Interreg
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Alpine Space

X-RISK-CC

RISK MANUAL

ASSESSING COMPOUND AND CASCADING RISKS OF WEATHER EXTREMES IN THE ALPINE SPACE UNDER CURRENT AND FUTURE CLIMATE

LEAD PARTNER PROJECT PARTNERS

IMPRESSUM

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- Slovenian Environment Agency
- Development Agency Sora
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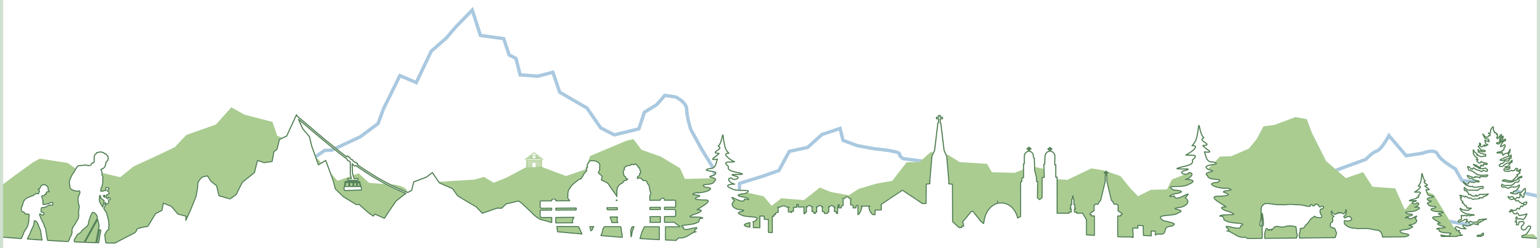

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INTRODUCTION

Climate change is influencing compound and cascading hazards associated with extreme weather events in the Alpine Space. The frequency and intensity of these events are increasing, creating new and often unforeseen risks. Understanding these interconnected risks is essential for developing effective mitigation and adaptation strategies.

Compound hazards refer to multiple hazard events occurring simultaneously or sequentially, often interacting to amplify overall impacts. For example, a prolonged drought followed by an intense rainfall event can lead to flash flooding and soil erosion. The dry, compacted ground resulting from the drought is less able to absorb water, causing more surface runoff during heavy rain, which increases the probability of flood hazards. Cascading hazards, on the other hand, occur when one hazard triggers another, creating a chain reaction of events. An example in the Alpine context might be a landslide caused by intense rainfall that subsequently blocks a river, leading to flooding. These interconnected hazards are becoming more frequent and complex due to climate change, underscoring the need for integrated risk assessment and management approaches.

Disaster risk managers often use tools such as scenario planning and simulations to understand and address the risks posed by extreme weather. These exercises –conducted as desktop planning and/or real-time simulations - help managers explore potential disasters, identify vulnerabilities, and improve strategies across all phases of risk management in their region.

However, many of these scenarios are based on historical events, which may not adequately prepare regions for new or unprecedented weather extremes. To reduce risks more effectively, managers should implement methods that identify potential future hazards and risks that go beyond past experience and observations.

In particular there is a growing need to consider risk assessments that account for how some climate-related events can evolve into compound or cascading impacts, affecting multiple systems simultaneously or sequentially. A single hazard – such as a heatwave – can trigger cascading impacts across multiple, interdependent systems, including public health, energy supply, agriculture, and mobility. Expanding risk assessment to incorporate these interconnected and dynamic impacts helps reveal vulnerabilities that may otherwise remain hidden and supports the development of more robust, cross-sectoral strategies.

As will be demonstrated in this **Risk Manual**, the insights gained from such future-oriented and system-aware approaches can be integrated into prevention strategies, preparedness plans, response operations, and recovery efforts, strengthening a region's capacity to manage weather-related hazards and fostering long-term resilience.

In Alpine regions, risk management follows a combination of international standards and region-specific guidelines to effectively address natural hazards. The international standard ISO 31000:2018 (Risk Management – Guidelines) is an international standard that provides principles and a structured framework for managing risks across sectors[1]. The **Risk Manual** follows the structure of the international standard. Designed for risk managers, it provides a conceptual approach to support the assessment and management of current and emerging weather-related risks. The approach described in this Manual was developed within X-RISK-CC, an applied research project co-financed by the European Union's Interreg

1 International Organization for Standardization, 2018. ISO 31000:2018

Alpine Space programme. For three years, research organisations and public authorities on national and local levels from five Alpine countries collaborated to address the common challenge of managing weather extremes and their associated risks under Climate Change (CC). To this end, the X-RISK-CC project assessed trends in weather extremes in the Alpine Space, developed risk management actions for five project pilot areas (see the description below), and formulated transnational guidelines and policy options for Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA).

WHO IS THIS MANUAL FOR?

The **Risk Manual** is intended for regional and local administrations operating in the Alpine Space that are involved in risk management, territorial planning, and disaster risk reduction. It is designed to support public sector professionals to understand and address the increasing complexity of climate-related hazards, particularly those associated with extreme weather and cascading events.

The **Risk Manual** is intended for practitioners who need to integrate climate risk considerations into strategic planning, emergency preparedness, and adaptation measures. Through guidance and practical tools tailored to the specific geographical context of the Alps, it offers structured approaches to help practitioners achieve this.

Primary target groups:

- → Regional disaster risk managers and civil protection authorities
- → Environmental and territorial planners
- → Climate change adaptation coordinators
- → Public officers involved in cross-border or inter-municipal collaboration within Alpine regions

The **Risk Manual** assumes an understanding of regional governance structures and risk management frameworks but no prior technical expertise in climate or risk modelling is required.

The following chapter outlines how to use this Manual with a structured workflow. This helps practitioners navigate the risk assessment process and apply the methods and tools to their own regional context.

OVERVIEW – HOW TO USE THE RISK MANUAL

The **Risk Manual** provides a methodological framework based on terminology and concepts consistent with the IPCC Sixth Assessment Report (AR6). Aligned with the structure of the International Risk Management Standard and drawing on the most recent and reliable climate data in the Alpine Space, it outlines approaches for analysing risk components and illustrates with practical examples. The selected approaches and data sources are based on applications in five pilot areas of the X-RISK-CC project (see the description below), with the aim of assessing their usability and practicability. This will contribute to the development of a relevant and effective framework and approaches to support regional risk managers in their work.

KEY TERMS

FIGURE 1 illustrates the components and interactions that shape climate-related risk, particularly in the context of extreme events and climate change. A climate-related hazard (such as a flood or heatwave) interacts with exposure (who or what is in harm's way), vulnerability (how prone they are to harm), and available risk management capacity (resources and systems to reduce risk). These interactions determine the overall risk to people, ecosystems, or infrastructure.

The diagram also highlights the importance of compound risks—where multiple hazards occur simultaneously or sequentially—and cascading impacts, where an initial hazard sets off a chain of effects across systems or sectors. Understanding these complex dynamics is essential for developing integrated, cross-sectoral approaches to risk assessment and disaster preparedness.

CLIMATE EXTREMES AND CLIMATE CHANGE

CLIMATE-RELATED HAZARD

A natural or human-induced climate event or trend (e.g., flood, drought) that may cause harm to people, ecosystems, property, or services.

EXPOSURE

The presence of people or assets in areas that could be affected by hazards; quantifiable by population or asset types.

POTENTIAL CASCADING IMPACTS

Interconnected, and escalating effects triggered by a climate-related hazard that impact multiple sectors or systems, amplifying risks.

VULNERABILITY

The degree to which individuals or systems are prone to harm, shaped by social, economic, environmental, or physical conditions.

RISK

The potential for adverse impacts on people or ecosystems, arising from the interaction of hazard, exposure, vulnerability, and capacity.

COMPOUND RISKS

Compound risks emerge when multiple climate hazards occur together or in succession, interacting with exposed and vulnerable systems to amplify impacts.

RISK MANAGEMENT CAPACITY

The resources, skills, infrastructure, and institutional strengths that enable a society or organization to manage and reduce disaster risk.

FIGURE 1: *Key components and interactions in climate-related risk, highlighting compound and cascading risks.*

NOTE: *Definitions have been adapted and summarised from authoritative sources including the IPCC (2019[2], 2022[3]), UNDRR (2023)[4], and the World Bank Climate Change Knowledge Portal (n.d.)[5].*

2 IPCC. (2019). *Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).* https://www.ipcc.ch/srocc/
3 IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability.* https://www.ipcc.ch/report/ar6/wg2/
4 *UNDRR Terminology on Disaster Risk Reduction.* https://www.undrr.org/terminologyth Assessment Report of the Intergovernmental Panel on Climate Change.
5 World Bank. (n.d.). *Climate Change Knowledge Portal Glossary.* https://climateknowledgeportal.worldbank.org/media/document/CCKP_glossary.pdf

COMPOUND CLIMATE RISK ASSESSMENT WORKFLOW

The Risk Manual provides a structured, step-by-step workflow to help users understand compound risks and inform action (***FIGURE 2***). The process guides users through three main phases:

1. Scoping
2. Risk Identification
3. Risk Analysis

The phases build on each other, progressing from defining the context and reviewing the data to identifying risks to be assessed and creating impact chains, and finally to analysing the risks in detail. This structured approach supports systematic risk assessment, ensuring consistency and transparency throughout the analysis.

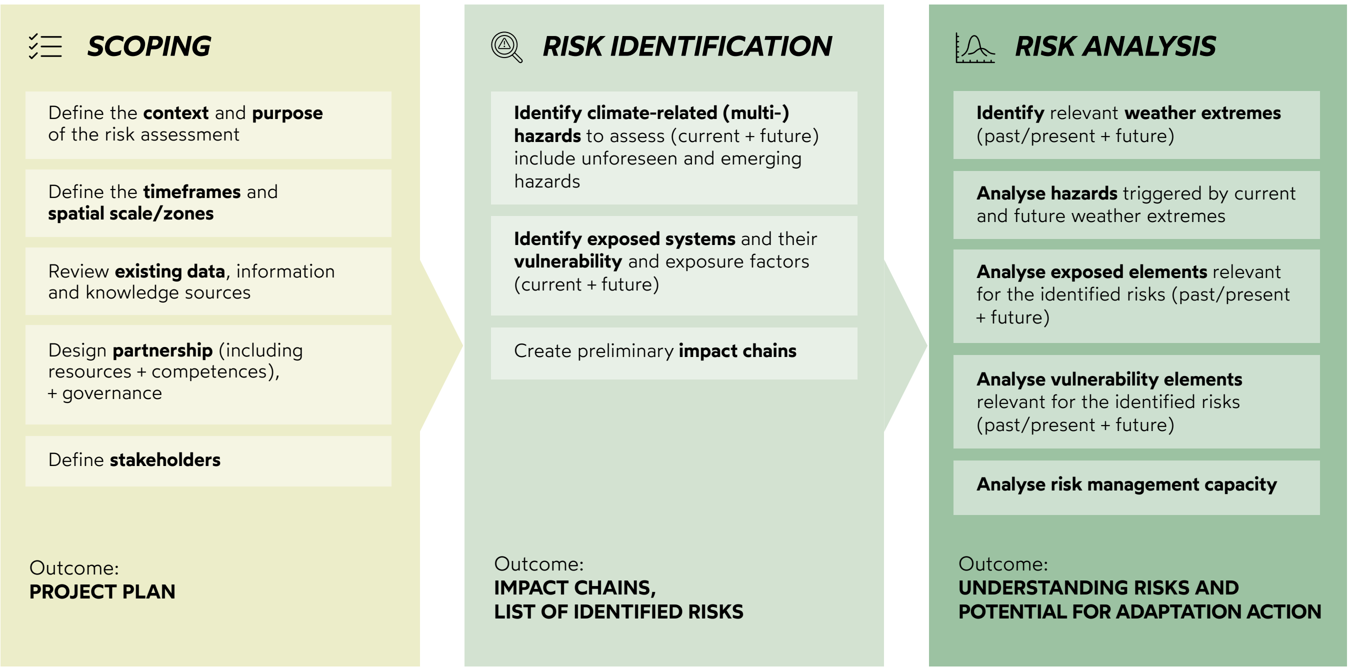


FIGURE 2: *Workflow for assessing compound risks, illustrating the phases from scoping and identifying risks to carrying out detailed risk analysis.*

THE X-RISK-CC PILOT AREAS

To demonstrate the practical applicability of the tools and methods outlined in this Risk Manual, five real-world pilot areas from across the Alpine Space are used. Each area represents a distinct geographical, socio-economic, and climatic context in a different Alpine country. The pilot areas also differ in climate-related risks they prioritise, reflecting local conditions. Data from these areas is used to illustrate key concepts and approaches from the Risk Manual, such as impact chains, hazard analysis, exposure and vulnerability assessments, and the presentation of results.

The map in ***FIGURE 3*** and ***TABLE 1*** provide an overview of the locations and key characteristics of the pilot areas, including the primary hazards analysed in each. Detailed documentation of the climate-related hazard and risk assessments in the X-RISK-CC pilot areas are available here: https://www.alpine-space.eu/wp-content/uploads/2025/07/D2.1.1_Report-on-past-an-future-hazards-in-the-pilot-areas.pdf and here: https://www.alpine-space.eu/wp-content/uploads/2025/07/D2.2.1_Report-on-past-and-future-risk-pathways-in-the-pilot-areas.pdf

The example-based approach helps to improve understanding of the methodology, emphasises its practical relevance, and encourages its adoption and replication in other Alpine or mountainous regions.

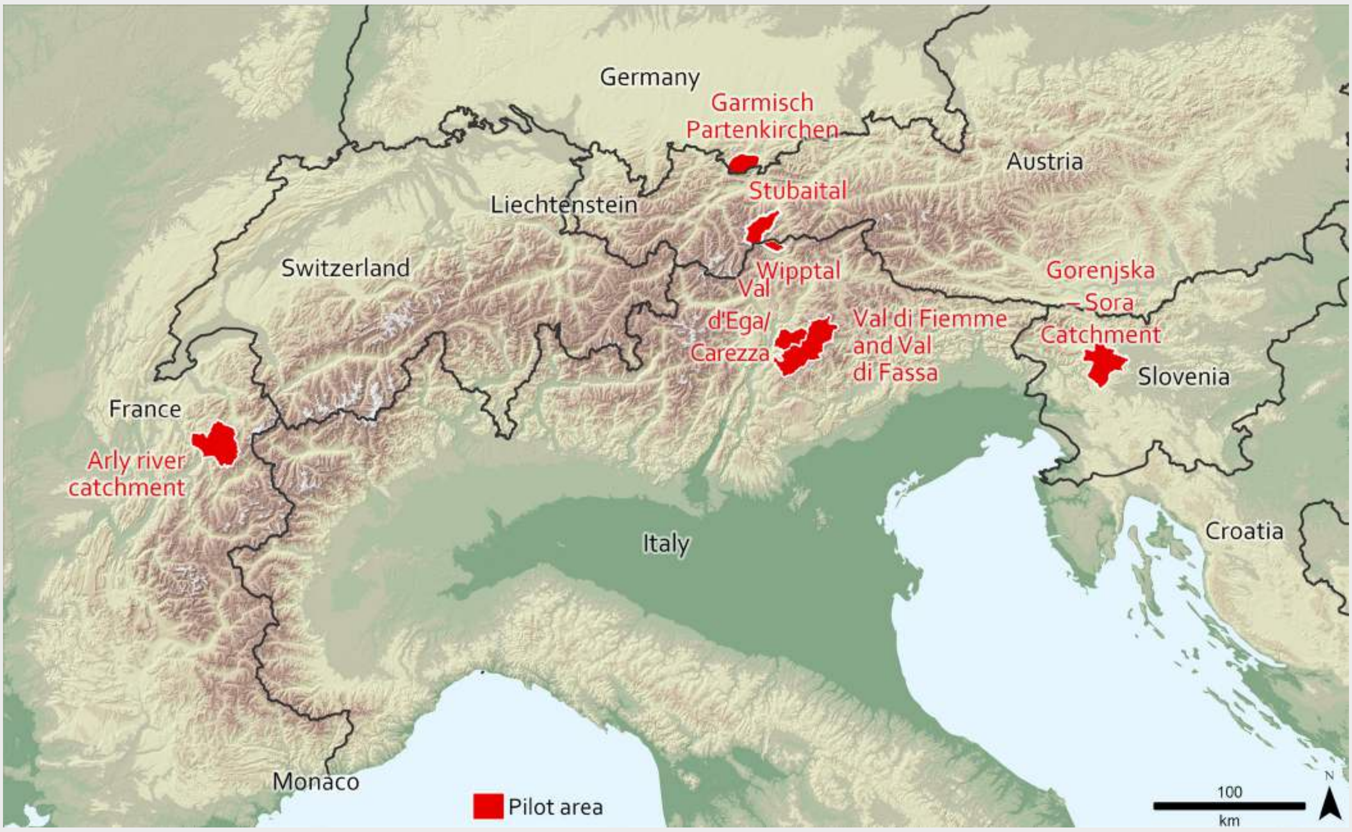


FIGURE 3: *Location of the five pilot areas across the Alps.*

Pilot Area Name	Country	Key Characteristics	Main Hazards Analysed (incl. compound and cascading events)	Risk Focus
Wipptal (ITA) & Stubaital (AUT)	Austria, Italy	Alpine valleys prone to intense rainstorms, glacier and permafrost-related cascading hazards	Debris flows, floods, permafrost and glacier melt, driftwood, infrastructure failure	Settlements, infrastructure, tourism, mobility, energy, forestry
Val di Fiemme/ Val di Fassa/Val d'Ega/Carezza	Italy	Forested, rural, mountainous Alpine area impacted by extreme windstorms and cascading impacts	Windstorm, forest blowdown, floods, debris flows, avalanches, bark beetle outbreak	Forestry, infrastructure, settlements
Garmisch-Partenkirchen	Germany	Glacier-fed alpine catchment, steep terrain, touristic gorges, convective storm events	Floods, debris/hyper concentrated flows, sediment cascades, rock slope failures	Tourism, infrastructure, settlements
Arly river catchment	France	Steep mountainous terrain, vulnerable road corridors, forested slopes, settlements at the valley bottom	Rain-on-snow events, landslides, debris flows, floods, avalanches	Infrastructure, forestry, tourism, settlements, industry
Gorenjska-Sora catchment	Slovenia	Alpine/pre-Alpine area, steep terrain, forested, scattered rural settlements	Droughts, heat, flash floods, floods, and landslides	Agriculture, forestry ecosystems, infrastructure, local water supply, tourism, settlements

TABLE 1: *Overview of pilot areas, including country, main hazards, and risk focus.*

SCOPING

PURPOSE: To define the objectives, scope, and context of the climate risk assessment, ensuring alignment with institutional priorities and decision-making needs. This phase establishes the foundation for a structured and feasible assessment process.

METHOD: Desk review of existing data, stakeholder mapping, and facilitated consultations to define goals, spatial and temporal frames, available resources, and governance arrangements.

This chapter outlines the scoping phase of the risk assessment process. It provides a structured approach to define the assessment's **purpose, context, and boundaries**. The aim is to support practitioners to formulate a project plan that is operationally sound, relevant to decision-making, and aligned with institutional and policy frameworks.

