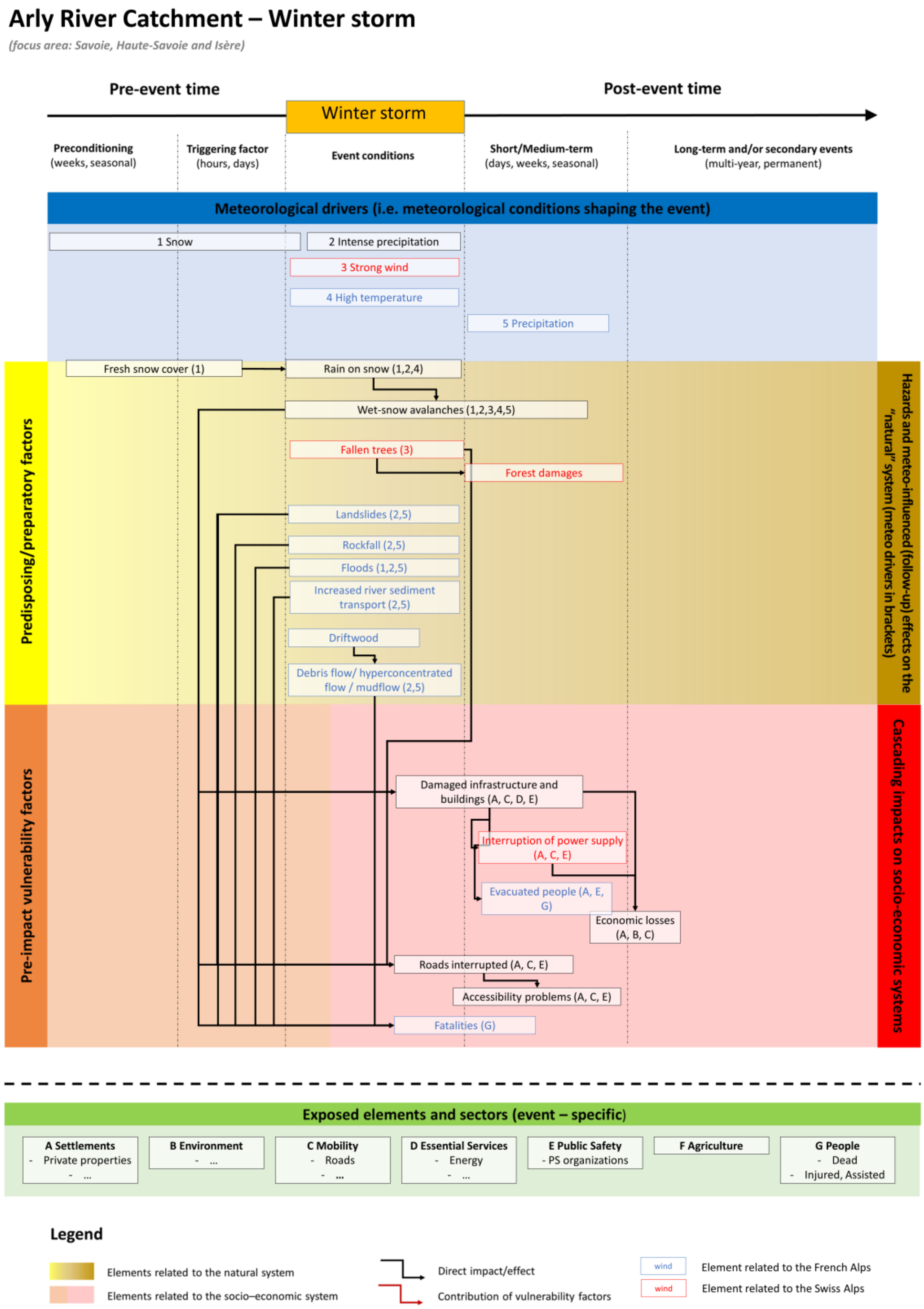


**Figure 20: Impact chain of winter storm Eleanor in the pilot area Arly River Catchment.**

#### 3.1.7.2 Weather extremes in the past and in the future

Relevant weather extremes in the Arly River Catchment are extreme 1- to 5-day precipitation and heavy winds, associated with larger storms. Temperature variations during these events play a major role in the occurrence of compound and cascading phenomena.
Trends in extreme precipitation and wind observations from 1990 to 2022 show 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. There is no trend in intensity of 2- to 5-day precipitation or in frequency of extreme precipitation.
For maximum daily wind speed, changes in intensity and frequency are observed only for slightly elevated station Col des Saisies for summer (significant positive trend). Compound extreme precipitation and wind speed events do not show significant change with time.