Guiding questions

- What is the primary objective of the risk assessment?
- What spatial and temporal scales are relevant?
- What resources (time, budget, staff) are available?
- Which data sources, local experts and previous assessments are available?
- Who are the key actors and stakeholders, and what are their roles?

Required input

- Contextual information (e.g. regional or sectoral characteristics)
- Access to climate scenarios and socio-economic projections
- Pre-existing assessments, plans, and datasets
- Initial stakeholder mapping
- Internal capacities and mandates

Expected output: a project plan

- Purpose and scope
- Timeframes and spatial scales
- Stakeholders and assigned roles
- Governance and resource frameworks
- Documents and data availability and gaps

STEP 1 - DEFINING PURPOSE AND OBJECTIVES

The objectives of the assessment must be explicitly defined. These objectives should be validated through stakeholder consultation to ensure that they address the relevant context of decision-making.

EXAMPLE 1:
Scoping – Purpose and Objectives in Val di Fiemme/Val di Fassa/Val d'Ega/Carezza in Trentino, Italy

In Trentino, Italy, the purpose of the climate risk assessment was to understand and evaluate the current and future risks posed by extreme weather events and their cascading impacts, particularly focusing on the pilot area of the Fiemme and Fassa Valleys. The assessment aimed to inform land use planning, disaster preparedness, and mitigation strategies by providing insights into how climate change is expected to affect the frequency and magnitude of natural hazards.

Objectives of the Risk Assessment:

- Identify Relevant Weather Extremes and Their Trends: Analyse past and projected changes in precipitation, wind, temperature, hail, and snowfall in the Trentino region.
- Determine Triggered Hazard Processes: Identify the natural hazards linked to these extremes, such as floods, landslides, debris flows, rockfalls, snow avalanches, and wildfires.

- Assess Cascading Impacts: Examine how initial hazards can lead to secondary impacts (e.g., windfall-induced bark beetle infestations, changes in forest cover affecting slope stability).
- Evaluate Future Changes in Hazard Frequency and Magnitude: Qualitatively assess how different climate change scenarios may influence the likelihood and intensity of hazards, using available data and expert knowledge despite some quantitative gaps.
- Inform Land Use Planning and Risk Management: Support updates to regulatory tools like the Hazard Synthesis Map (Carta di Sintesi della Pericolosità) to guide urban planning, land management, and risk reduction strategies.
- Highlight Data Gaps and Research Needs: Identify areas requiring further research, such as more precise quantification of flood and torrential trends, bark beetle spread, and the evolution of avalanche risks.

The time required to conduct a climate risk assessment varies depending on its scope and complexity, the availability of data, and the needs of stakeholders. ***TABLE 2*** below provides indicative timelines to help with project planning and resource allocation.

The time indicated for each component of the assessment (***TABLE 2***) represents the typical duration required to complete its core activities— from initial planning and scoping to data collection, stakeholder engagement, risk analysis, and reporting. This timeframe includes setting objectives, gathering and reviewing relevant data, holding consultations and workshops, applying analytical tools, and synthesising the results to create actionable outputs. Actual durations may vary depending on factors such as data availability, geographic complexity, the number of hazards and sectors considered, and the level of stakeholder participation. Where possible, some tasks can be conducted in parallel, however, more comprehensive or iterative approaches generally require additional time. Practitioners should allow for sufficient flexibility to address potential challenges and ensure a robust and decision-relevant assessment.

Workflow Stage	Main Activities	Assessment Types & Resource Needs	Duration Estimate
Scoping	Define context, purpose, spatial/temporal framing; review data; design partnership and stakeholder engagement.	• Initial project planning • Small teams focused on data review and stakeholder mapping • Moderate coordination effort.	2–6 weeks
Risk Identification	Identify climate-related hazards (including emerging), exposed systems, vulnerabilities; develop preliminary impact chains.	• Risk identification scan • Teams with expertise in hazard and vulnerability analysis • Moderate data input.	4–8 weeks
Risk Analysis	Identify weather extremes; analyse hazards, exposure, vulnerability; assess risk management capacity.	• Local/municipal to regional assessments • Multi-disciplinary teams • Requires modelling, data analysis, stakeholder input.	3–9 months
Result: Understanding Risks & Action Demands	Compile and validate the risk report. Prepare stakeholder-oriented outputs such as risk factsheets summarising key compound and cascading risks. Update and finalise sequential impact chains with insights from the analysis to visualise interdependencies.	• Requires coordination across analysis teams, expert validation, and stakeholder feedback. • Visual design capacity for impact chains and factsheets supports effective communication.	2–4 weeks

TABLE 2: *Estimated durations for various types of climate risk assessments on regional and local levels.*

The duration is also closely linked to the availability of **resources**, such as skilled personnel, technical expertise, data infrastructure, and financial support. Limited resources can hinder activities such as data collection, analysis, and stakeholder engagement. This can extend timelines. Conversely, well-resourced teams with access to high-quality data and tools can streamline processes and reduce the overall time required. To ensure effective and timely risk assessment outcomes, it is essential to align the project scope and timelines with available resources.

STEP 2 - TEMPORAL AND SPATIAL FRAMING

The selection of time horizons and spatial units should be based on scientific relevance and policy cycles. This includes:

- → Mid- and long-term climate projections
- → Socio-economic baselines and trends
- → Administrative and functional planning zones

EXAMPLE 2:
Scoping – Stakeholder Engagement in the Wipptal Valley, Italy

A first round of workshops was conducted with local experts to determine the appropriate temporal and spatial scales for the assessment. It was agreed that the risk assessment would focus on the present and the mid-term future (up to 2050), affecting the planning horizons relevant to local decision-making. However, climate projections were also considered for the long-term future (beyond 2050) to provide insight into potential future trends and emerging risks that could influence adaptation strategies today. The assessment covers a local area in the Wipptal Valley.

STEP 3 - REVIEW EXISTING DATA, INFORMATION AND KNOWLEDGE SOURCES

An important initial step in a compound risk assessment is to evaluate the availability, quality, and resolution of relevant datasets. Identifying both existing resources and data gaps is essential to plan and implement effective regional strategies. In the Alpine Space, this often involves integrating national datasets with regional data and local knowledge.

Key data categories typically include:

- → **Climate data**: Historical records and climate projections (including useful climate indices), particularly relating to key extremes, e.g., extreme precipitation, extreme temperatures, wind and meteorological drought.
- → **Hazard data**: Records of past natural hazard events (e.g., floods, landslides, avalanches, storms, droughts and wildfires), including compound and cascading events. Modelled projections of future hazard frequency, intensity, and spatial extent are also included.
- → **Impact data and inventories**: Systematic documentation of the consequences of past hazard events, including physical damage (e.g., to buildings, infrastructure), economic losses, disruptions to services, and human impacts (e.g., injuries, fatalities, displacement). These are critical for validating risk models and informing preparedness and recovery planning.
- → **Exposure data**: Population density and distribution, land cover/use, critical infrastructure (e.g. roads, energy supply and water systems), and tourism infrastructure.
- → **Vulnerability indicators**: Data on socioeconomic vulnerability (e.g., age structure, income level and poverty, education and risk awareness, health status), physical vulnerability (e.g., building stock, terrain features), and functional aspects such as accessibility and emergency response capacity.

The required data varies significantly depending on the spatial scale and assessment scope. ***TABLE 3*** provides an overview of the typical data requirements at different scales:

Scale / Scope	Typical Use	Key Data Requirements	Common Gaps / Challenges
Regional (Alpine regions)	Operational risk management, adaptation planning, cross-municipality coordination	High-resolution hazard and vulnerability maps, regional climate projections, infrastructure networks, population data, impact inventories	Fragmented data ownership, aggregated information, limited interoperability between regional authorities
Local / Municipal	Community-level planning, emergency preparedness, public awareness	Records of historical hazard impacts, detailed land use information, locations of critical infrastructure and local demographic data	Lack of digitised/ localised data, informal knowledge not systematically recorded
Sector-specific (e.g., tourism, agriculture, energy)	Assessing sector vulnerability, targeted adaptation measures	Snow reliability, forest health, slope stability, water availability, infrastructure dependencies	Sparse long-term monitoring, proprietary data, low spatial/ temporal granularity

TABLE 3: *Overview of data requirements at different scales.*

For effective compound risk assessment in the Alpine Space, data should be drawn from a combination of local, regional, national, and European sources. Key providers include:

→ **Local authorities and municipalities** – Provide detailed data on land use, infrastructure, population distribution, and records of past hazard impacts; also serve as sources of local and site-specific knowledge.
Example: *Municipality of Bolzano (Italy)*

→ **Regional agencies and authorities** – Provide hazard maps, regional climate data, vulnerability indicators, impact inventories and sector-relevant datasets (e.g., transport networks, critical facilities) at an intermediate spatial resolution.
Example: *Bavarian Environment Agency (Germany)*

→ **National data platforms** – Provide demographic, land cover, infrastructure, hazard-related datasets, including national disaster loss databases, and climate datasets.
Example: *Geoportal.ch (Switzerland), Geoportale Nazionale (Italy), INSPIRE Portal (EU)*

→ **National and regional weather services** – Provide real-time and historical meteorological data (e.g. temperature, precipitation, wind, snowfall), weather forecasts, early warning bulletins, and climate monitoring products crucial for hazard and risk assessment.
Example: *MeteoSwiss (Switzerland), GeoSphere (Austria), DWD (Germany)*

→ **European platforms and initiatives** – Including Copernicus, the European Environment Agency (EEA), and other EU data services which deliver EU-wide climate observations, remote sensing data, environmental indicators and disaster impact datasets relevant to risk analysis.
Example: *Copernicus Climate Data Store, EEA Climate-ADAPT, EFAS (European Flood Awareness System)*

→ **Sector-specific institutions** – Such as tourism, agriculture, energy, and forestry agencies, which hold data on snow reliability, forest conditions, water availability, infrastructure interdependencies and sector-specific impact reports.
Example: *Austrian Federal Forests (ÖBf), Club Arc Alpin (tourism sector), Alpine Convention working groups*

- **The X-RISK-CC WebGIS platform** – Climate extreme indices for the past and the future in the Alpine Space helping the visualisation and identification of relevant trends for different climate scenarios (see chapter Risk Analysis - Step 1).

- **Research institutions and projects** – Provide high-resolution studies, model outputs, risk-relevant indices, as well as post-disaster assessments and event-specific impact analyses. ***Example:*** *Eurac Research, University of Innsbruck, ETH Zurich, Geosphere Austria*

Engaging local stakeholders from the beginning can also help to identify critical information that is not digitised or formally recorded but may include valuable **impact observations** and experiences of the community.

EXAMPLE 3:
Scoping – Review existing data, information and knowledge sources in Val di Fiemme/Val di Fassa/Val d'Ega/Carezza in Trentino, Italy

Data was gathered from regional agencies, research institutions, and specialised organisations.

Key Data Categories and Sources**:**

- Climate Data: Historical and projected trends for extreme precipitation, temperature, and wind from Meteotrentino and University of Trento.

- Hazard Data: Records of past floods, landslides, bark beetle outbreaks, hail, avalanches, and wildfires from Vaia reports, Fondazione Mach, and the province's Forestry Service. Also, qualitative future hazard projections.

- Impact Data: Documented damage and cascading effects from past events.

- Exposure & Vulnerability Data: Information on at-risk areas (inhabited areas, agricultural land, forests) and factors influencing susceptibility (slope stability, protective works).

Gaps: Noted needs for quantitative future hazard projections and integrating local knowledge.

STEP 4 - TEAM, STAKEHOLDERS AND RESOURCES

Define roles based on the required competencies, to ensure interdisciplinary coverage (e.g., climatology, spatial planning, social sciences, emergency response). Clarify institutional responsibilities and secure the necessary technical, financial, and human resources. Consider setting up steering committees or working groups to promote continuity and accountability.

STEP 5 - STAKEHOLDER ENGAGEMENT

Involving stakeholders early on helps to ensure relevance, transparency, and uptake. Engagement should be prioritised based on influence and interest. Mapping stakeholder roles early on improves coordination and management of expectation.

Scoping Outcomes

- The operational framework for the risk assessment is defined.
- The scope, timelines, and resources are clarified.
- Existing data, information, and knowledge sources are reviewed, and data gaps are identified.
- Stakeholder roles and governance are defined.
- The basis for the risk identification phase is set.

RISK IDENTIFICATION

PURPOSE: To identify and list climate risks that should be prioritised for detailed assessment in the Risk Analysis phase. This phase focuses on recognising potential risks rather than quantifying them or evaluating their significance.

METHOD: Qualitative analysis led by domain experts, informed by data reviews, expert elicitation and stakeholder consultations.

This chapter focuses on identifying climate change-related compound risks within the assessment context defined in the Scoping. Its aim is to systematically recognise climate-related hazards, exposed systems, vulnerability factors, and potential impacts, to produce a comprehensive list of relevant risks. The focus is on capturing the breadth of risks within the defined spatial and temporal scope, ensuring no critical risk is overlooked before deeper analysis.

At this stage, a list of identified climate risks should emerge from the structured identification process, including stakeholder workshops, expert consultations, and data screening.

Risk identification should occur after the spatial and temporal scope is defined and relevant climate, hazard and socio-economic data are collected, but before any quantitative or detailed modelling is initiated. A preliminary data collection ensures stakeholder and expert inputs are well-informed. However, the process may also uncover data gaps that must be addressed before moving to Risk Analysis.

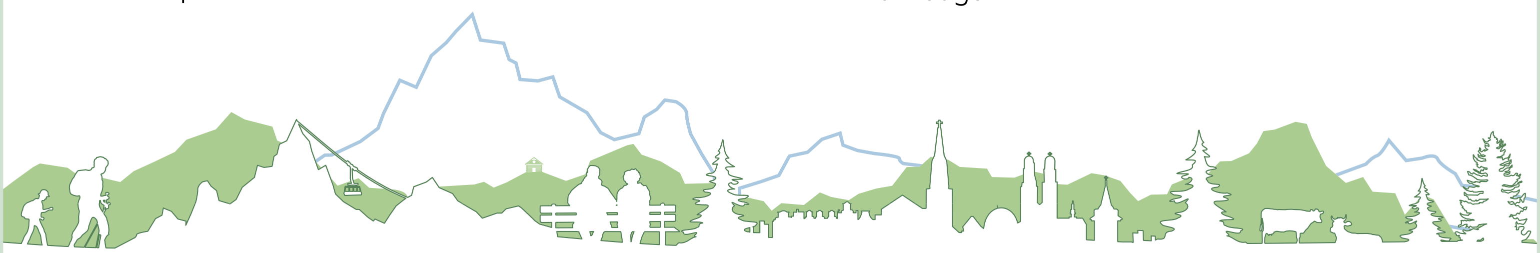
Guiding questions and key steps

- → Which climate-related hazards are relevant within the defined spatial and temporal scope?
- → Which systems and populations are potentially exposed to climate-related hazards?
- → What vulnerability factors may influence potential impacts?
- → What are the potential impacts of these hazards on exposed systems and populations?
- → What plausible risks emerge from hazard–exposure–vulnerability-impact linkages and should be considered for further analysis?

These questions are addressed through a structured, qualitative process, such as an expert workshop, that should be documented in a traceable and transparent manner.

Required input

- → Climate and meteorological drivers (e.g., temperature trends, rainfall variability, storms),
- → Information on climate-related (compound) hazards (recorded in the past and emerging),
- → Socio-economic and environmental exposure data (who and what is exposed to these events),
- → Vulnerability factors,
- → Expert knowledge from diverse domains,
- → Stakeholder perspectives and contextual knowledge.



Expected output: List and Visualisation of Identified Climate Risks

- → Depiction of relevant climate drivers and associated climate-related (compound) hazards,
- → Description of potentially affected systems, exposed assets, vulnerability factors and potential impacts,
- → A list of identified climate risks selected for detailed assessment in the Risk Analysis phase,
- → Impact chains for each identified risk illustrating the causal links from climate drivers to impacts.

Risk identification is primarily a qualitative exercise, led by subject-matter experts and informed by existing data and structured stakeholder input. It involves a desktop study and expert exchanges.

Methodological steps include:

1. Climatic driver and hazard screening (past events and emerging hazards)
2. Exposure, vulnerability and potential impact identification
3. Risk visualisation using impact chains

STEP 1 - IDENTIFY CLIMATE-RELATED HAZARDS TO ASSESS

The initial step is to identify natural hazards triggered by extreme weather events, that have occurred in the region of interest in the past. These can be single hazards or compound and cascading hazards observed during extreme weather events. The hazard identification exercise can range in spatial scale, including catchment-specific to region-wide approaches, while the temporal scale can focus on a single event or cover a series of hazardous events within the region of interest over several years or decades.

NOTE: *The risk identification phase is primarily a qualitative, descriptive exercise aimed at compiling a comprehensive list of climate-related risks relevant to the area under consideration. It draws on available data, expert judgement, and stakeholder input. Users should document data sources, and any knowledge gaps or uncertainties encountered during the process to guide subsequent detailed risk analysis and data collection efforts.*

Previously observed climate-related hazards form the baseline for the analysis of risk. However, to adequately assess future risk, it is crucial to consider that climate change may alter known hazard processes and new scenarios may emerge that have not previously been observed.

When identifying and evaluating risks for detailed assessment, it is important to account for the following possibilities:

1. Some hazards may decrease in relevance (e.g., fewer avalanches at lower altitudes),
2. New hazards may emerge (e.g., prolonged droughts, wildfires),
3. Existing hazards may change in magnitude or frequency, and
4. Some hazards may remain unchanged.

These considerations are crucial for understanding how future risks may differ from past patterns.

EMERGING CLIMATE-RELATED HAZARDS

Climate change is increasing the frequency, severity, and unpredictability of extreme-weather events in the Alpine Space. Risk managers must consider **compound and cascading hazards, as well as emerging hazards**—hazards that occur together or evolve in ways that have not been seen before.

RELEVANCE TO THE ALPINE SPACE

In mountainous terrain weather can trigger complex events. Its interaction with terrain, snowpack, infrastructure, and human activity makes the Alps vulnerable to multi-hazard and evolving climate risks.

EXAMPLES OF ALPINE-RELEVANT EMERGING HAZARDS

- Rain-on-snow events causing rapid snowmelt and flooding
- Glacial lake outburst floods (GLOFs) caused by heavy precipitation or permafrost thaw
- Glacier retreat providing newly mobilizable material (debris, sediment), which may be set in motion during intense rainfall events and could contribute to more severe damage occurrences
- Increased frequency and magnitude of landslides and rockfalls due to loss of protection forest
- Forest fires

KEY CONSIDERATIONS FOR HAZARD IDENTIFICATION

Risk managers and experts should:

- Take a broad and flexible approach, considering evolving hazards and how they interact
- Recognise that new hazard types and combinations may emerge due to climate change
- Involve experts from diverse domains (e.g., meteorology, hydrology, ecology) to include complex hazard dynamics

STEP 2 - IDENTIFY EXPOSURE AND VULNERABILITY FACTORS

For each climate-related hazard selected in the previous step, **identify the exposed elements** of the ecological and socio-economic systems that might be affected. Describe the conditions that influence the risk, including predisposing/preparatory factors, pre-impact **vulnerability factors** and the potential impacts expected.

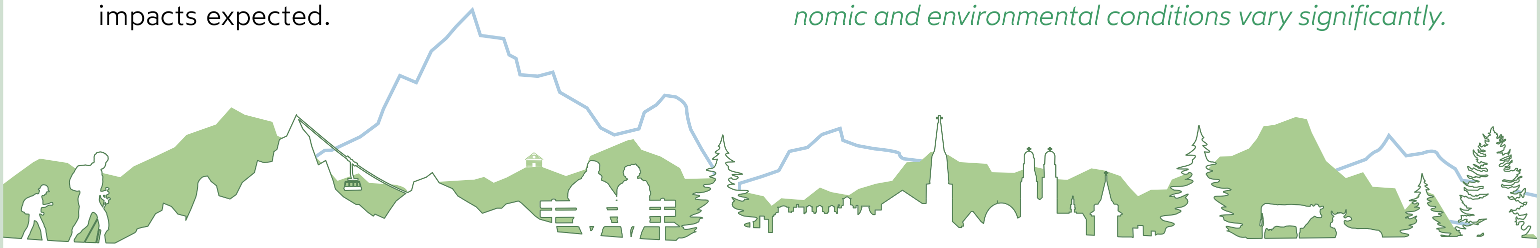
Exposed sectors and systems may include:

- **People:** Population and tourists
- **Infrastructure:** Transport networks, energy grids, communication systems
- **Buildings:** Residential, commercial, or industrial buildings in hazard-prone areas
- **Economic sectors:**
  - **Agriculture:** Crops, livestock, farmland
  - **Forestry:** Forest ecosystems and related infrastructure
  - **Water resources:** Reservoirs, dams, irrigation systems
  - **Tourism:** Mountain tourism infrastructure, cultural heritage sites
  - **Industry:** Production facilities, supply chains, warehouses
- **Critical services:** Hospitals, schools, emergency services
- **Natural systems:** Forests, wetlands, rivers

Vulnerability factors include, for example:

- **Sensitivity or susceptibility:**
  - Age-related vulnerabilities (e.g., elderly, infants)
  - Degraded ecosystems or loss of biodiversity
  - Soil degradation or poor water retention in landscapes
  - Inadequate infrastructure prone to damage (e.g., outdated drainage systems, weak buildings)
- **Lack of capacity:**
  - Lack of (specific) knowledge
  - Lack of (specific) technology or limited access to technology
  - Lack of financial resources
  - Lack of (specific) institutional structures and resources
  - Lack of (specific) legal frameworks, regulations, or strategies

***NOTE:** Engaging local stakeholders, including community representatives, industry experts, and ecological specialists, can provide valuable insights into exposure patterns and vulnerability factors that may not be evident from data alone. This is especially important in mountain regions where local socio-economic and environmental conditions vary significantly.*



Knowledge gained from past events and their documentation informs the understanding of both past and current processes that affect ecological and socio-economic systems and can lead to impacts. Future developments in socio-economic systems may contribute to compound and cascading impacts or emerging risks, which risk managers need to anticipate. For instance, ecological and socio-economic systems may be affected simultaneously – such as extreme wind and precipitation - or impacted more intensely than before, as seen in forests increasingly exposed to more severe drought and heat.

In addition to changing hazards, it is essential to report **developments in exposure and vulnerability** factors that may influence future risks associated with climate-related hazards. Exposure and vulnerability are dynamic and may evolve due to environmental, demographic, or economic changes.

EXAMPLES OF ALPINE-SPACE-RELEVANT EMERGING EXPOSURE AND VULNERABILITY FACTORS

Developments in Exposure.

- → Population shifts and urban expansion in valley floors
- → Infrastructure development: expansion of transport networks, tourism facilities, and energy infrastructure
- → Agricultural land use changes: shifts in agriculture, such as expansion of cultivated land or intensification of farming at higher elevations
- → Ecosystem exposure: changes in vegetation zones and species distributions
- → Increased exposure of assets to gravitational hazards due to the loss of protective forests
- → Increased tourism due to a shift from Mediterranean to cooler regions in Europe

Vulnerability trends:

- → Demographic changes: Aging populations in mountain communities increase vulnerability due to reduced mobility and health challenges
- → Infrastructure limitations: ageing or insufficient infrastructure, e.g. outdated water management systems, poorly maintained roads and buildings
- → Environmental degradation: Loss of biodiversity, soil degradation, and deforestation reduce the natural buffers protecting mountain communities from impacts
- → Health vulnerabilities increased due to heat stress, vector-borne diseases and respiratory illnesses
- → Limited access to warnings (e.g., language barriers or inadequate warning tools) (capacity)
- → Lack of awareness about appropriate behaviour during emergencies (capacity)
- → Ageing protection structures and insufficient design standards, leading to increasing residual risk (sensitivity)
- → Decreasing number of volunteers in response organisations (lack of capacity)

KEY CONSIDERATIONS FOR EXPOSURE AND VULNERABILITY IDENTIFICATION

Risk managers should:

- → Take a broad, flexible view of risks, considering evolving socio-economic and ecological systems and their interdependencies
- → Use multi-hazard risk assessments including emerging threats
- → Collaborate across sectors, involving civil protection services and community partners
- → Monitor the development of socio-economic systems to anticipate changing risk patterns

STEP 3 - PRELIMINARY IMPACT CHAINS FOR EACH IDENTIFIED RISK

In the previous steps, the relevant climate-related (multi-) hazards, the exposed sectors and assets, and their vulnerability factors were identified for the area under consideration. To enhance understanding and visualisation of complex risks, **preliminary impact chains** can now be developed individually for each identified risk as a conceptual tool. These chains provide a structured visualisation of how climate-related events unfold and interact - particularly useful in cases involving compound, cascading, or systemic risks.

A sequential impact chain plots how climate-related events evolve over time, starting with preconditions and triggering factors, moving through the event itself, and continuing into short-, medium-, and long-term impacts. Creating separate impact chains for each relevant risk supports targeted analysis. ***FIGURE 4*** shows the sequential impact chain concept.

The impact chain framework highlights the following components:

- → **Meteorological drivers**: Climate and weather phenomena that initiate or influence hazards (e.g., precipitation deficit, high temperature).
- → **Predisposing/preparatory factors**: Static or dynamic pre-existing environmental conditions (e.g., slope gradient, vegetation type, sediment availability).
- → **Extreme event conditions**: The specific event (e.g., drought).
- → **Vulnerability factors:** Technical or socio-institutional weaknesses influencing impacts (e.g., lack of an irrigation system in place or an early warning system) or social vulnerability (e.g., old population, low education, poverty).
- → **Hazards and climate-influenced effects**: Hazards or processes influenced or triggered by the meteorological drivers (e.g., wildfires).
- → **Cascading socio-economic impacts**: Observed negative impacts on sectors and communities (e.g., fatalities and economic losses).
- → **Exposed elements and sectors**: Sectors and assets affected by the event (e.g. agriculture, energy, or residential areas).

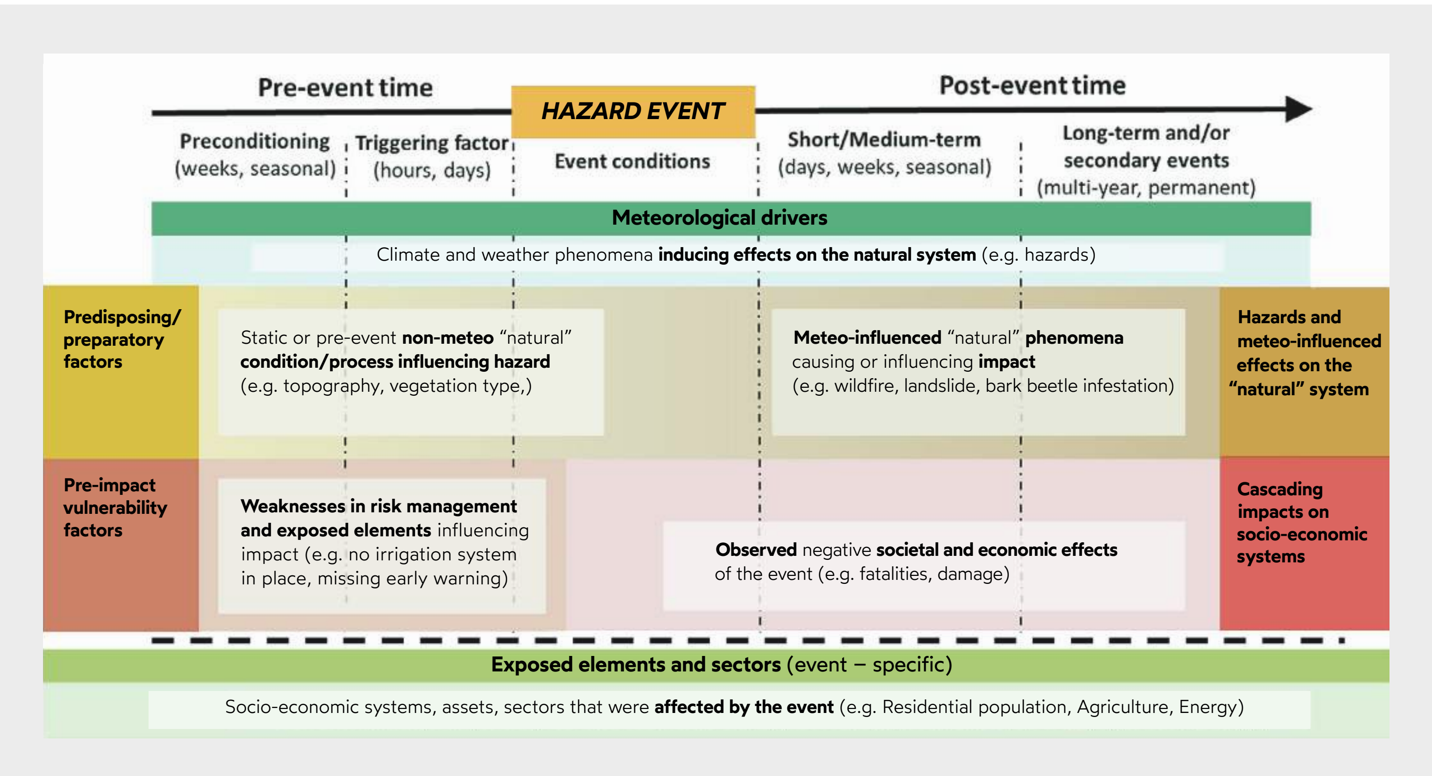


FIGURE 4: *Generic structure of a sequential impact chain illustrating causal links from hazards to systemic impacts. It plots the evolution of climate-related events over time—from preconditions and triggering factors to the event itself, and its short-, medium-, and long-term impacts.*

FIGURE 5 illustrates a very simplified sequential impact chain using drought as an example.

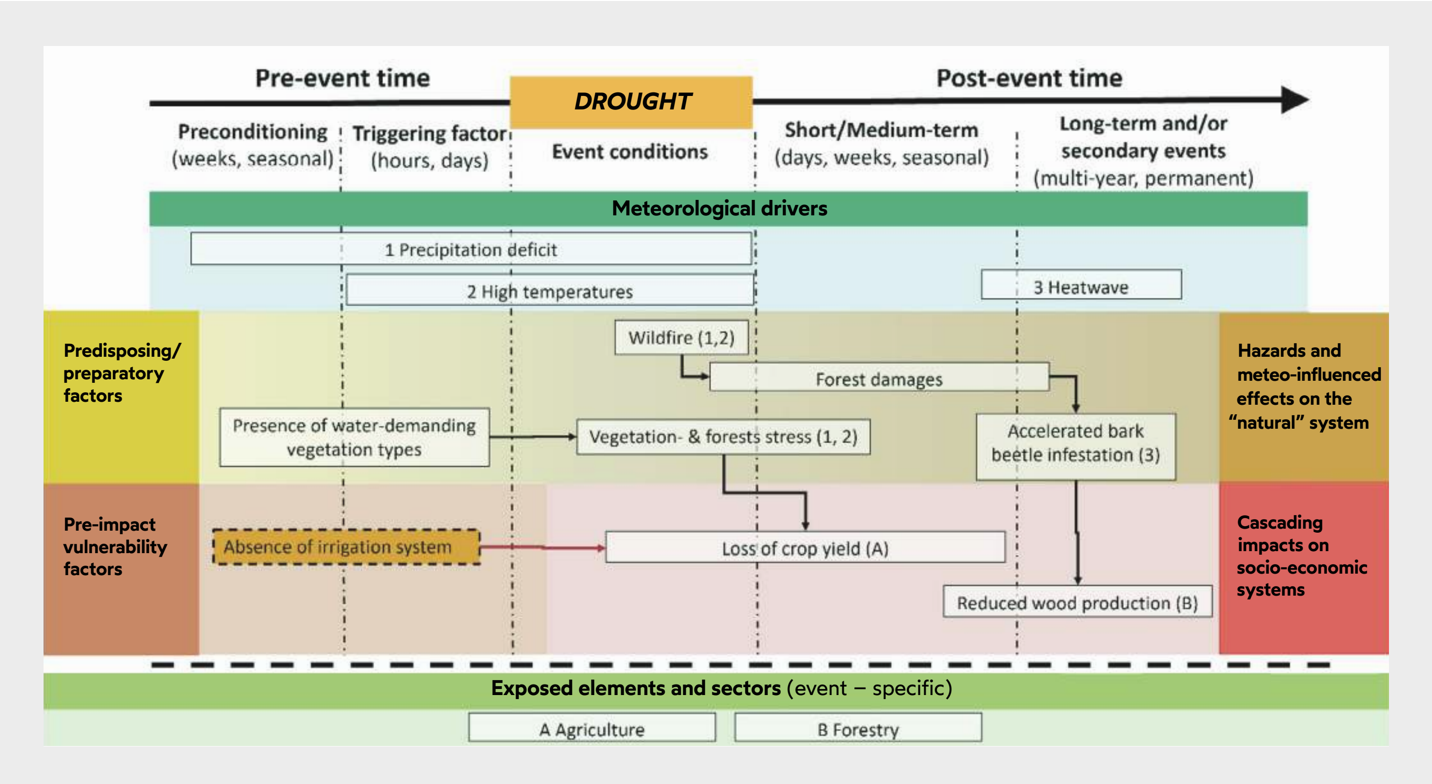


FIGURE 5: *A simplified impact chain illustrating a drought scenario reveals a sequence of climate triggers, a predisposing factor, a vulnerability, cascading impacts and exposed elements and systems.*

Impact chains provide an initial hypothesis of how specific risks may occur and evolve. They facilitate an understanding of risk components, structure discussions, and guide the collation and integration of data from hazard screening, vulnerability and exposure assessments. When used in expert and stakeholder workshops, impact chains foster shared understanding and help prioritise the most relevant and actionable risk management measures.

PRACTICAL TIP: Use workshop facilitation tools or templates to develop impact chains collaboratively with stakeholders, ensuring all relevant factors and linkages are captured. Iteratively refine the chains as new information emerges.

Based on the preliminary impact chains developed for each risk, a consolidated list of identified risks can be compiled (***TABLE 4***). This list summarises the risks identified in the risk identification phase, each characterised by the relevant hazards, exposed elements, vulnerability factors, and potential impacts. The following table provides illustrative examples of such risks for an alpine region. These examples demonstrate how risks can be systematically described to inform and structure the subsequent Risk Analysis, where each identified risk will be assessed in greater detail.

Risk ID	Risk Name	Hazard	Exposed System or Sector	Vulnerability Factors	Impacts
R1	Risk to grassland ecosystems, food security, transport and accessibility due to heavy rainfall and floods	Heavy rainfall and floods	Grasslands, agricultural lands, transport infrastructure	Soil erosion susceptibility, poor drainage, ageing infrastructure	Crop loss, reduced pasture productivity, transport disruptions, soil degradation
R2	Risk to mountain forests and biodiversity due to droughts and heatwaves	Droughts and heatwaves	Forest ecosystems, biodiversity hotspots	Low water retention soils, forest degradation, species sensitivity	Tree mortality, loss of biodiversity, increased fire risk
R3	Risk to tourism infrastructure and cultural heritage from avalanches and storms	Avalanches and storms	Tourism facilities, cultural heritage sites	Structural weaknesses, limited early warning systems	Infrastructure damage, loss of tourism revenue, heritage site degradation
R4	Risk to water supply and hydroelectric power due to droughts and prolonged dry spells	Droughts	Reservoirs, dams, hydroelectric plants	Reduced water availability, ageing infrastructure	Water shortages, reduced energy production, economic losses
R5	Risk to energy supply and public health due to heatwaves	Heatwaves	Energy infrastructure, vulnerable populations (elderly, infants)	Aging power grid, lack of cooling capacity, limited emergency preparedness	Power outages, heat-related illnesses, reduced hospital capacity
R6	Risk to urban settlements and critical services due to compound flooding and landslides	Floods and landslides	Residential areas, hospitals, schools	Inadequate flood defences, vulnerable populations	Property damage, service disruptions, displacement of people
R7	Risk to agriculture and transport networks from compound heavy rainfall and landslides	Heavy rainfall and landslides	Croplands, roads, bridges	Soil instability, insufficient maintenance	Crop destruction, transport network breakdown, economic losses
R8	Risk to forests and air quality from wildfires triggered by drought and heatwaves	Wildfires, drought, heatwaves	Forests, residential areas	Lack of fire management, increased fuel loads	Forest loss, air pollution, health impacts, property damage

TABLE 4: *Example of identified risks.*

Risk Identification Outcomes

- → Summary of identified hazards
- → Summary of identified vulnerability, exposure and impacts
- → Identification of unforeseen and emerging risks
- → Initial impact chains
- → List of identified risks to be addressed in Risk Analysis

RISK ANALYSIS

PURPOSE: To develop an in-depth understanding of **climate change-related risks** identified and prioritised during the Risk Identification phase, within a defined assessment context. This chapter guides practitioners through a systematic approach to investigate climate-related hazards, their current and future impacts, and the vulnerabilities and exposure that shape risk severity. The ultimate goal is to provide a sound evidence base for identifying adaptation needs and options that can enhance resilience under changing climate conditions.

METHOD: This phase employs a combination of quantitative and qualitative methods. Quantitative analysis of hazards, exposure, and vulnerability data is complemented by expert judgment and stakeholder inputs to ensure contextual relevance and robustness.

This chapter builds directly on the outcomes of the Risk Identification phase, focusing on detailed assessment of each prioritised risk to understand how hazards, exposures, and vulnerabilities interact and evolve now and in future climate scenarios.

The Risk Questionnaire in Annex 4 provides a set of guiding questions to guide through the risk analysis process. The aim of the risk questionnaire is to improve understanding of risks and their drivers. Risk managers and decision makers can provide answers to these questions based on quantitative investigation or qualitatively based on the collective expertise available in their organisations and other important stakeholders in their region of interest.