Precipitation extremes will be stronger and more frequent in the future, as the number of days above the 97$^{th}$ percentile also shows an increase of 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 smallest in spring and summer.
The frequency of days with extreme wind speed shows a slight increase mainly under global warming level +4 °C, about 10 % on an annual level and for winter. The maxima of daily mean wind speed show a small increase mainly under global warming level +4 °C, particularly for winter (+3 %). Yet, projected changes in frequency and intensity of storms are accompanied by large uncertainties.

See the WP1 pilot report of storm Eleanor for further information on the climate projections.

#### 3.1.7.3 Hazard events due to weather extremes in the past

The pilot area of the Arly River Catchment is frequently affected by alpine hazards like landslides, rockfalls, floods, debris flows and snow avalanches. These phenomena can occur in combination or in cascade, simultaneously or successively.
For example, at the beginning of May 2015, extensive flooding and landslide events in the Arly Gorges mobilised approximately 400,000 m$^3$ of sediment and inundated infrastructure downstream. The passage of storm Eleanor in winter 2017/2018 triggered at least 30 natural hazard events, including torrential floods, landslides and mudslides, causing numerous disorders in the Arly River Catchment. The repeated events of November-December 2023 once again caused numerous compound and cascading hydrological, gravitational and torrential phenomena in the Arly catchment.

#### 3.1.7.4 Hazard events due to weather extremes in the future

With climate change, we can expect an increase in the frequency of milder periods likely to cause rapid melting of the snowpack and rain-on-snow events such as those observed in January 2018 during storm Eleanor and during the repeated flooding events in November-December 2023.
We expect that the risk of flooding is likely to increase, as 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.

### 3.1.7.5 Past/present hazard frequencies and magnitudes

In the Arly River Catchment, changes in the activity of certain natural hazards, such as landslides, rockfalls, floods and debris flows, have already been observed. The database used for the analysis is the ONF-RTM database of the French Torrent and Avalanche Control Service, which records natural mountain events. The database spans back to 1715, but systematic recording started in the late 1970s. Floods of the river Arly are monitored since 2012 and data are available on the HYDROPORTAIL database.

Analysis of hazard frequencies since the 1980s has shown

an unclear trend in landslide activity

an increase in rockfall activity

that flood peaks exceeding 300 $m^3$/s (~5-year flood) have been occurring more frequently in recent years

an increased frequency of debris flows since late 1980s, controlled by more convective rainfalls in summer but also sediment availability in the catchments

that snow avalanche activity happened earlier in winter than in the past, with an increase in the number of avalanche events in December and a decrease in January. In the French Alps, in general, the number of avalanches has reduced since 1980 at low altitudes (<2000 m a.m.s.l.), while it recently increased at high altitudes.

### 3.1.7.6 Potential future hazard frequencies and magnitudes

The effect of climate change on the activity of landslides is unclear. The same applies for projections of the future development of floods. Cascading effects between landslides and torrential floods (debris flows) remain challenging hazard phenomena, involving blockage of the Arly River by a landslide dam, dam failure and torrential flooding downstream, with extreme sediment input that potentially exceeds 100,000 $m^3$.