Guiding questions and key steps (each question is asked for each risk identified for the risk analysis)

- Which climate extremes are driving the specific risk? How might their frequency and intensity change, and could new extremes emerge under future climate scenarios?
- Which climate-related hazards and impacts are triggered by these extremes, and how might their magnitude, frequency, and interactions evolve?
- Which sectors, populations, or assets are exposed and how critical are they in terms of potential impacts?
- Which physical and social vulnerabilities influence the severity of impacts, and how might these vulnerabilities change over time?
- How effective is the current risk management system in reducing impacts? What gaps exist under future conditions?

Required input (tailored to the scope of analysis for each risk)

- Climate data (historical and future projections)
- Information on past climate-related hazards, including their frequency and magnitude
- Current and projected socio-economic and environmental exposure data
- Vulnerability data across relevant sectors
- Scientific and applied models with computational resources
- Expert knowledge and stakeholder perspectives

Expected outcomes

- A technical risk report documenting methods, data, analysis and conclusions
- Concise factsheets summarising each analysed risk for stakeholder communication
- Revised and detailed impact chains illustrating complex risk drivers and interactions

STEP 1 - IDENTIFY RELEVANT WEATHER EXTREMES

PURPOSE: *To identify relevant weather extremes for the area under consideration, based on past and current observations as well as future projections, using climate data available.*

An important first step is to use available **local datasets**, where possible, as these provide more accurate, high-resolution insights into regional climate dynamics. **National meteorological services, regional climate centres, or research institutes** often elaborate climate information about extreme precipitation, temperature, wind, and drought. These institutions typically tailor specific indices to reflect the region's **specific topographic, climatic, and hazard characteristics**. Such data can help to detect trends, assess return periods, and identify critical thresholds for hazard occurrence.

EXAMPLE 4:
Risk Analysis - Rainfall extremes in Wipptal catchment in Italy and Stubaital valley in Austria using local data

Recent extreme rainfall events in the Wipptal (Italy) and Stubaital (Austria) regions were analysed using local daily and sub-daily precipitation data from 15 meteorological stations. Two short-duration rainfall events occurred in **August 2021** (Wipptal) and **July 2022** (Stubaital) and led to debris flows and infrastructure damage. These events were the focus of the analysis.

Key findings:

→ On **16 August 2021** in Wipptal, Ladurno recorded **85 mm/day**, while Fleres registered up to **40 mm in 3 hours**. Although the daily return period was less than 5 years, the short duration and high intensity triggered a **debris flow and a cascading flood** along the Fleres river.

→ On **22 July 2022** in Stubaital, Neustift recorded **70 mm/day,** including **30 mm in just one hour**. The estimated **hourly return period was 30 years**, highlighting the hazard posed by intense, short bursts of rainfall.

→ A **trend analysis for 1980–2022** indicated a general increase in the frequency and intensity of one-day precipitation events at most stations, particularly in Wipptal. However, these trends were not statistically significant.

This case highlights the value of **high-resolution, locally validated datasets** for identifying site-specific hazard dynamics and estimating event probabilities, particularly in **mountainous, cross-border regions**.

Future projections:
Climate projections suggest a continuous increase in the intensity and frequency of one-day precipitation extremes, both annually and during summer. Under a +4°C global warming scenario (GWL4, where *GWL* refers to the **Global Warming Level** relative to pre-industrial temperatures), the intensity of one-day precipitation events is projected to increase by approximately 15% across the region compared to current values. The frequency of such events could rise up to 46% in Wipptal and 23% in Stubaital. Return levels for rare events (e.g., 50-year events) are expected to increase by 20–28%. Furthermore, the intensity of short-duration precipitation extremes is projected to rise substantially. With a +4°C warming, the 99th percentile of hourly precipitation could become three times as intense as today.

Where local data are unavailable or incomplete, or where a broader regional comparison is required, the **X-RISK-CC WebGIS** platform (https://cct.eurac.edu/x-risk-cc) is a valuable supplementary resource. It provides a consistent set of 20 climate indices for the Alpine Space derived from European datasets, covering both historical conditions (1991–2020) and projected future scenarios under different levels of global warming (GWL). These indices support the identification of relevant weather extremes across the Alpine Space and can help practitioners to quickly screen for key climate drivers of specific hazards.

The 20 climate indices in the X-RISK-CC WebGIS include:

- → Precipitation extremes (e.g., maximum daily rainfall)
- → Temperature and heatwave indices (e.g., maximum temperatures, warm spell duration)
- → Wind and storm indicators (e.g., maximum wind speeds, number of extreme wind days)
- → Drought and compound indices (e.g., hot-dry conditions, extreme precipitation and wind speed)

What risk managers can do with these data:

- → Visualise spatial maps of these climate indices showing current conditions and projected future changes. These maps are available at a resolution of 5.5 km for historical data (1991–2020) and at a resolution of 12 km for future projections.
- → Derive current conditions and future changes for the area of interest (at NUTS-3 level).
- → Download data for baseline and future climate scenarios.
- → Compare different climate scenarios to understand potential changes in the frequency and intensity of weather extremes.

This information helps to identify weather extremes that are likely to cause hazards such as floods, landslides, heatwaves, droughts, or storms.

NOTE: *The X-RISK-CC WebGIS provides pre-calculated indices to help identify the main changes in weather extremes potentially affecting future hazards. The indices are designed to highlight general trends and patterns, but they may not capture* ***rare, high-impact extremes*** *at a local scale. Locally relevant information for risk management, such as local return periods for very intense events and specific critical thresholds, are not covered by the WebGIS and must be derived, where possible, from analyses based on local data. The information for provincial areas (NUTS-3) provides a more local perspective but still must be interpreted as average patterns with a certain range of variability, and not as absolute numbers relative to a specific location.*

Outcome

This step identifies the relevant weather extremes that may trigger hazards in the region, providing essential information for the subsequent hazard analysis. The findings form the basis for Step 2, which focuses on evaluating the types, magnitudes, and interactions of hazards in the context of observed and projected climate conditions.

Further Reading:

- → X-RISK-CC WebGIS User Guide and Data Documentation — detailed descriptions of climate indices, data sources, and how to navigate the https://cct.eurac.edu/x-risk-cc platform.
- → X-RISK-CC pilot area report: https://cct.eurac.edu/x-risk-cc/data/ceph/webgis-diglib/pilot_reports/Wipptal-Stubaital.pdf

STEP 2 - ANALYSE HAZARDS TRIGGERED BY CURRENT AND FUTURE WEATHER

PURPOSE: *Evaluation of relevant (compound and cascading) hazards that can arise from identified weather extremes in combination with each identified risk, in terms of hazard frequency and magnitude, interactions between different types of hazards (cascading/compound character), and potential future changes.*

This section builds on the weather extremes identified in Step 1, using them as a basis to assess which climate-related hazards may be triggered under current and future conditions.

The basis of any hazard analysis relies on a systematic collection of data on past events which provides a better understanding of the different types of prevailing natural hazards, and how often they have occurred and how intense they have been in the past. Ideally, a comprehensive **compilation of event data** would cover:

1. The type, magnitude and characteristics of the hazard event,
2. The recorded meteorological drivers of the respective event (see also Step 1).

This information can be obtained from automated stations (e.g., weather stations), national or local event databases, event reports, and published scientific literature.

EXAMPLE 5:
Risk Analysis – Hazard data sources, South Tyrol, Italy

The Hazard Browser is a web-based geographic information system platform (https://mapview.civis.bz.it/) for South Tyrol in Italy. It allows users to view and access data on natural hazards, including an event cadastre with information about the type, date, location, extent and magnitude of past events.

When assessing natural hazards triggered by extreme weather events, it is essential to consider **multi-hazard situations**. The hazard interaction matrix can be used to identify relevant compound or cascading hazard processes relevant under current conditions, as well as emerging hazards that could become significant in the future (e.g., wildfires as an emerging hazard due to increasingly long drought periods and heatwaves). Emerging hazards have not yet been observed or have only been observed to a minor degree but they could pose a risk under future climate conditions (see "climate projections" in the X-RISK-CC WebGIS). The hazard interaction matrix in ***FIGURE 6*** helps to examine the interactions between the nine different hazard processes analysed in the X-RISK-CC pilot areas.

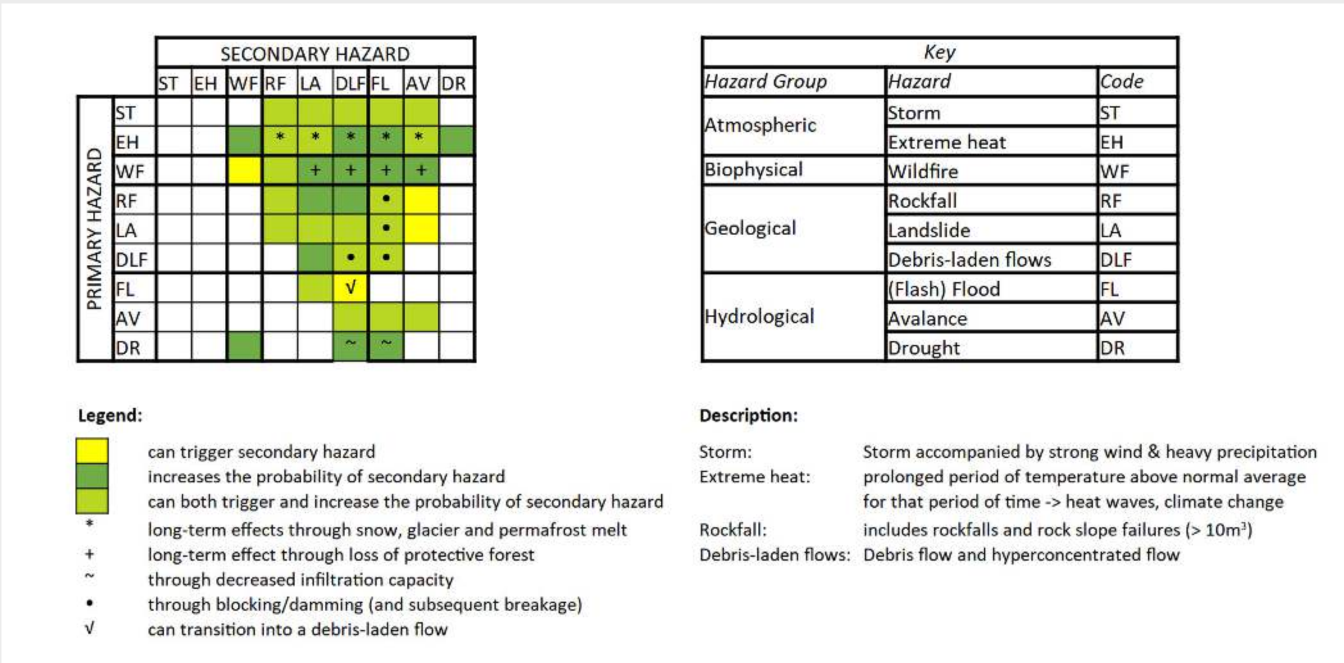


FIGURE 6: *Hazard interaction matrix examining interactions between different hazard processes (modified after Gill & Malamud, 2014[6]).*

6 Gill, J. C. and B. D. Malamud (2014): Reviewing and visualizing the interactions of natural hazards, Rev. Geophys., 52, 680–722.

EXAMPLE 6:
Risk Analysis – Compound and cascading hazards for Garmisch-Partenkirchen, Germany

The region of Garmisch-Partenkirchen, which includes the catchments of Partnach, Ferchenbach, Kanker and Hammersbach rivers, is exposed to various alpine hazards including rock slope failures, landslides, river floods, debris flows, hyperconcentrated flows, and flash floods. Recurrent extreme precipitation events in recent decades have caused numerous natural hazard events, affecting the touristic attractions Partnach Gorge & Höllental Gorge as well as the town of Garmisch-Partenkirchen itself.

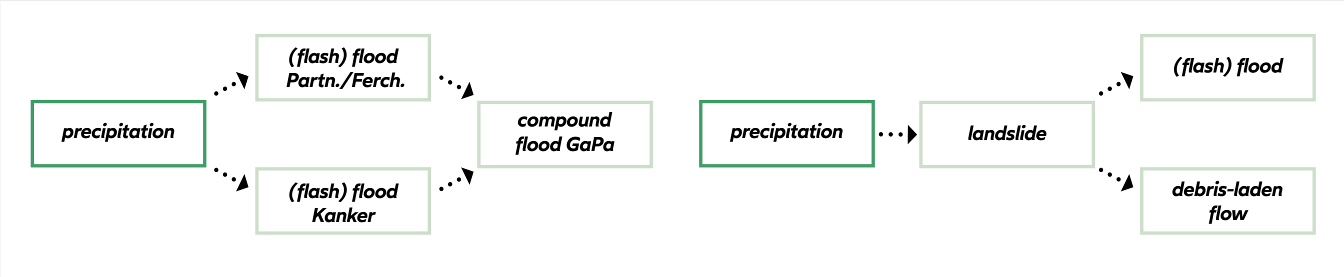


FIGURE 7: *Two possibilities of how compound or cascading hazard events can emerge in Garmisch-Partenkirchen, Germany.*

Hazard frequency and magnitude are particularly important variables in hazard assessment and risk analysis. Use the collected inventory of hazard processes to quantify how often and to what extent relevant types of hazards have occurred. Inventories covering several decades can provide valuable insights into recent climate change effects on natural hazards.

Inventories of hazard magnitude over a given time period for which data are available can be processed and visualised in various ways. These include:

1. Reconstructed time series of hazard magnitudes either as individual magnitudes or as magnitude classes.
2. Statistical representations of the temporal frequency of hazard events for different magnitude classes in a table.
3. Frequency-magnitude curves which plot a range of return periods (frequency) against the associated return level (magnitude) using the rank order analysis.

The most suitable approach depends on the type of hazard, the number of data entries, and the level of detail in historical records. Different options for visualisation of magnitude-frequency relationships are provided in Annex 1.

EXAMPLE 7:
Risk Analysis – Frequency and magnitude of hazard events in Stubaital, Austria

The systematic event documentation by the Austrian Service for Torrent and Avalanche Control (WLV) spans back to the 1970s. In the Stubaital, Tyrol, the number of debris-laden flow events has increased significantly since 2010, with a particularly notable rise in the most recent years (2020–2024). Analysis of debris flow volumes per decade also shows a substantial increase in mobilised material between 2010 –2019, with an even more pronounced event magnitude between 2020 –2024.

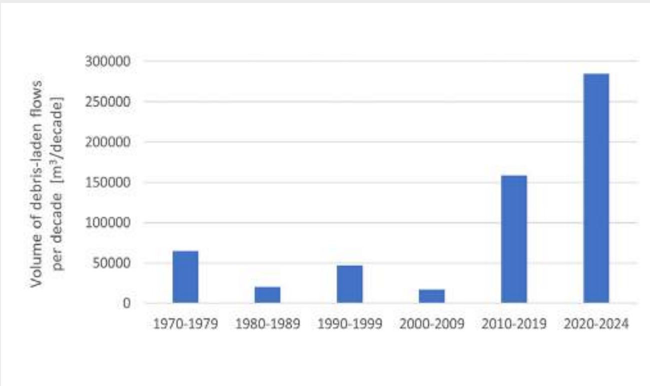


FIGURE 8: *Absolut volume of debris-laden flows per decade in Stubaital, Austria.*

Climate change affects many aspects of natural hazards, including predisposition (or preconditioning), triggering and impact. Future changes in weather extremes (triggering), such as precipitation, wind speed, heatwaves and droughts, can be identified in the climate projections provided by the X-RISK-CC WebGIS. However, how these changes turn into changes in geological or hydrological hazards is often more difficult to predict. The concept of **preconditioning** can help to understand **complex, non-linear interactions between climate change and hazard activity.** The impact of climate change on these factors can be manifold, affecting debris and driftwood availability, the warming and thawing of permafrost and high alpine-/or glacier environments, antecedent soil moisture conditions and the state of (protective) forests and vegetation. By identifying local, catchment-specific conditions it is also possible to estimate how possible future changes may influence the frequency and magnitude of natural hazards in the area of interest.

EXAMPLE 8:
Risk Analysis – Future changes in predisposing factors for debris flows

In the Stubaital in Tyrol, Austria, sediment availability has been identified as a crucial factor for future debris flow activity. When deriving future hazard scenarios for the sub-catchments, it is expected that the high-alpine Oberbergbach Catchment will produce larger debris flows due to the increased availability of loose sediment, driven by permafrost degradation and a rising snow line.

Tools:

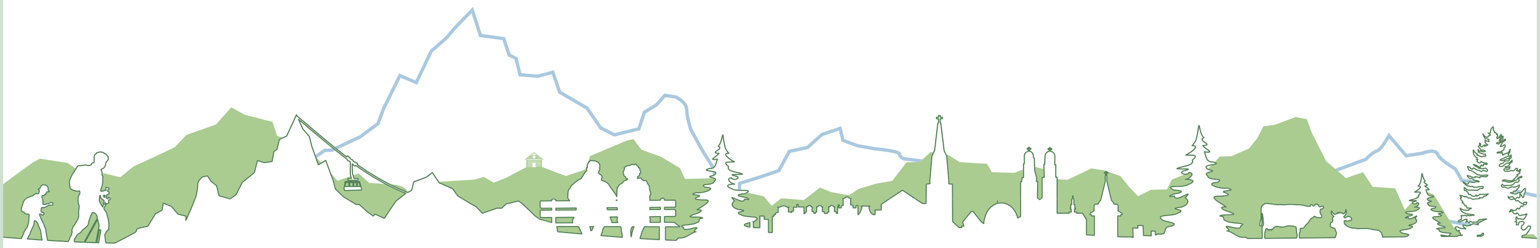
- → GIS-Software like QGIS and ArcGIS are used to visualise and analyse hazard maps. Hazard maps are often provided as WMS/WFS services by regional and national organisations.
- → Visualisation examples of magnitude-frequency relationships
- → Checklist for (changing) predisposing factors (Annex 2)

Outcome

Relevant climate-induced hazards, a deeper understanding of their magnitude and frequency, hazard interactions (cascading/compound character) and potential future development under climate change.

Further Reading

- → Jacquemart, M., Weber, S., Chiarle, M., Chmiel, M., Cicoira, A., Corona, C., Eckert, N., Gaume, J., Giacona, F., Hirschberg, J., Kaitna, R., Magnin, F., Mayer, S., Moos, C., van Herwijnen, A., and Stoffel, M.: Detecting the impact of climate change on alpine mass movements in observational records from the European Alps, Earth-Sci. Rev., 258, 104886.
- → Jakob, M. and Nolde, N.: Statistical Techniques for Debris-Flow Frequency–Magnitude Analyses, in: Advances in Debris-flow Science and Practice, edited by: Jakob, M., McDougall, S., and Santi, P., Springer International Publishing, Cham, 249–271.



STEP 3 - ANALYSE EXPOSED ELEMENTS RELEVANT FOR IDENTIFIED RISKS

PURPOSE: *To analyse the elements exposed to the identified climate-related hazards for each risk, based on current exposure data, and to understand how these may change in the future.*

After identifying and analysing the relevant (compound) hazards and their meteorological drivers in Step 1, this step looks at which systems and assets are located in areas prone to hazards and may therefore be affected. This analysis of exposure is a critical step in understanding the full risk picture.

It is important to note that this step is conducted individually for **each risk identified** in the Risk Identification phase. This ensures that the specific characteristics of exposure are systematically examined for every distinct risk

Exposure - also referred to as *exposed elements, exposed assets, exposed systems, or elements-at-risk* - includes all components of socio-economic and ecological systems located in areas prone to hazards and therefore susceptible to adverse effects. This includes private properties; public and industrial facilities and retail outlets and their economic activities; mobility and essential services infrastructure; agricultural land and activities; as well as local populations and tourists. ***FIGURE 9*** provides an overview of the types of systems that may be affected.

SETTLEMENT

- Private properties
- Administrative facilities
- Tourism and accommodation
- ...

MOBILITY INFRASTRUCTURE

- Roads
- Railway
- Lifts
- ...

ESSENTIAL SERVICES

- Energy
- Communication
- Potable water
- ...

PUBLIC SAFETY

- Monitoring systems
- Protective structures
- Evacuation routes
- ...

AGRICULTURE AND FORESTRY

- Agricultural lands
- Agricultutal infrastructure
- Cultivated forests
- ...

ENVIRONMENT

- Air quality
- Water bodies
- Wildlife
- ...

MOBILE ASSETS

- People
- Vehicles
- Livestock
- ...

Exposure categories
Exposure types

FIGURE 9: *Examples of exposure types grouped by category.*

Perform exposure mapping to systematically analyse which elements or systems may be affected for each identified risk.

Exposure mapping in the context of natural hazards involves identifying and visualising the people, infrastructure, and other assets that could be affected by a hazard. This mapping is crucial for risk assessment, disaster preparedness, and emergency response, as it helps determine potential impacts and prioritise mitigation efforts.

The level of detail in the data sources should match the scope and purpose of the assessment and, ideally, remain consistent across the entire study area. For national-scale assessments a coarse resolution or aggregated data may suffice, whereas local assessments may require more detailed, locally sourced data. Where such data is lacking, additional information may need to be collected. A strong understanding of local conditions is critical for validating exposure data. In most regions, official sources such as land registries or census data can provide a solid basis.

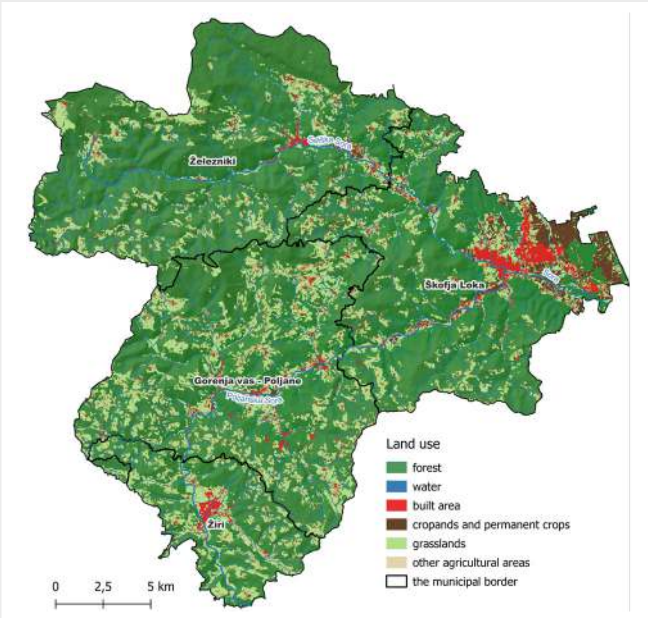
Quantify the degree of exposure for each exposure type or category using appropriate metrics.

Depending on the scope of the analysis and the available data, suitable metrics can include:

- → Amounts (e.g., number of people, quantity of individual assets)
- → Length (e.g., transportation networks, power lines)
- → Area (e.g., agricultural land, forests, urban areas)
- → Asset values (e.g., values of private housing, businesses or industrial facilities)

EXAMPLE 9:
Risk Analysis – Drought exposure in the Sora catchment, Slovenia

To assess the exposure to top-soil drought of the Sora catchment in Slovenia, the land use structure of the area was analysed based on data collected by the Ministry of Agriculture, Forestry and Food (https://rkg.gov.si/). The predominant land uses are forests (71 %) and agricultural land (24 %). Agricultural land can be adversely affected by drought due to damaged crops and increased costs associated with irrigation, feeding and watering of animals. Historically, farms and agricultural businesses have been the sectors most affected by drought.



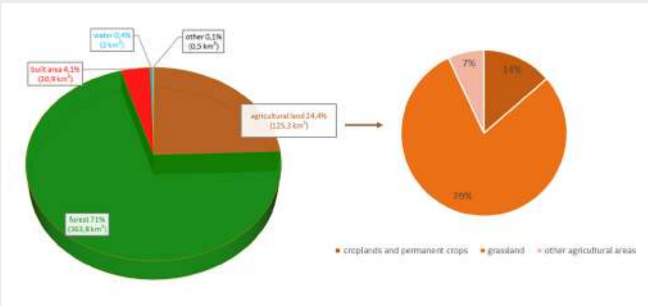


FIGURE 10: *Quantitative analysis of the land uses exposed to drought in the Sora catchment, Slovenia.*

Describe the direct and indirect impacts associated with identified exposed elements.

Exposed elements may be affected both directly and indirectly by the hazards.

- **Direct impacts** result from physical contact with a hazard and may include the destruction of buildings and infrastructure, loss of life, health impacts, and damage to environmental assets and cultural heritage. Compound or cascading hazard events can extend impacts beyond the area typically affected by a single hazard.
- **Indirect impacts** occur beyond the immediate hazard area or emerge over time. Examples include economic losses among suppliers and customers of affected businesses, or service disruptions due to damaged infrastructure. These effects often result from cascading impacts.

INTEGRATING COMPOUND EFFECTS INTO EXPOSURE ANALYSIS

When analysing exposure, it is essential to anticipate the impacts of compound hazards on systems and how these systems are interconnected, for example:

- Are systems more exposed in the case of **compound or cascading hazard events**?
- Are there additional systems exposed to cascading impacts due to **interdependencies with systems** directly impacted?
- Do compound hazards and impacts bear the risk of exceeding existing mitigation and management measures **resulting in new exposure**?

It can be helpful to assess the **severity of impacts** and rank them according to their contribution to the overall consequences of an event. Depending on the purpose of the assessment, indicators may include qualitative descriptions, monetary damages, business interruption, evacuation requirements and recovery times.

Identify key trends based on recent developments and projections and explain how these are likely to influence future exposure patterns.

Future changes in exposure are often driven by:

- Demographic shifts (e.g., population growth or decline)
- Economic developments (e.g., expansion in industry, tourism or agriculture)
- Increased traffic volumes (e.g., transalpine transport, tourism influx)
- Policy changes (e.g., spatial planning, building regulations)
- Changes in hazard-prone areas due to climate-related processes

These trends must be considered to anticipate how exposure patterns may evolve over time.

EXAMPLE 10:
Risk Analysis – Tourism exposure trends in South Tyrol, Italy

In the absence of sophisticated models to estimate future exposure, tourist numbers for the near future can be projected based on an extrapolation of recent trends in tourism records. The figure shows records of tourists booking overnight-stays in three municipalities in South Tyrol, Italy, from 2001-2023.

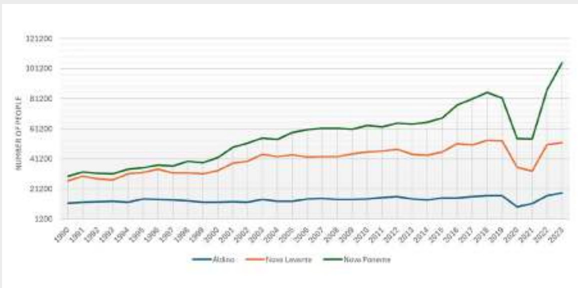


FIGURE 11: *Number of tourists booking overnight stays for three municipalities in the Vaia pilot area between 2001 and 2023. Lower numbers were observed from 2020 onwards following the COVID-19 pandemic and subsequent travel restrictions.*

EXAMPLE 11:
Risk Analysis – Future development of exposure in Wipptal, Italy

The exposure of assets in Wipptal, Italy to hazards including mass movements, hydraulic hazards and avalanches varies as reflected by their distribution across the hazard classes. A relevant portion of expansion areas, i.e., areas earmarked for future development, is located in hazard zones, but outside the most critical H4 areas, since the local laws forbids new construction in those zones. However, potential changes of hazard classification due to a future intensification of extreme events may result in a higher percentage of exposed assets in the most affected hazard classes, e.g., current H3 areas might then be classified as H4.

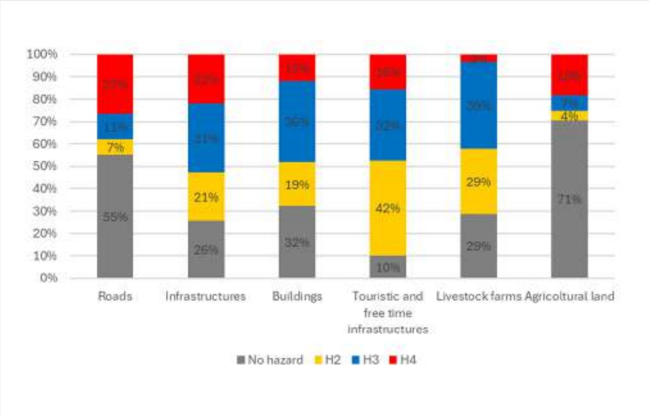


FIGURE 12: *Percentages of exposed assets in different hazard classes in Wipptal, Italy.*

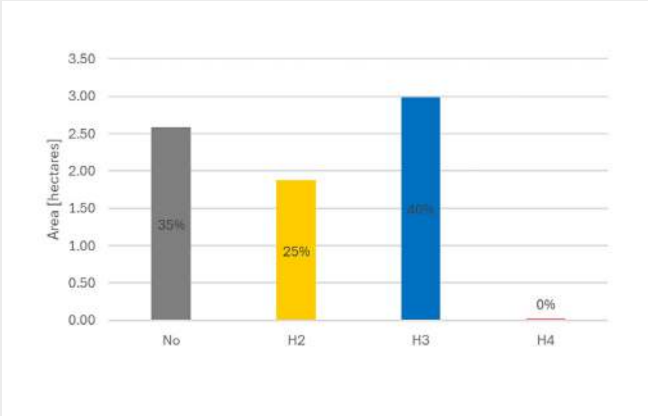


FIGURE 13: *Percentages of expansion sites located in different hazard classes in Wipptal, Italy.*

Tools:

- **GIS Software**: Tools such as QGIS and ArcGIS for creating and analysing exposure maps.
- **Remote Sensing information**: Satellite imagery products, e.g., the Global Human Settlement Layer (GHSL) and OpenStreetMap (OSM), support exposure mapping.
- Exposure checklist: See Annex 3.

Outcome

A prioritised list of elements-at-risk for each identified risk, ranked by the criticality of potential impacts.

Further Reading

- Example of exposure mapping: European Environment Agency. Exposure of European ecosystems to drought. www.water.europa.eu/freshwater/europe-freshwater/freshwater-themes/drought.
- UN-SPIDER Advisory Support. Recommended Practice: Exposure Mapping — step-by-step guidance of how to estimate the exposure to a natural hazard or disaster. www.un-spider.org/advisory-support.

STEP 4 - ANALYSE VULNERABILITY ELEMENTS RELEVANT FOR EACH IDENTIFIED RISK

***PURPOSE:** To analyse the vulnerability factors that influence the severity of impacts from climate-related compound and cascading hazards for each identified risk, and to understand how these factors may change in the future.*

Having identified the exposed elements in Step 3, the next step is to assess their vulnerability—i.e., the characteristics that influence the likelihood and severity of impacts when hazards occur. These include physical attributes, social conditions, and dynamic factors that shape the transition from exposure to actual damage or disruption. Analysing vulnerability is essential for a comprehensive understanding of each identified risk.

Vulnerability refers to the susceptibility of socio-economic and ecological systems to adverse effects when exposed to hazards. It encompasses multiple dimensions:

- → **Physical vulnerability**: The susceptibility of assets, infrastructure, or systems to damage, determined by factors such as design, construction quality, location, and maintenance[7].
- → **Social vulnerability**: The characteristics of individuals or groups that affect their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard[8],[9].

Analyse the vulnerability factors for each identified risk

For each identified risk, examine past events and evidence to determine the factors that influenced the severity of impacts. Consider:

- → Why similar hazard events cause high impacts in some areas but not in other;
- → Why the same hazard event may lead to varying levels of impacts in different circumstances.

EXAMPLE 12:
Risk Analysis – Investigating the vulnerability of road infrastructure in the aftermath of Storm Eleanor in the Arly catchment, France

Combining information on the occurrence of hazard events and the cost of repair operations on the road network and structures in the aftermath of Storm Eleanor can help to identify the vulnerability factors that lead to high damages in some areas compared to lesser damages in others.

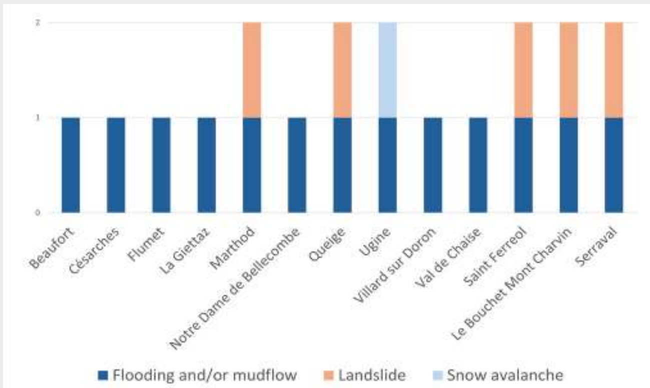


***FIGURE 14:** Number of requests for CatNat decrees following the storm Eleanor in the municipalities of the Arly catchment.*

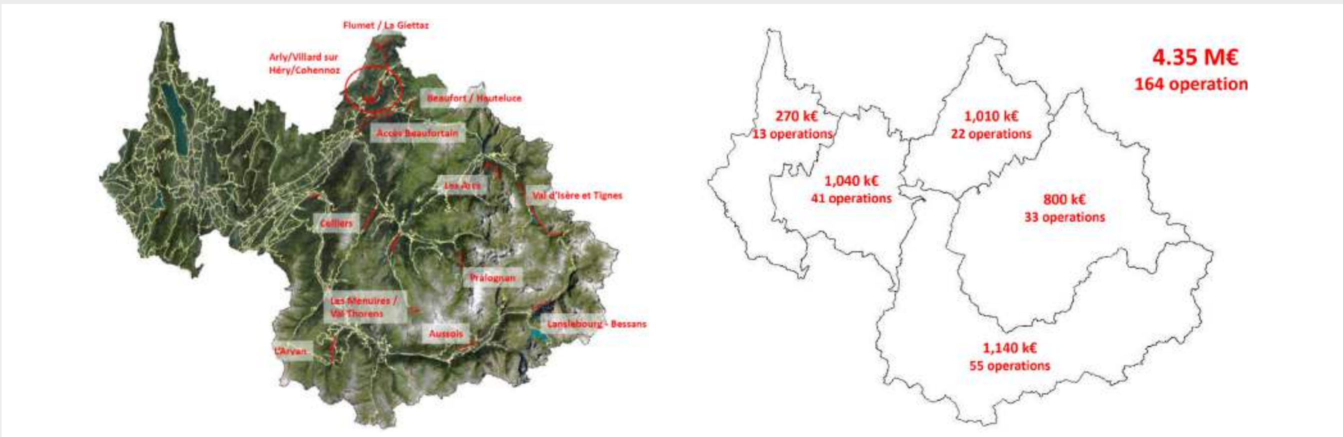


***FIGURE 15:** Maps of impacts and costs incurred in the aftermath of storm Eleanor in the Arly catchment.*

7 Blaikie, P., Cannon, T., Davis, I., and Wisner, B.: At Risk, 0 ed., Routledge, https://doi.org/10.4324/9780203714775, 2014.
8 IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC), edited by: Field, C. B., Barros, V., Stocker, T. F., Qin, D. J., Dokken, K. L., Ebi, M. D., Mastrandrea, M. D., Mach, G.-K., Plattner, S. K., Allen, M., Tignor, M., and Midgley, P. M., Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU ENGLAND, 2012.
9 *UNISDR: 2009 UNISDR Terminology on Disaster Risk Reduction., United Nations International Strategy for Disaster Reduction, Geneva, Switzerland, 2009.*

The relevant vulnerability factors will depend on the type of exposed elements and the hazard(s) it is subject to.

EXAMPLE 13:
Risk Analysis – Vulnerability of people to flash floods in the Partnach Gorge, Germany

Characteristics of flooding relevant for assessing the vulnerability of people inside the Partnach Gorge include the discharge, the flow velocity, the amount of debris or driftwood as well as the rise rate of the river, and the time to evacuate.

EXAMPLE 14:
Risk Analysis – Vulnerability of private properties to flooding

Typical vulnerability characteristic of property exposed to floods are the construction material, the number of floors, the condition of the building, and the presence of a basement.

Describe vulnerability qualitatively or quantitatively

Vulnerability information can be gained from past observations in the area of interest. However, data may be insufficient to provide meaningful insights for all identified risks. The scientific community has developed various qualitative, semi-quantitative and quantitative methods to assess the susceptibility of systems or elements to the impacts of natural hazards. Different hazard types typically have distinct conventions for describing vulnerability.

This section introduces two commonly used approaches:

1. Vulnerability indicators - a set of factors that influence a system's vulnerability,
2. Vulnerability curves – representation of the relationship between hazard intensity and the degree of loss.

Both approaches are crucial for risk assessment and the development of mitigation strategies.

Vulnerability indicators help understand the underlying factors that make a system more vulnerable to a risk. These indicators are selected based on their relevance to both the hazard and the characteristics of the system being assessed. Indicators can also be weighted to reflect their relative importance.

Indicator-based approaches are commonly used to assess **social vulnerability** by identifying characteristics shared with certain population groups that increase their susceptibility to the impacts of climate-related hazards. Examples of such indicators for communities include:

- → Age distributions: Children and the elderly are generally more vulnerable.
- → Health and disability status: Physical or health limitations can restrict mobility and the ability to move outside the hazard area.
- → Awareness, skills and knowledge: Higher awareness and preparedness skills can reduce vulnerability.
- → Knowledge of the local language: Limited understanding of the official language can hinder comprehension of risk communications civil protection instructions.

Indicator-based approaches can be applied to areas where historical data is limited.