## 3.2 Observed drivers of mass movement events in the Alpine Space

### 3.2.1 Evaluating the performance of mass movement impact models

Model performance of the large-scale impact models (described in Section 2.3 and in D 2.2.1) was evaluated using the area under the Receiver Operating Characteristic curve (AUROC). Overall, the model fitting performance was excellent (Hosmer and Lemeshow, 2000). The flow-type impact model had the best fit with an AUC of 0.895, followed by the slide-type impact model (0.871), and the rockfall model (0.825). In terms of predictive performance, which was quantified using CV procedures, the median AUC was 0.862 using 30-day antecedent precipitation for the slide-type, 0.887 for the flow-type using a 21-day window and 0.803 for the rockfall model using a 14-day window. An example of modelled predictions is provided by Figure 21 for a scenario based on 100 mm triggering precipitation and 50 mm antecedent precipitation for a summer day. The predictions shown control for effects due to exposed infrastructure by applying fixed values based on the average across all spatial units, i.e. the predictions shown exclude effects related to exposed infrastructure within the PPAs. This allows a comparison to be made based on a hazard-perspective controlled by climatic and geomorphologically relevant variables. For this scenario, the slide-type model has the greatest spatial extent in terms of areas potentially affected across the alpine space, since medium-sloped terrain is more wide-spread than the steep topography generally required by flow-type and rockfall mass movements.

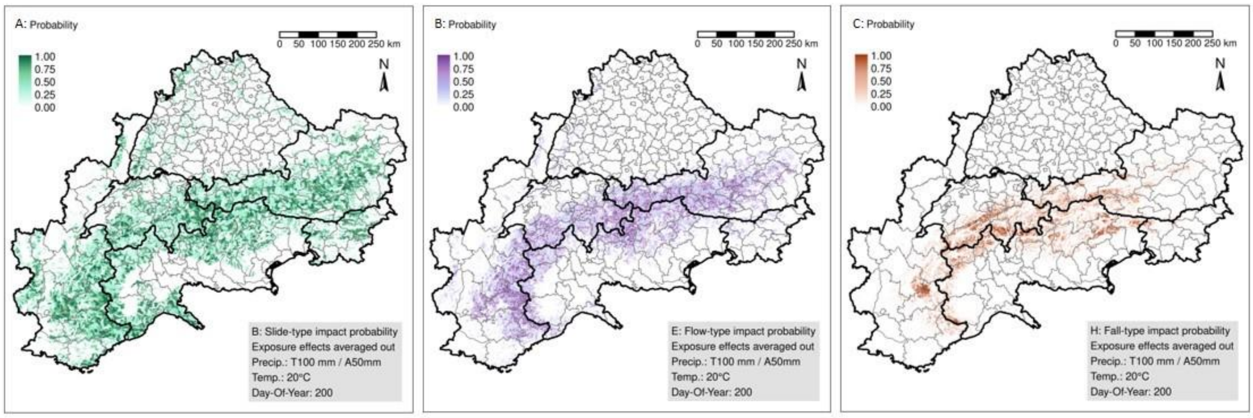


**Figure 21: Predictions of slide-type, flow-type and rockfall impact models for a hypothetical scenario using a triggering precipitation of 100 mm and an antecedent precipitation of 50 mm. Note, the exposure-effect has been removed (averaged) to simulate a hazard perspective for the three model predictions.**

An evaluation of the space-time models for slide, flow and fall mass movement types can inform on key drivers of impact events. There are two steps in evaluating the determinants of impact events using the GAMMs. First, the overall variable importance is computed, followed by assessing the direction and shape of the relationship between individual variables and the target variable with partial effect plots.

Permutation-based variable importance is common method to determine the contribution of a specific variable in machine-learning models (Molnar, 2022). The contribution of explanatory variables is assessed by randomly shuffling its values and evaluating the impact on model performance. If a variable is important, disrupting its relationship with the target variable will significantly reduce predictive accuracy. To quantify the effect, the variable is permuted (100x) while keeping all other data unchanged, and the model's performance is recalculated (AUROC). The mean drop in performance is therefore a metric for the variable's overall importance (Figure 22, **Error! Reference source not found.**, Figure 24). This approach captures the variable's specific and interaction effects, making it particularly valuable for assessing complex, nonlinear relationships modelled in GAMMs.

### 3.2.2 Drivers of slide-type mass movement events

The most important variables for shallow landslide impact events include the short-term triggering precipitation and mean annual precipitation, closely followed by the mean slope in the process path area. Additional variables that have an important influence, albeit to a lesser extent, include antecedent precipitation, the dominant lithology in the process path area as well as seasonal effects reflected by the day of year and daily temperature. The partial effect plots provide further insights related to the shape of the relationship between each variable and the predicted outcome. Specifically, the smooth functions account for non-linearity in the relationships and the direction and magnitude thereof.