Vulnerability curves quantify the **physical vulnerability** of elements at risk, providing a means to estimate potential damage under different hazard scenarios. These curves are valuable for various applications, including:

- → Loss estimation: Estimating potential financial and economic losses, such as from earthquakes, to inform insurance and emergency planning.
- → Risk mapping: Identifying areas most susceptible to specific hazards to prioritise mitigation efforts.
- → Urban planning: Guiding the development of resilient infrastructure by highlighting areas of higher vulnerability.
- → Mitigation planning: Evaluating the effectiveness of protective structures and informing investment decisions in risk reduction measures.

Vulnerability curves can be derived from:

- → Empirical data (e.g., past event records)
- → Experimental studies
- → Physical modelling
- → Expert judgement

These curves are often specific to a particular region, hazard type, and asset characteristics and may not be easily transferable to other contexts.

The most suitable approach should be chosen depending on the aim and scope of the analysis as well as the data available to support semi-quantitative or quantitative approaches.

EXAMPLE 15:
Risk Analysis - Vulnerability analysis in Garmisch-Partenkirchen, Germany

Vulnerability functions were employed to assess the monetary expected damage by compound flooding from two streams, Partnach and Ferchenbach, in Garmisch-Partenkirchen, Germany. The functions have been developed in combination with the Basic European Asset Map (BEAM) dataset for river flooding applications in Germany and validated on selected flood events. The results serve as a first indication of expected damages but must be interpreted carefully given the special characteristics of torrential flooding, such as high flow velocities and shorter warning times.

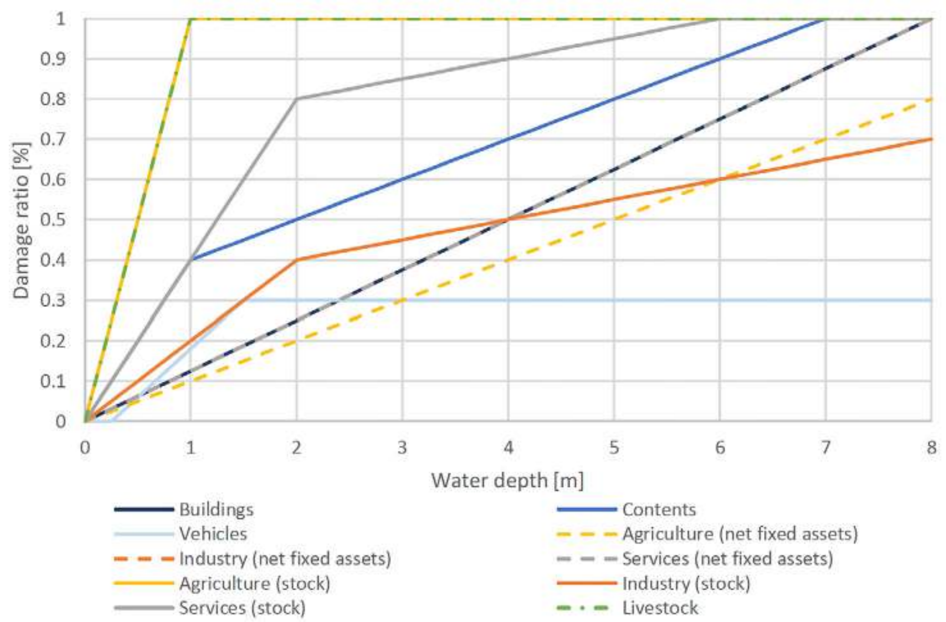


FIGURE 16: *Vulnerability functions for assessing the expected damage in the Garmisch-Partenkirchen, Germany*[10].

10 *geomer GmbH and Ruiz Rodriguez + Zeisler + Blank GbR. Bewertung des Hochwasserrisikos auf der Grundlage von Schadenspotenzialen – Anwendung von Schadensfunktionen in repräsentativen Beispielsregionen im Rahmen des Länderfinanzierungsprogramms „Wasser, Boden und Abfall". Technical report, 2020.*

Identify effects of compound or cascading events that influence vulnerability.

The combined effects of multiple hazards affecting the same area within a short period of time can result in dynamic changes in vulnerability. The impact of these compound or cascading events may be greater than the sum of their individual impacts. It is important to identify the factors that may increase - or sometimes decrease - vulnerability in the context of such events. This step involves assessing whether significant changes in potential damage or loss can be expected and understanding the reasons behind these changes.

INTEGRATING COMPOUND EFFECTS INTO VULNERABILITY ANALYSIS

When analysing vulnerability, consider that the consequences of **compound hazard events** could be much greater than the sum of the individual hazard events, for example:

- When the vulnerability of systems increases due to prior exposure to other hazards;
- Because of a disadvantageous redistribution of people and assets due to evacuation or relocation over the course of a compound hazard event;
- Because of the limited capacity of emergency services to deal with all impacts simultaneously.

Identify trends in vulnerability factors likely to influence future risk

Vulnerability is not static; it evolves over time due to changes in physical, social, economic, and environmental conditions. A hazard event of the same intensity can have very different consequences depending on:

- Changes in the elements and systems exposed,
- Implementation of risk management measures,
- Variations in disaster response and recovery capacities.

Identifying trends in vulnerability factors is therefore critical to understanding how future risks may evolve. Trends may result from factors such as demographic shifts, urban development, land use changes, or improvements in infrastructure and emergency preparedness.

Tools:

- **Vulnerability curves**: Graphically represent the relationship between hazard intensity (e.g., flood depth, ground acceleration) and expected damage or loss (e.g., percentage of buildings damaged, economic loss).
- **Vulnerability indicators**: A set of factors that influence a system's susceptibility to hazards, including physical, social, economic, and environmental characteristics.

Outcome

A list of **relevant vulnerability factors** for all identified risks, ranked by importance and with an indication of which factors are expected to change in the future.

Further Reading

- Drought:

  Meza, I., Hagenlocher, M., Naumann, G., Vogt, J. and Frischen, J., 2019.Drought vulnerability indicators for global-scale drought risk assessments, EUR 29824 EN, Publications Office of the European Union, Luxembourg.

- Debris flows:

  Papathoma-Köhle, M., Gems, B., Sturm, M., Fuchs, S., 2017. Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows. Earth-Sci. Rev. 171, 272-288.

- Flooding:

  Papathoma-Köhle M, Schlögl M, Dosser L, Roesch F, Borga M, Erlicher M, Erlicher M, Keiler M, Fuchs S, 2022. Physical vulnerability to dynamic flooding: Vulnerability curves and vulnerability indices. Journal of Hydrology.

STEP 5 - ANALYSE RISK MANAGEMENT CAPACITY

***PURPOSE:** To evaluate the adequacy of existing and planned risk management measures across the disaster risk management cycle. This will involve identifying strengths and weaknesses of current practices and assessing preparedness for future climate-related and compound hazard events.*

Once the vulnerability factors influencing the susceptibility of exposed elements have been understood for each risk analysed, the next step is to evaluate risk management capacity for each risk. This involves reviewing how effectively current and planned measures for risk mitigation, preparedness, response, and recovery address the identified exposure and vulnerability. The **Rapid Risk Management Appraisal (RRMA)** can be used to highlight areas of strength and uncover critical gaps, particularly in in the context of evolving climate conditions and compound hazard scenarios.

INTEGRATING COMPOUND EFFECTS INTO RISK MANAGEMENT CAPACITY ANALYSIS

When analysing risk management capacity, it is important to explicitly assess how current and planned measures perform under **compound risk scenarios.** Key questions to consider include:

- Are systems such as emergency response, infrastructure and coordination mechanisms designed to function effectively during **multiple, simultaneous or cascading risks**?
- Do preparedness and contingency plans account for potential **interactions between risks**?
- Could solutions developed for single risks become inadequate or even maladaptive under future compound risk conditions?

Using compound risks to **stress-test capacity limits**, can help reveal critical weaknesses, while also identifying opportunities to develop integrated, climate-resilient risk management strategies.

What to consider:

- What structural or non-structural mitigation measures are currently in place (e.g., dams, forest management, land use planning, natural retention areas)?
- Which mitigation measures are planned or under development?
- Are preparedness tools - such as early warning systems, emergency protocols, or contingency plans – functional and fit for purpose?
- How effectively do response and recovery systems operate during events? Are roles, responsibilities, and coordination mechanisms clearly defined and effective?
- Where are the critical gaps - in policy, coordination, funding, monitoring, or technical capacity — especially considering future climate risks and compound events?

Rapid Risk Management Appraisal (RRMA)

The Rapid Risk Management Appraisal (RRMA) is a participatory, workshop-based method designed to evaluate the adequacy of existing and planned risk management measures in the context of both current and future climate-related risks.

The RRMA uses structured discussion and scoring, involving key local and regional stakeholders - including public authorities, civil protection services, planners, infrastructure operators, and sectoral experts.

Key questions for discussion:

- Are current measures effective in reducing the impacts of past and future hazards?
- How well would these measures perform under future scenarios involving compound or more extreme events?
- Did the risk management plan achieve its intended objectives, and are those objectives still relevant given projected climate change?
- Were the resources allocated efficiently and used effectively, and will they remain sufficient under future risk conditions?
- Were response and recovery plans adequate in past events, and how might they need to adapt to future hazard patterns and cascading impacts?

- Which risks, particularly emerging climate-related risks, remain unaddressed or insufficiently considered?
- Are there missing policies, procedures, or resources that could limit preparedness for future conditions?
- Are there gaps in communication, monitoring or coordination that may become critical under future scenarios?
- Are any current assumptions, frameworks or planned strategies no longer valid in a changing climate?

Climate Risk Storylines (used as RRMA input)

RRMA workshops are supported by **climate risk storylines** — narrative scenarios illustrating plausible, high-impact future hazard events. These storylines help local stakeholders "stress test" current systems and identify critical gaps in a tangible and engaging format.

Key features of climate risk storylines:

- **Impact-focused**: Illustrate cascading or compound impacts (e.g., heavy rainfall combined with windstorms, or a multi-week drought triggering wildfires and infrastructure failures).
- **Narrative and qualitative**: Combine climate projections with local knowledge to explore how hazards and vulnerabilities may evolve.
- **Plausibility over probability**: Based on observed trends, climate model outputs and expert/local knowledge input rather than precise likelihoods.
- **Context-specific**: Tailored to the geographical, social, and institutional realities of the area under consideration.
- **System stress-testing**: Scenarios could be set for around 2040, assuming events with return periods of between 100 and 300 years, in order to test the limits of risk management capacity.

Storylines are developed in advance and adapted by risk managers to reflect local conditions and past experiences. During RRMA workshops, these storylines are presented using maps and visual materials to facilitate structured discussions and scoring.

EXAMPLE 16:
Risk Analysis – Risk Management in Gorenjska Sora Catchment, Slovenia

a) Current risk management measures

- Sušomer (drought observation): Developed by the Slovenian Environment Agency (ARSO), Sušomer is an online portal where estimated drought conditions for topsoil, surface water, and groundwater and forecasts are published on a weekly basis throughout the year enabling informed stakeholder response.
- Water supply operators monitor quality and quantity.
- Water supply systems are fed by multiple dispersed water sources and usage restrictions are activated.
- Emergency water delivery is managed by civil protection and firefighters.
- Damage assessments and financial compensation are carried out by government agencies.

NOTE: *Although current water management protocols effectively address individual severe droughts, they may not be sufficient for potential compound events — such as the combination of agricultural and hydrological droughts with major forest fires.*

b) Potential Future Risk Management Measures

- Sušomer is set to expand by adding more monitoring stations and new data layers. Future upgrades may include impact-based forecasts tailored to specific sectors (e.g., agriculture, public health).
- Irrigation systems may be developed in areas with substantial groundwater reserves and water reservoirs can be developed to enhance agricultural resilience.
- Further interconnection of water supply systems in smaller rural settlements is planned to increase reliability. Where full integration is not feasible, local reservoirs and intervention plans will be strengthened.
- Wastewater reuse has been identified as a strategic opportunity for reducing the vulnerability to drought.

Tools

- RRMA,
- Climate Risk Storylines

Outcomes

- A comprehensive overview of **risk management capacity** in the area under consideration.
- Identification of **effective mechanisms** as well as **critical capacity gaps**.
- A **prioritised list of needs and recommendations** to strengthen preparedness, governance, and resilience in the face of current and future climate-related hazards.

Further Reading

- Annex 5 - The RRMA methodology
- Annex 6 - Example of a climate risk storyline

RESULT

Understanding risks and potential for adaptation action

The key output of the risk analysis is a technical risk report that provides a comprehensive understanding of each identified risk and its underlying drivers. The report should be structured with a dedicated chapter for each risk and meet the following requirements:

- → Describe in detail the key factors shaping climate-related risks, including the relevant hazards, exposure, vulnerability, risk management capacity and potential impacts,
- → Explain how specific drivers contribute to the risk, by linking them to hazard, exposure and vulnerability factors,
- → Document the data sources, methods, and expert inputs used to support the analysis and conclusions,
- → Indentify processes or trends likely to increase or decrease climate-related risks in the future,
- → Summarise the findings of the Rapid Risk Management Appraisal (RRMA), particularly the identified gaps in existing risk management and the potential for adaptation,
- → Disclose relevant uncertainties, data limitations and knowledge gaps, which may affect the robustness of the findings.

It is recommended that the report is validated by the experts involved in the risk assessment and shared with the local stakeholders to ensure transparency, credibility, and relevance for decision-making.

To support communication to stakeholders, additional outputs such as **risk factsheets** can be prepared. Each factsheet should:

- → Focus on a specific risk (defined by a combination of hazard and exposure),
- → Provide a concise summary of the main factors influencing current and future risk,
- → Where feasible, rank the key risk drivers within the categories of *hazard*, *exposure* and *vulnerability* according to their importance for the overall risk,
- → Be tailored for targeted dissemination to the most relevant stakeholders.

An example of a risk factsheet developed for the Garmisch Partenkirchen region is presented in ***TABLE 5***.

RISK TO PARTNACH GORGE DUE TO HEAVY PRECIPITATION			
		Current (2000-2020)	**Near future (2020-2040)**
Importance of the system		• As a natural monument the gorge attracts visitors to the GAP region providing a source of tourist revenue for the city and the surrounding hotel and gastronomy industry. • The gorge provides first responders with access to the Reintal in case of emergencies.	• No major changes expected.
Climate-related hazard	Flash floods	Moderate: • intense convective rainfall events can result in sudden rise of discharges along Ferchenbach and Partnach. • very local rainfall events are difficult to predict, which makes it more difficult to warn and prepare for them.	High: • More frequent intense precipitation events expected. • Longer periods of drought will decrease infiltration. Heavy precipitation on dry soils will lead to faster runoff in the catchment.
	Log-jams	Moderate: • Logs and driftwood from the Ferchenbach catchment have been washed into the gorge. The formation and bursting of logjams have exacerbated flash floods, leading to fast rising water levels inside the gorge and dangerous flooding downstream.	Moderate: • Increasing stress on forests due to drought, infestations, and wildfires will lead to an increased amount of deadwood along the streams. • The construction of a new rake upstream of the Ferchenbach confluence will reduce the amount of driftwood load in the Partnach for most events. In the case of rare discharges from the Ferchenbach river or backwater flooding from the Partnach driftwood might float above the rake's design height.
	Debris-laden flows	Low: • No problems with debris in the past. Regular debris management measures are performed along the upstream embankments.	Moderate: • More frequent and intense precipitation events expected. • Increasing wildfires potential in the catchment. The availability of debris increases by up to factor 10 after wildfires. • Increasing risk of landslides along Ferchenbach river which could provide large amounts of debris to the torrents.
Exposure	People	Moderate: • Visitor numbers are highest during the summer months, when heavy precipitation is expected. There are no visitors in the night. • People are mainly at risk along the lowest lying stretch of the path upstream of the Madonna.	Moderate: • Gorge is already operating close to its maximum capacity. There is no expectation of a significant increase in visitor numbers.
	Gorge Infra-structure	Moderate: • Embankments, paths and railings are regularly exposed to hazard events.	Moderate: • No major changes expected.

Vulnerability factors	People	Low • The formation of logjams or dams inside the gorge can expose people to rapidly rising water levels and pose a threat downstream when the retained water suddenly releases as a flood wave. • Even shallow flooding of the path can be critical for people in the gorge, with the most critical being the time available for evacuation and the rate at which the water level rises, as well as the transport of, debris and driftwood transport in the flow.	Low • No major changes expected.
	Gorge Infra-structure	Moderate • The transport of driftwood and debris is critical in determining the degree of damage sustained by embankments, paths and railings. • Removing driftwood from inside the gorge can take time-consuming.	Moderate • Debris-laden flows can irreversibly alter the shape of a gorge and the direction of the flow irreversibly. This is because they move rocks and cause lateral erosion which can result in stability issues regarding usability and accessibility issues of gorge infrastructure.
Risk manage-ment capacity		• Extensive monitoring of weather forecasts and the downstream gorge is in place. • Controlled access to the gorge (turnstile system) and an emergency call system is in place inside the gorge. • Forest and debris management measures undertaken throughout the year. • Contracts in place for the fast recovery of the gorge infrastructure.	• Upstream gauging station will be installed. • Ferchenbach landslide early warning system will be installed. • Extensive (and expensive) forest and debris management measures will be required to maintain a comparable level of safety in the gorge.
Sources of uncertainty		• A qualitative and quantitative description of past events and the corresponding recovery efforts. • Density of weather stations too low to register smaller cells of heavy precipitation. • No discharge data from inside/upstream the gorge during past events. Inference from the downstream gauging station and photographic evidence in the aftermath of the event.	• Rate of changes in debris availability.

TABLE 5: *Result 'Risk Factsheet' for the example of compound risk due to heavy precipitation (Garmisch-Partenkirchen, Germany).*

The sequential impact chains introduced in chapter Risk Identification - Step 3 can be updated with new insights gained during the analysis process. They serve as an additional tool for visualising and communicating relevant risk drivers and their interactions (***FIGURE 16***).

The risk assessment for the Gorenjska-Sora catchment revealed that drought-related risk is **compound** in nature, resulting from the interplay of multiple meteorological drivers and cascading effects on sectors such as agriculture, water, and ecosystems.