For triggering precipitation, the contribution is negative below 100 mm, then shows a linear increase with increasing rainfall amount. The greater the amount of rainfall above 100 mm, the greater the likelihood of a landslide impact event. Interestingly, the smooth function for mean annual precipitation shows an inverse relationship to the outcome. This result is geomorphologically plausible since landscapes that experience large quantities of precipitation on a regular basis are more resilient and generally require a higher short-term precipitation threshold for landslides to be triggered (Marc et al., 2019; Crozier and Preston, 1999). The smooth function for slope shows that the steeper the process path area the greater the contribution to a landslide impact event. Process path areas with mean slopes less than 15 degrees are less likely to experience landslide impact events. The antecedent precipitation function increases to a peak 400 mm 30-day precipitation, then reducing its contribution up to 600 mm. This suggests that antecedent precipitation as a proxy for soil moisture is an important pre-conditioning factor, whereby the higher the antecedent precipitation, the more significant its contribution towards potential impact events. While lithology was not assessed to be a particularly important variable in our model setup, half-basins with pure carbonates as the dominant rock type are considerably less susceptible to landslides. The most susceptible lithologies include the mixed carbonates which include calcarenites and marls, sandstones (includes greywacke), and claystones with high clay content.

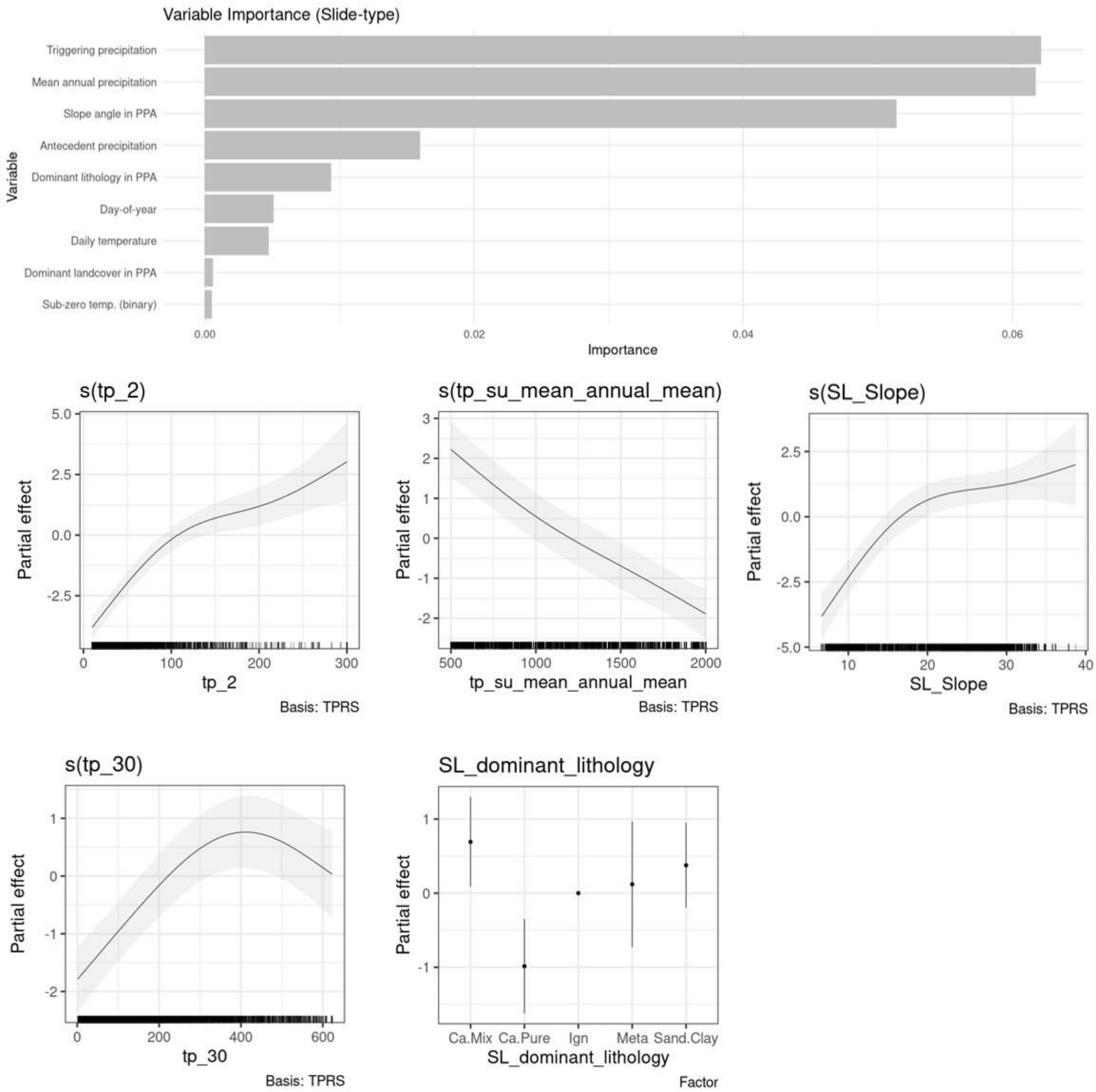


**Figure 22: Permutation-based variable importance for the slide-type impact model computed using 100 iterations. Note, only the most important climatic and environmental variables are shown and partial effect smooth functions for the five most important variables.**

### 3.2.3 Drivers of flow-type mass movement events

The variable importance plot for the flow-type shows similar tendencies to the slide-type plot. The exception is the increased importance of day of year, which is a seasonal variable and has a similar degree of importance as the daily temperature. These variables are likely reflecting convective rainfall events during summer months that are more intense than precipitation during the remainder of the year. The partial effect plot for daily temperature confirms that temperatures between 20 and 30 degrees have a far greater effect on the outcome. The remaining variables and smooth functions mirror those discussed for the landslide model above.

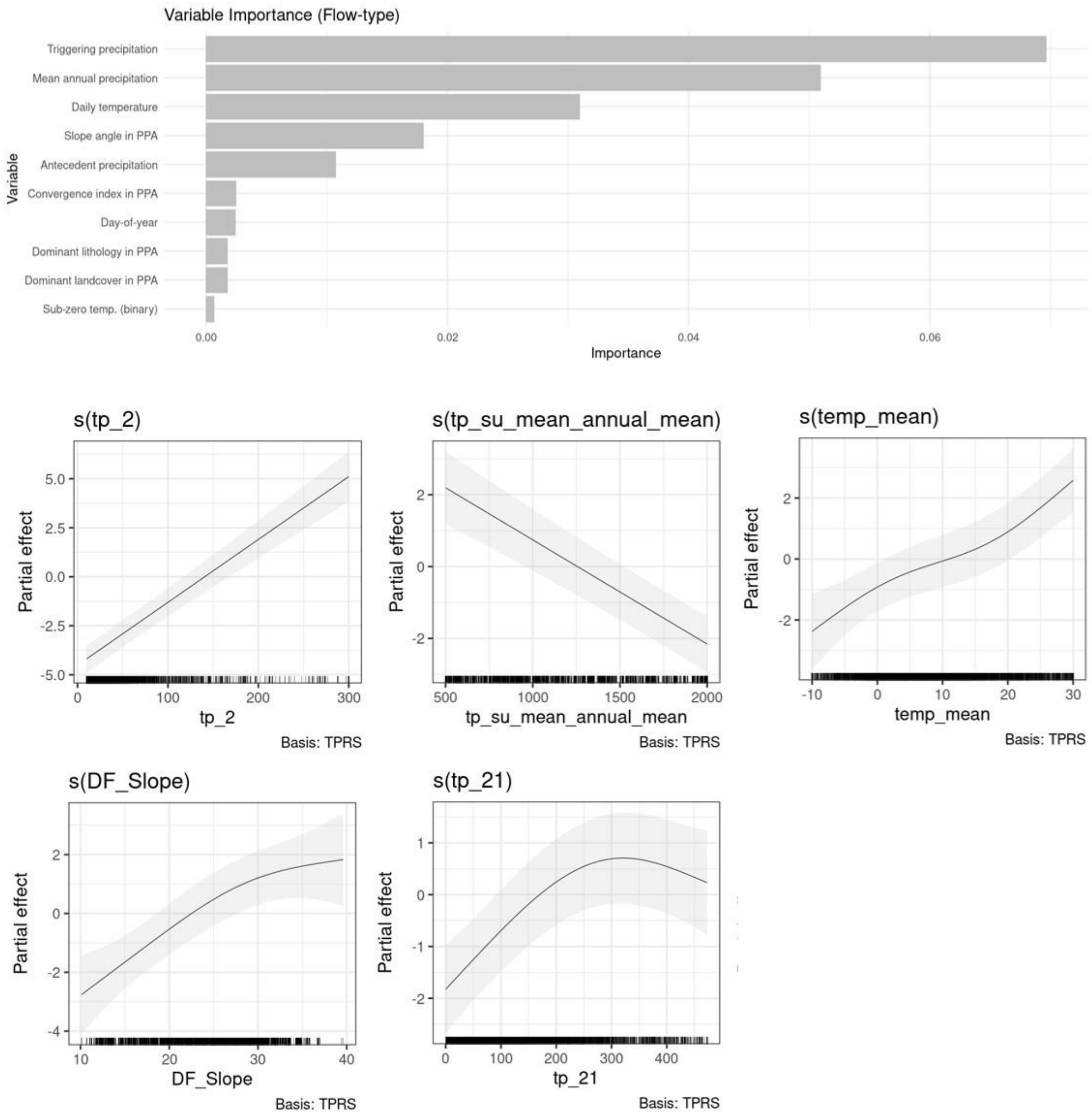


Figure 23: Permutation-based variable importance for the flow-type mass movement impact model computed using 100 iterations. Note, only the most important climatic and environmental variables are shown and partial effect smooth functions for the five most important variable.

### 3.2.4 Drivers of rockfall mass movement events

In contrast, the rockfall impact events are less well predicted by precipitation variables, which is why the model relies heavily on static predictors. The most important variables here are the dominant lithology, slope, proportion of bare ground and the convergence index – all within the PPAs. The most susceptible lithologies igneous (acid rocks), metamorphic rock and mixed carbonate rock. Since the slope threshold used for defining initiation zones of rockfall was relatively high to begin with (35°), process path areas – which include the runout zones, with a mean slope >36° have a much greater effect compared to lower mean slopes. The larger the proportion of unvegetated land in the process path area, the more likely infrastructure is to be affected by rockfall, confirming the importance of protection forests. Specifically, half-basins with 40-60 % of process path areas with bare ground are much more susceptible to impact events due to rockfall.