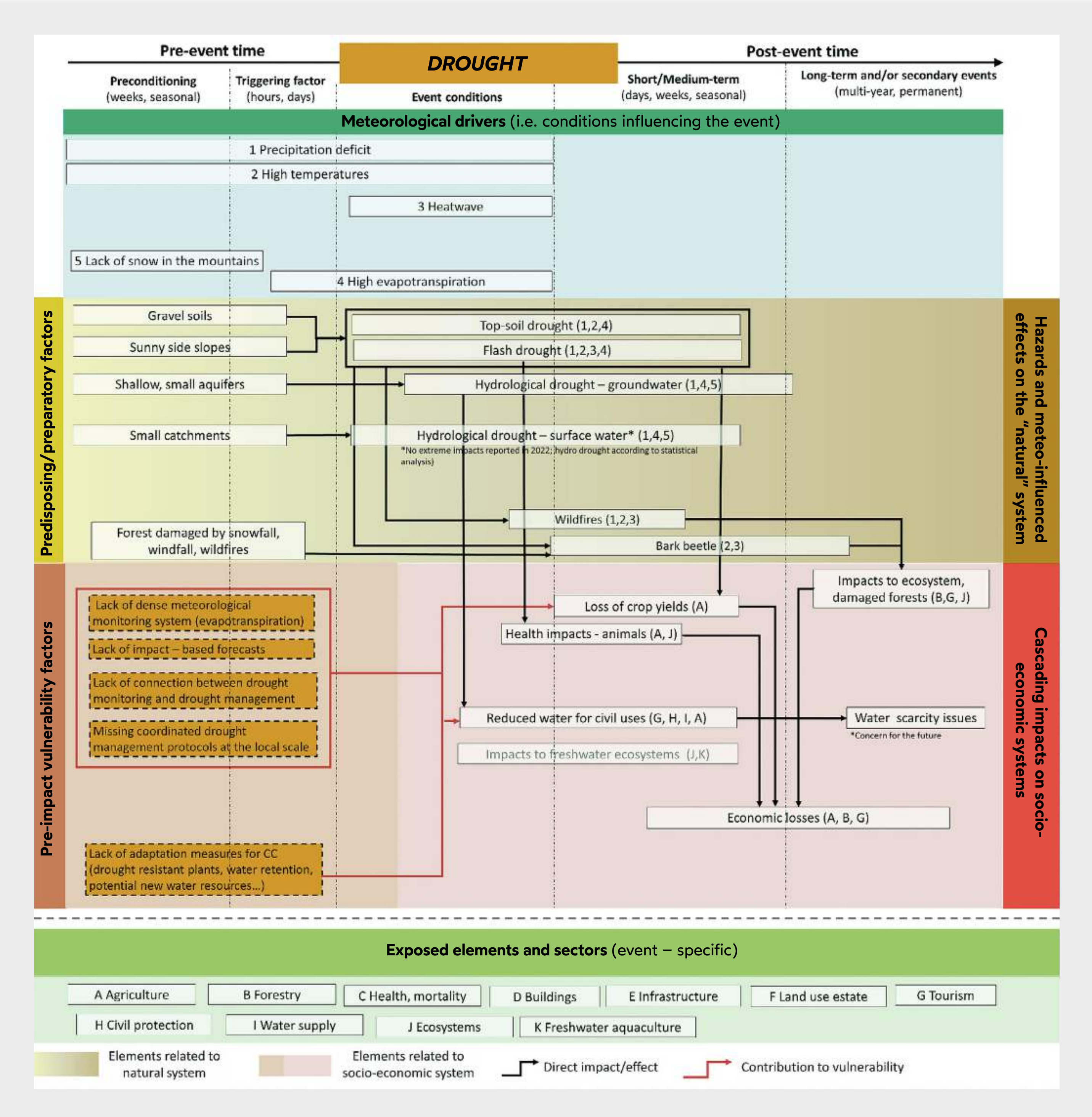


FIGURE 17: *Sequential impact chain illustrating the components of compound risk associated with drought.*

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ANNEX 1

EXAMPLES FOR VISUALISATION OF FREQUENCY-MAGNITUDE RELATIONS OF HAZARD PROCESSES

1. Reconstructed time series of hazard magnitudes either as individual magnitudes or magnitude classes

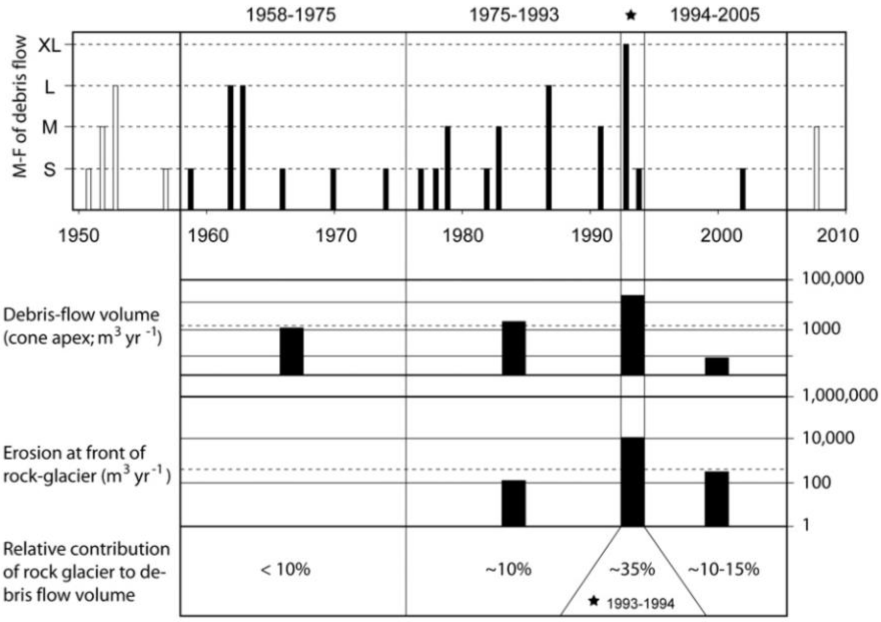


Fig. 6. Sediment delivery of the rock glacier and M–F relationships of debris flows at Ritigraben.

Source: Lugon & Stoffel (2010)

2. Statistical representation of the temporal frequency of hazard events for different magnitude classes in a table

Statistics of temporal frequency of debris-flow events for different magnitude classes.[a]

Temporal frequency of events	*Class S*	*Class M*	*Class L*	*Class XL*	Total
Events (no.)	25	20	14	3	62
Debris-flow frequency	0.18	0.14	0.10	–	0.42
Mean debris-flow interval (yr)	5.42	7.37	9.54	–	2.38
Weibull median interval (yr)	4.94	5.96	8.14	–	2.18
Standard deviation (yr)	3.19	6.65	6.88	–	1.49
Debris-flow interval (min., yr)	1	2	1	–	1
Debris-flow interval (max., yr)	12	27	24	–	8
Lower exceedance interval (yr)[a]	1.95	1.60	2.59	–	0.85
Upper exceedance interval (yr)[a]	9.20	14.31	17.48	–	4.09

[a] Thresholds for the lower and upper exceedances set at 0.125 and 0.875.

Source: Stoffel (2010)

3. Frequency-magnitude curves which plot a range of return periods (frequency) against the associated return level (magnitude) using the rank order analysis

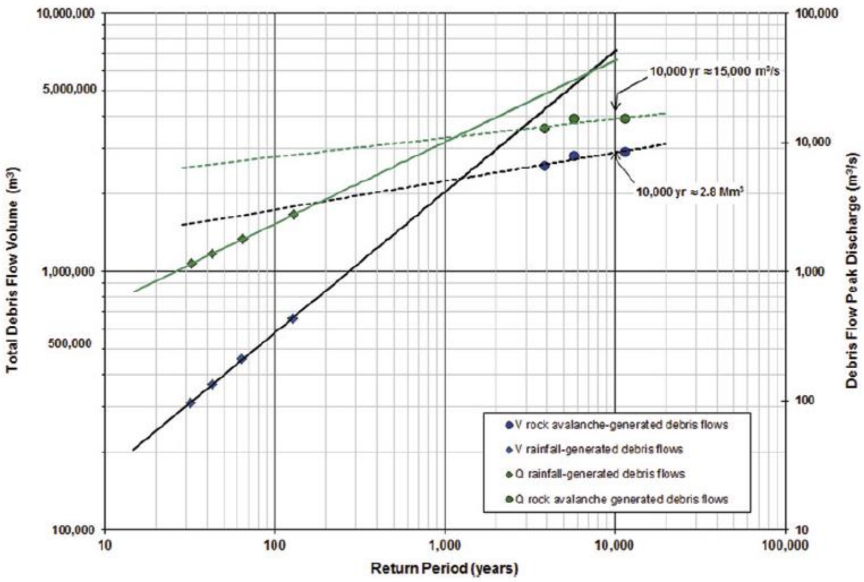


Fig. 9.7 Frequency-volume and frequency-peak discharge relationship at Cheekye river

Source: Jakob & Nolde, 2024

Rank order analysis:

Plotting positions by using the Weibull formula (Weibull, 1939):

$$P_m = m/T + 1, m = 1, \ldots, n$$

where Pm is the cumulative probability, m is the rank of individual observations and T as above is the number of years in the data record.

REFERENCES

Jakob, M., Nolde, N. (2024): Statistical Techniques for Debris-Flow Frequency–Magnitude Analyses. In: Jakob, M., McDougall, S., Santi, P. (eds): Advances in Debris-flow Science and Practice. Geoenvironmental Disaster Reduction. Springer, Cham. https://doi.org/10.1007/978-3-031-48691-3_9

Lugon, R. & Stoffel, M. (2010): Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben, Swiss Alps. Global and Planetary Change, 73 (3–4), 202-210. https://doi.org/10.1016/j.gloplacha.2010.06.004

Stoffel, M. (2010): Magnitude–frequency relationships of debris flows— A case study based on field surveys and tree-ring records. Geomorphology, 116, 67–76. https://doi.org/10.1016/j.geomorph.2009.10.009

ANNEX 2

CHECKLIST FOR (CHANGING) PREDISPOSING FACTORS

INTRODUCTION

Natural hazards are potentially damaging physical events.

- Case 1: Weather extreme = natural hazard
  Hydroclimatic hazards, such as storms and heatwaves, are a first order effect of weather extremes.
- Case 2: Weather extreme as trigger of natural hazard
  Weather extremes act as triggers of geological, hydrological, or biophysical hazards, such as debris-laden flows, landslides, rockfalls, and (flash) floods. These hazards are a higher order effect of weather extremes and climate change. The susceptibility of an area to these specific hazards is influenced by a number of predisposing factors, which can dynamically change (dynamic predisposing factors) due to climate change.

This document serves as a checklist for groups of predisposing factors of natural hazards (as in first column of "Sequential Impact Chains") that can become relevant due to climate change, and that can apply to the different pilot areas. Each pilot has to consider specific/local characteristics of the catchment or the pilot area. The focus here is on **dynamic** predisposing/preparatory factors and their possible changes due to climate change. *Static* predisposing/preparatory factors (e.g., lithology, slope, etc.) are not considered to change in the near future.

Floods and Flash floods

Antecedent soil moisture conditions

- ☐ high saturation of the soil inhibits infiltration of water, leading to surface runoff
- ☐ shift in flood seasonality: earlier melting of snowpacks in spring building up antecedent soil moisture content
- ☐ prolonged drought periods leading to decreased infiltration capacity and enhanced surface runoff during heavy rainfall events

Forest and Vegetation

- ☐ loss of vegetation/protective forest due to enhanced debris flow activity
- ☐ loss of protective forest due to preceding wildfire
- ☐ loss of protective forest due to more frequent storms
- ☐ loss of protective forest due to bark beetle infestation
- ☐ deforestation (man-made)

→ affects runoff generation and concentration by changing infiltration capacity, runoff coefficient, water storage capacity, and evapotranspiration. Forests may increase the infiltration because coarse woody roots of trees tend to create preferential flow paths in the soil which enhance the fast flow of water from the surface into the subsurface. A forest/ tree stand will also increase evaporation and reduce soil moisture (Blöschl et al., 2015)

Debris-laden flows
and
landslides (shallow slides)

Antecedent soil moisture conditions

- ☐ high saturation of the soil inhibits infiltration of water, leading to surface runoff
- ☐ shift in seasonality: earlier melting of snowpacks in spring building up antecedent soil moisture content
- ☐ prolonged drought periods leading to decreased infiltration capacity and enhanced surface runoff during heavy rainfall events

(Protective) Forest and Vegetation

- ☐ loss of vegetation/protective forest due to enhanced debris flow activity
- ☐ loss of protective forest due to preceding wildfire
- ☐ loss of protective forest due to more frequent storms
- ☐ loss of protective forest due to bark beetle infestation
- ☐ deforestation (man-made)

→ affects runoff generation and concentration by changing infiltration capacity, runoff coefficient, water storage capacity, and evapotranspiration. Forests may increase the infiltration because coarse woody roots of trees tend to create preferential flow paths in the soil which enhance the fast flow of water from the surface into the subsurface. A forest/ tree stand will also increase evaporation and reduce soil moisture (Blöschl et al., 2015)

Debris availability

- ☐ increased hillslope-channel-coupling
- ☐ increased sediment supply due mass movements (e.g., due to acceleration during heavy rainfalls)
- ☐ increased sediment supply due to loss of vegetation (e.g. due to wildfire, bark beetle infestation)
- ☐ increased sediment supply due to permafrost degradation of rock and scree slopes

High alpine environment and glaciers

- ☐ liquid precipitation in high altitudes (rising snowline level) leading to enhanced surface runoff on (non-vegetated) bedrock
- ☐ glacier retreat exposes bedrock/glacial polish bedrock, leading to extreme surface runoff
- ☐ loss of retention capacity of snowpack on glaciers leading to enhanced surface runoff on glacier blank ice

Availability of driftwood/deadwood

- ☐ higher availability due to storm (wind fallen trees)
- ☐ higher availability due to bark beetle infestation

Wild fires

Moisture content

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

Availability of deadwood

- increased ignition probability of deadwood stock

General remark on general (static), environmental driving factors, which include elevation, slope, and land cover: E.g. in the Swiss Alps, fires caused by lightning often occurred at higher elevations on steep relief, and were usually harder to extinguish because they led to ground fires.
A review of main driving factors can be found in Ganteaume et al., 2013.

REFERENCES

Ganteaume, A., Camia, A., Jappiot, M., San-Miguel-Ayanz, J., Long-Fournel, M., & Lampin, C. (2013). A review of the main driving factors of forest fire ignition over Europe. *Environmental management*, *51*, 651-662.
Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., Para- jka, J., Perdigão, R. A. P., Plavcová, L., Rogger, M., Salinas, J. L., and Viglione, A.: Increasing river floods: fiction or reality?, WIREs Water, 2, 329–344, 2015.

ANNEX 3

EXPOSURE CHECKLIST

The Exposure Checklist provides an overview of various categories of exposure and the types of assets within each category. It serves as a foundation for understanding the types of assets located in hazard-prone areas, which could be affected in the event of a hazard. The potential consequences—both direct and indirect—along with dependence on mitigation measures and response capacity, should be considered.

These asset types generally include structures, as well as contents, equipment, and other mobile components that could be damaged during an event. The actual impacts observed for a specific asset type in a hazard event also depend on the ability to move or evacuate mobile assets such as people, livestock, vehicles, and equipment or contents.

The Exposure Checklist separately points out major mobile exposure types such as people, livestock, and vehicles. However, in many cases, the evaluation of affected populations, livestock, or vehicles will be linked to the analysis of immovable assets and can be assessed jointly—for example private properties (incl. populations), road infrastructure (incl. vehicles), and agricultural land (incl. livestock).

Different metrics can be used to assess exposure, depending on the size of the study area and the data available. Very localized hazard processes—e.g., landslides—should be studied at a micro scale. In such cases, exposure can be assessed at the level of individual buildings and current population or tourist data. For larger-scale processes—e.g., drought—or when data and resources are limited, assessments can be conducted at a broader scale.

Asset values are necessary when conducting a quantitative risk assessment. These values can be based on net-value estimates, reconstruction costs, or similar approaches. Sometimes this information is available through local inquiry; other times, broader-scale data is used. Ideally, a consistent approach should be selected for the analysis.

Exposure Checklist			Exposure					
			Relevance	**Description of direct impacts**	**Description interactions with other exposure types and indirect impacts**	**Metric**	**Quantity**	**Asset value**
Category	**#**	**Type**						
Settlement	**1.1**	**Private properties**	☐					
	1.2	**Healthcare and social facilities**	☐					
	1.3	**Tourism and accomodation**	☐					
	1.4	**Cultural property**	☐					
	1.5	**Educational facilities**	☐					
	1.6	**Administrative facilities**	☐					
	1.7	**Commercial facilities**	☐					
	1.8	**Industrial facilities**	☐					
	1.9	**Services**	☐					
		...						
Environment	**2.1**	**Air quality**	☐					
	2.2	**Water bodies**	☐					
	2.3	**Wildlife**	☐					
		...						
Mobility Infrastructure	**3.1**	**Road infrastructure**	☐					
	3.2	**Railway infrastructure**	☐					
	3.3	**Lifts**	☐					
	3.4	**Airports**	☐					
		...						
Essential services	**4.1**	**Energy**	☐					
	4.2	**Communication**	☐					
	4.3	**Potable water**	☐					
	4.4	**Waste water**	☐					
	4.5	**Waste**	☐					
		...						
Public Safety	**5.1**	**Protective structures**	☐					
	5.2	**Public safety organisations**	☐					
	5.3	**Public safety communication network**	☐					
	5.4	**Monitoring systems**	☐					
		...						
Agriculture and forestry	**6.1**	**Agricultural lands**	☐					
	6.2	**Agricultural equipment**	☐					
	6.2	**Agricultural infrastructure**	☐					
	6.3	**(Cultivated) Forest**	☐					
		...						
Mobile Assets	**7.1**	**People**	☐					
	7.2	**Vehicles**	☐					
	7.3	**Livestock**	☐					
		...						

ANNEX 4

RISK QUESTIONNAIRE

The Risk Questionnaire provides a set of guiding question to structure the risk analysis process and aid in the investigation of factors contributing to current hazards and risks due to extreme weather events and how these are likely to change in the future.

The aim of the risk questionnaire is to improve understanding of risks and their drivers. Risk managers and decision makers can provide answers to these questions based on quantitative investigation or qualitatively based on the collective expertise available in their organisations and other important stakeholders in their region of interest.

PART 1: GENRERAL CLIMATE AND (COMPOUND AND CASCADING) HAZARD SITUATION

I. **Which are relevant weather extremes and how do you expect them to change in the future?**
[Relevant weather extremes are those that in the past have triggered hazard processes that were responsible for impacts and damages in your area. Based on climate change the frequency and severity of weather extremes might change in the future. Additionally, extreme weather conditions might arise, which so far have not directly triggered any damaging hazard processes. Which of these have the potential to trigger or change the predisposition of hazard processes?]

II. **Which hazard processes can be triggered by current and future weather extremes?**
[Which single hazards but also cascading and compound hazards can occur in your area during extreme weather events? In general, it is possible to focus on selected hazard processes in your area, or on hazard processes that can be triggered by one specific type of weather extreme. Hazard-Interaction-Matrices can be applied to help develop sequential or compound hazard processes that might apply under current conditions but also identify new processes that may become relevant (e.g., wildfire as a new hazard due to increasingly long drought periods and heat), which have not yet been observed but can pose a risk in the future.]

III. **Which processes occur with high/low frequency and with high/low magnitude and how do you expect this to change in the future?**
[Describe how often and how large relevant types of hazards may occur either by using existing (national) frequency-magnitude relationships (e.g. gauging statistics) or by analysing the frequency-magnitude relationships based on event records. Future changes in frequencies and magnitudes can relate to changes in meteorological events. Which hazard processes might be affected by the changing climatic drivers in the future. Frequencies and magnitudes can also change because of developments in predisposing factors (i.e. conditions that make an area more susceptible to hazard processes, e.g., an increase in debris availability leads to more debris flows and fewer flash floods. Investigate how changing predisposing factors can influence the frequency or magnitude of hazards, e.g. more likely to increase/decrease, or stay the same.]