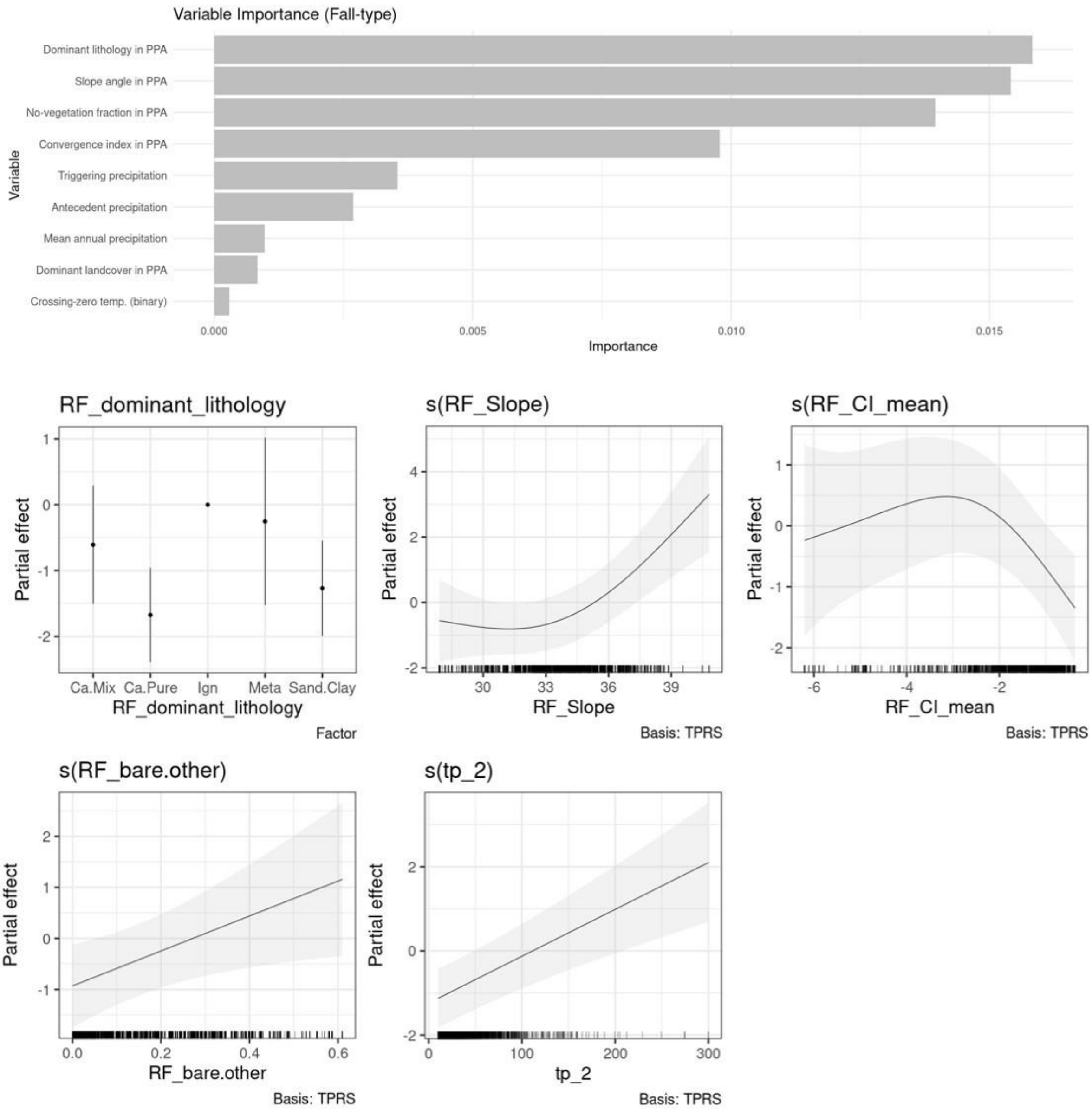


**Figure 24: Permutation-based variable importance for the rockfall impact model computed using 100 iterations. Note, only the most important climatic and environmental variables are shown and partial effect smooth functions for the five most important variables.**

# 4 Conclusions

The five pilot areas have been affected by weather extremes such as heavy precipitation, drought, heatwaves and storms, which have triggered different types of natural hazards – not only as individual hazards but often as compound or cascading hazards. This report presents the analysis of past and future (compound) hazards in the pilot areas, conceptually based on the visualisation and understanding of weather-hazard-impact interrelations through sequential impact chains, the compilation of event inventories, and the structured assessment of past and future natural hazards as part of the risk questionnaire.
For each pilot area and sub-region, we compiled information from event databases and publications to analyse observed changes in the frequency, intensity and spatial pattern of past hazardous events. The observed trends together with an analysis of past climate and future climate projections (WP1) served as a basis for anticipating future changes of hazardous events.

Drought hazards have played a major role in the Gorenjska area and are projected to become more intense and frequent in the future. The same applies to the compound occurrence of droughts in combination with heatwaves, making the area more susceptible to cascading effects like wildfires and plant diseases (e.g. bark beetle infestation). These effects have also been identified as influencing the hazard situation in Val di Fassa, Val di Fiemme, and Garmisch-Partenkirchen, where prolonged drought conditions (in combination with heatwaves) are expected to become more significant due to climate change.
Severe flooding events have impacted the Sora River Catchment in Gorenjska, as seen most recently in 2023. Given the projected increase in extreme precipitation over 1-3 days (with a 50-year event potentially becoming a 21-year event under GWL 3 and 4), it is expected that flooding events will become more intense and frequent in the future, with an increased susceptibility of debris-laden flows due to enhanced sediment supply.
Garmisch-Partenkirchen experienced severe river flood events in the past, and an increasing frequency of flash flood events affecting the touristic-popular Partnach Gorge has been observed over the past four decades. Climate projections indicate that 12-25 more extreme precipitation days can be expected under GWL 4, increasing the likelihood of future floods. This is also increasing the susceptibility of debris-laden flows and log-jams in the gorge due to enhanced debris and wood supply from landslides and debris flows in the upstream catchments.
Debris-laden flows are identified as key hazards in the pilot area Wipptal/Stubaital and have shown their potential for cascading hazards of flooding behind debris-flow deposits. Systematic event records have revealed a strong increase in debris flow magnitude in the period 2020-2024 in Stubaital. For the future, 1-day precipitation extremes as well as convective, 1-hour precipitation events are projected to increase in frequency and intensity. The system response to trigger debris-laden flows is expected to vary depending on sediment availability in the tributaries. In high-alpine catchments with abundant loose sediment due to glacier retreat and permafrost degradation, the probability of large debris-laden flows is expected to increase. For Wipptal, projected Intensity Duration Frequency curves and modelled hydrographs were used to simulate the runout of potential future debris flows.
Strong winds and heavy precipitation during storm events, as the storm Vaia in 2018, triggered compound and cascading hazards in the pilot area encompassing Val d'Ega/Carezza (South Tyrol) and Val die Fiemme and Val di Fassa (Trentino). Large areas with windthrown trees were infested by bark beetles in the subsequent years, losing the protective function of the forests until they recover and increasing the potential of secondary hazards such as rockfalls and avalanches. Climate simulations indicate an increase in frequency and intensity of extreme precipitation events; no

significant changes in wind speed are projected, but compound events of heavy precipitation and strong winds may increase. In response to changing precipitation, floods and debris-laden flows can be expected to increase in frequency and magnitude.
Similar results have been found for storm events, such as the winter storm Eleanor in 2017/2018, in the Arly River Catchment. Future projections for extreme wind speeds indicate only a small increase in frequency and intensity and are accompanied by large uncertainties. Extreme 1-day, 2-day, and 3-day precipitation events are projected to become more frequent and intense, thus it is expected that the likelihood of hazard cascades involving landslides, blockage by landslide dams and subsequent debris-laden flows is increasing in the area.

For the analysis of past and future hazards in the pilot areas, systematic and consistent records in event databases is key. Although substantial progress has been made in the recent decades (e.g. inventories since 1970 in Stubaital, or since 1999 in Wipptal), the periods covered are often not long enough to enable statistically robust trend analysis. Nevertheless, even in short time series of hazardous events, the impact of climate change has become visible in the last years. The knowledge generated through the comprehensive analysis of past and future weather extremes, hazards and the related risks (see D 2.2.1) in the pilot areas served as the basis for the climate risk storylines, a narrative approach to communicate potential future climate risks in the pilot areas.
To complement the detailed analyses in the X-RISK-CC pilot areas, a larger dataset of recorded impact events was used to develop data-driven machine learning models. The models can be used to predict the likelihood of past and future weather extremes leading to societal impacts from mass movements (slide-, flow- and fall-types) across the Alpine Space. Extreme hydro-meteorological and geomorphic events, often driven by localized intense precipitation, pose challenges for early warning and risk reduction more generally. The models aim to enhance understanding of the relationships between driving factors and the conditions triggering high-impact geomorphic events by integrating meteorological, morphometric, geological, and land-use variables. They can therefore help practitioners improve emergency response, anticipate adverse consequences, and identify where and when critical conditions are most likely to occur.
For the slide type, triggering precipitation and mean annual precipitation are primary drivers, with slope, antecedent precipitation, and lithology playing important roles. Debris flows are also influenced by seasonal and temperature variables, reflecting the intensity of summer convective rainfall. Rockfall occurrences are less effectively explained by dynamic meteorological variables, which is why the models relied more heavily on static conditions, such as slope, lithology, and land cover - with bare ground increasing susceptibility. The findings offer critical insights into the environmental conditions underpinning geomorphic hazards and inform risk reduction strategies. Understanding the environmental drivers and triggering conditions of mass movement events enhances predictive capabilities and supports risk mitigation efforts. By quantifying the relationships between precipitation, terrain, lithology, and land cover, the models provide a robust foundation for implementing targeted, impact-based forecasting and warning systems across the Alpine Space.

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