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?

[Which ecological and socio-economic systems and elements are at risk of being adversely affected by the hazards? Analyse the exposure quantitatively using a suitable metrics, i.e. number of affected elements, area, length, etc., and describe the direct impacts that can be expected in exposed elements. Describe how systems are interconnected and under what conditions specific elements might be indirectly affected. Identify the most critical indirect impacts in terms of the overall consequences of a hazard event considering the temporal and spatial distribution of elements. Changes in exposure are often the result of demographic (population changes), and economic development (e.g., growing industry, tourism, or agricultural sector), changes in traffic volume (transalpine traffic, touristic destinations), or policy changes (e.g., spatial planning, building regulations). Identify the main trends that are relevant in your area based on recent years and explain how this affects exposure. Do you expect these trends to continue or change in the future?]

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?

[Use the knowledge from past events to describe the factors that determine the physical and social vulnerability of exposure. Identify which factors were decisive to the damages and impacts you have observed in the past and which were of lesser importance. Apply vulnerability models to investigate expected consequences. Validate any model using event records to understand if the model suitably describes the damages observed in your area and explain why these might differ. Changes in vulnerability are often the result of demographic (population changes), and economic development (e.g., growing industry, tourism, or agricultural sector), changes in traffic volume (transalpine traffic, touristic destinations), or policy changes (e.g., spatial planning, building regulations). Additionally, risk management practice can have an immediate effect on exposure or vulnerability. Identify the main trends that are relevant in your area based on recent years and explain how these affect vulnerability. Do you expect these trends to continue or 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?

[Describe what structures and systems exist in your area and the acting organizations that help mitigate the effects of a hazard. Think about structural mitigation and other prevention tools, preparedness tools (e.g., early warning systems), and response tools. Workshop-based methods such as Rapid Risk Management Appraisal (RRMA) can provide additional insights about risk management practices in your region. Make gaps in

the management of current and future hazards explicit. Based on current developments/projects in relevant organisations, describe what future structures and systems will be implemented.
Explain how existing and new measures help reduce exposure/vulnerabilities to the hazards.]

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

[Compound events are either linked to the same meteorological trigger or incidentally occur simultaneously because the region has a high susceptibility to multiple hazards. We speak of cascading events when one hazard directly triggers the occurrence of another or when a hazard significantly changes the predisposition/preparatory factors that influence the frequency or magnitude of secondary hazard events. Whenever multiple hazard events affect the same region within a reasonably short time frame the potential damages or losses resulting from their impact may be smaller or greater than the sum of their individual effects. Investigate relevant compound and cascading hazards for their potential to influence the exposure or the vulnerability of elements that could be exposed to multiple hazards. How do you expect the impacts in specific systems or elements to change if subjected to multiple hazard?]

ANNEX 5

RRMA Categories and indicators

Structural prevention

1.1 To what extent were structural prevention/protective measures/systems in place for the event (presence of measures)?

1.2 To what extent did the structural prevention/protective measures/systems fulfil their function during the event (efficiency of measures)?

1.3 How do you assess the condition of the structural protective measures and their maintenance before the event?

Non structural prevention

2.1 To what extent were contingency plans (i.e. action plans for risks) implemented and known by various organizations?

2.2 To what extent did existing contingency plans (i.e. action plans for risks) cover the occurred scenarios?

2.3 How do you rate the quality of the hazard map in terms of its alignment with the actual event that occurred?

Preparedness tools

3.1 How well were the phenomena of the event forecasted?

3.2 To what degree have the predicted phenomena been assessed with respect to possible impacts and risks for warning purposes prior to the event?

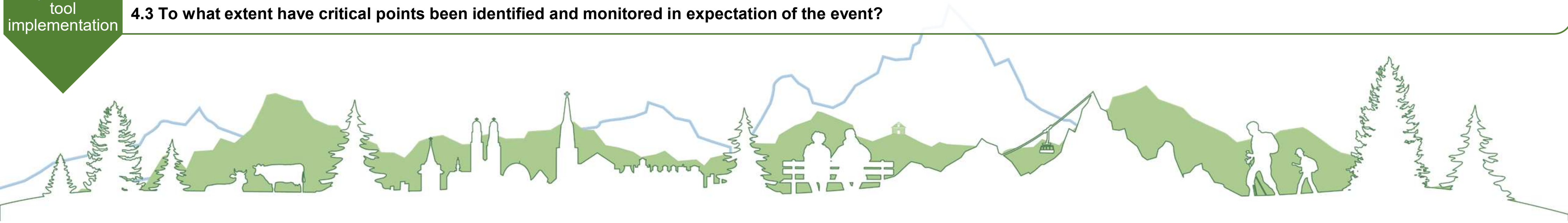
3.3 To what extent was a warning system in place to inform the target groups of the possible impacts and risks?

Preparedness tool implementation

4.1 To what degree were the standard procedures for authorities and civil protection organizations accessible and implemented in response to the warning?

4.2 How do you evaluate the effectiveness of the short-term prevention measures implemented in anticipation of the event?

4.3 To what extent have critical points been identified and monitored in expectation of the event?



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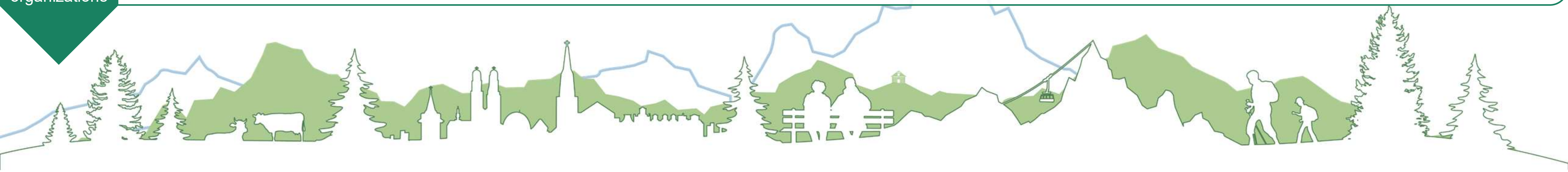
RRMA Categories and indicators

Response tools	5.1 To what extent was an organizational structure established, outlining key roles, responsibilities, communication channels and key players? 5.2 How do you rate the quality/procedure of information shared by the involved authorities during the response phase? 5.3 To what extent were decision support tools available for managing the situation?
Response tool implementation	6.1 To what extent were the exiting protocols followed by managing authorities and other involved target groups? 6.2 How effective was the organizational structure in adapting to the event and handling unexpected situations? 6.3 How do you evaluate the adequacy of the administrative procedures to implement the measures?
Structural recovery	7.1 To what degree were recovery measures planned and prioritized according to the established planning? 7.2 To what degree did the implementation of recovery match the planned time and costs? 7.3 To what degree was the funding for structural recovery adequate?
Recovery learning organizations	8.1 To what extent has the management of the event been debriefed and documented? 8.2 To what degree was the information collected in the debriefing evaluated to identify possible improvements for the future? 8.3 To what extent were „lessons learned“ implemented in concrete strategies for future improvement?



Structural prevention

1.1 To what extent were structural prevention/protective measures/systems in place for the event (presence of measures)? (e.g. check dams for debris flow, bridges etc.)

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
Structural protective measures were in place for **all processes** that occured	Structural protective measures were in place for **most processes** that occured	Structural protective measures were in place for **few processes** that occured	**No structural protective measures** in place

10 – 9 – 8 – 7 – 6 – 5 – 4 – 3 – 2 – 1

Structural prevention

1.2 To what extent did the structural prevention/protective measures/systems fulfil their function during the event (efficiency of measures)?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Structural protective measures have **fully fulfilled** their protective function for the processes that have occured • Structural protective measures have reacted in a good-natured manner to the overload of the system (e.g. no collapse-like failure)	• Structural protective measures have **mostly fulfilled** their protective function for the processes that have occured • Structural protective measures have reacted in a good-natured manner to the overload of the system (e.g. no collapse-like failure)	• Structural protective measures have **only partially** protected against the processes that have occured • Some structural protective measures have failed	• Structural protective measures have **not fulfilled** their protective function at all • Collapse of structural protective measures made situation even worse (no good-natured manner)

10 9 8 7 6 5 4 3 2 1

Structural prevention

1.3 How do you assess the condition of the structural protective measures and their maintenance before the event?

Good practice	“Satisfactory” Improvements possible	“Partly satisfactory” Improvements desirable	“Not considered” Improvements needed
• Structural protective measures were in **excellent condition** • Condition of structural protective measures was **checked regularly** • necessary maintenance measures were **implemented promptly**	• Structural protective measures were in **excellent condition but not regularly inspected** • Structural protective measures were in **good condition and regularly inspected** • Necessary maintenance measures were **carried out with delay**	• Structural protective measures were in **poor condition** • Structural protective measures were **only rarely inspected** • Necessary maintenance measures were **not implemented**	• Structural protective measures were in **very poor condition** • Condition of structural protective measures was **never checked** • **No maintenance**

10	9	8	7	6	5	4	3	2	1

Non structural prevention

2.1 To what extent were contingency plans (i.e. action plans for risks) implemented and known/practised by various organizations?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Contingency plans were **up to date** and **in force** • Plans known on all levels • The **complex scenario** of the event was practised	• Contingency plans **in force** but **not up to date** • **Most of the scenarios** that occured were practised	• Contingency plans **in elaboration** • Plans only known by decision makers • **Only few specific scenarios** of the contingency plans are practised	• **No** existing **contingency plans** • No practice of contingency plans

10 9 8 7 6 5 4 3 2 1

Non structural prevention

2.2 To what extent did existing contingency plans (i.e. action plans for risks) cover the occurred situations?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• **All situations** that occured were considered in the scenarios included in the contingency plans	• The **most important situations** that occured were considered in the scenarios included in the contingency plans	• **Only few situations** that occured were considered in the scenarios included in the contingency plans	• **None of the situations** that occured were considered in the scenarios included in the contingency plans

10	9	8	7	6	5	4	3	2	1

Non structural prevention

2.3 How do you rate the quality of the hazard map in terms of ist alignment with the actual event that occurred?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Event occured **as „mapped"** in the hazard map	• Most of the affected areas shown in the hazard map, **only few deviations**	• **Large deviation** between hazard map and areas affected by the event	• Hazard map and event **completely different** • Hazard map not existing

10	9	8	7	6	5	4	3	2	1

Preparedness tools

3.1 How well were the weather- and hazard phenomena of the event forecasted?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• **All weather- and hazard phenomena** were forecasted in the intensity they have occured	• **All weather- and hazard phenomena** were forecasted but **not with the intensity** they have occured	• **Not all weather- and hazard phenomena** that occured were forecasted and **not with the intensity** they have occured	• **Not all weather- and hazard phenomena** that occured were forecasted and their **intensity was highly underestimated**

10 9 8 7 6 5 4 3 2 1

Preparedness tools

3.2 To what degree have the forecasted phenomena been assessed with respect to possible impacts and risks for warning purposes prior to the event?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Forecasted phenomena **have been assessed** with respect to possible impacts and risks • Impacts and risks were predicted **in the magnitude that occured** at the event	• Forecasted phenomena **have been assessed** with respect to possible impacts and risks • Impacts and risks were **underestimated** compared to the magnitude that occured at the event	• **Some** forecasted phenomena have been assessed with respect to possible impacts and risks • Impacts and risks were **underestimated** compared to the magnitude that occured at the event	• Forecasted phenomena have **not been assessed** with respect to possible impacts and risks

10 9 8 7 6 5 4 3 2 1

Preparedness tools

3.3 To what extent was a warning system in place to inform the population of the possible impacts and risks?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Warning system **in place** • **Big part of population** received warnings of possible impacts and risks including tips to avoid risks	• Warning system **in place** • **Some people** received warnings of possible impacts and risks	• Warning system **partially in place / in trial** • Population didn't receive information	• **No warning system** in place

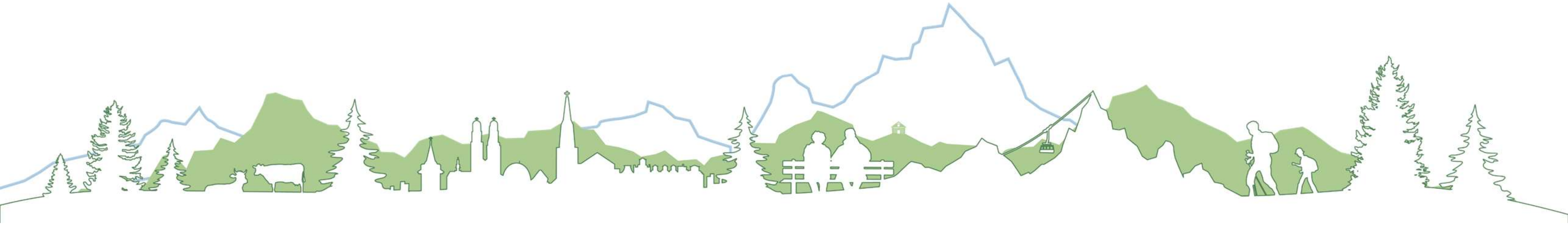
10 9 8 7 6 5 4 3 2 1

Preparedness tool implementation

4.1 To what degree were the standard procedures for authorities and civil protection organizations accessible and implemented in response to the warning?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Standard procedures exist **for all** involved authorities and civil protection organizations • Standard procedures were adopted by **all** involved authorities and civil protection organizations	• Standard procedures exist **for most** involved authorities and civil protection organizations • Existing standard procedures were adopted by **most** involved authorities and civil protection organizations	• Standard procedures exist **for few** involved authorities and civil protection organizations • Existing standard procedures were **not adopted** by involved authorities and civil protection organizations	• **No** existing standard procedures

10	9	8	7	6	5	4	3	2	1



Preparedness tool implementation

4.2 How do you evaluate the effectiveness of the short-term prevention measures implemented in anticipation of the event?

Good practice	“Satisfactory” Improvements possible	“Partly satisfactory” Improvements desirable	“Not considered” Improvements needed
• **All necessary** short-term prevention measures were taken • Short-term prevention measures taken were **fully appropriate** to the given warning	• **Some** short-term prevention measures were taken • Short-term prevention measures taken were **mostly appropriate** to the given warning	• **Some** short-term prevention measures were taken • Short-term prevention measures taken were **not appropriate** to the given warning	• **No** short-term prevention measures were taken

10 9 8 7 6 5 4 3 2 1

Preparedness tool implementation

4.3 To what extent have critical aspects/points been identified and monitored in expectation of the event? (e.g. critical bridges)

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• **All** Critical points were identified and monitored	• **Most** critical points were identified and monitored	• **Some** critical points were identified and monitored	• Critical points were **not** identified

10 9 8 7 6 5 4 3 2 1

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Response tools

5.1 To what extent was an organizational structure established, outlining key roles, responsibilities, communication channels and key players?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Organizational structure put in place **already in phase of „preparedness"** • responsibilities and communications chains were **totally clear** • **All** necessary key players / experts available when the event happened	• Organizational structure put in place **right after start of the event** • Responsibilites and communication chains were **mostly clear** • **Most** key players/ experts available when the event happened	• Organizational structure **evolved during the phase of response** to the event • Responsibilities and communication chains were **mostly unclear** • **Some** key players/ experts not available when the event happened	• **No** organizational structure in place • Responsibilities and communication chains were **not clear at all**

10 9 8 7 6 5 4 3 2 1

Response tools

5.2 How do you rate the quality/procedure of information shared by the involved authorities during the response phase?

Good practice	“Satisfactory” Improvements possible	“Partly satisfactory” Improvements desirable	“Not considered” Improvements needed
• Information was shared **promptly / in time** • Information was shared **directly** • Sharing of information was **unbureaucratic**	• Information was **mostly shared in time** • Information was shared **mostly directly** • Sharing of information was **mostly unbureaucratic**	• Information was **shared with delay** • Information was shared via **complicated procedures** • Sharing of information was **bureaucratic**	• Information was **not shared** at all

10	9	8	7	6	5	4	3	2	1

Response tools

5.3 To what extent were decision support tools available for managing the situation? (e.g. GIS applications , digital map of situation, platforms for information sharing, checklists)

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Instruments for decision support were available • **Existing tools** for the assessment of damage/ loss on a economical/ social/ environmental level	• Instruments for decision support were available • **No existing tools** for the assessment of damage/loss on a economical/ social/ environmental level	• **Few instruments** for decision support available	• **No instruments** for decision support available

10	9	8	7	6	5	4	3	2	1

6.1 To what extent were the existing protocols followed by managing authorities and other involved target groups?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Protocols existed and were followed for **all scenarios** of the event • Protocols were **available for all** involved target groups	• Protocols existed and were followed only for **some scenarios** of the event • Protocols were **available only for some** target groups	• Protocols existed, but were **not followed** • Protocols existed, but were **not available** to the target groups	• **No protocols** existed

10 9 8 7 6 5 4 3 2 1

Response Tool implementation

6.2 How effective was the organizational structure in adapting to the event and handling unexpected situations?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• The organizational structure adapted **proactively** to the event and unexpected scenarios	• The organizational structure adapted **well** to the event and unexpected scenarios	• The organizational structure adapted well to the event • **Unexpected scenarios** were **not handled** well by the organizational structure	• The event and unexpected scenarios were **not handled at all**

10 9 8 7 6 5 4 3 2 1

6.3 How do you evaluate the adequacy of the administrative procedures to implement the measures?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Administrative procedures to take measures were **fast, simple** and could be done **efficiently**	• Administrative procedures to take measures were **mostly fast, simple** and could **mostly** be done **efficiently**	• Administrative procedures to take measures were mostly **slow, complicated** and took mostly a **lot of effort**	• Administrative procedures to take measures were **too slow, complicated** and took a **lot of effort**

10 9 8 7 6 5 4 3 2 1

Structural recovery

7.1 To what degree were recovery measures planned and prioritized according to the established planning?

Good practice	“Satisfactory” Improvements possible	“Partly satisfactory” Improvements desirable	“Not considered” Improvements needed
• Recovery plan was was **multi-sectorial** and **well integrated** • Recovery plan was used to **prioritize** measures	• Recovery plan elaborated for **most sectors** • Recovery plan was **mostly well integrated** • Recovery plan was used to **prioritize** measures	• Recovery plan elaborated for **few sectors** • Recovery plan **not well integrated** • Recovery plan was **not** used to **prioritize** measures	• **No recovery plan** was elaborated

10	9	8	7	6	5	4	3	2	1

Structural recovery

7.2 To what degree did the implementation of recovery measures match the planned timeline and costs?

Good practice

- Implementation of recovery matched planned time and costs **very well**
- recovery measures and response measures with synergies

"Satisfactory" Improvements possible

- Correspondance of time and costs for implementation of recovery with planned time and costs was **satisfactory**

"Partly satisfactory" Improvements desirable

- Implementation of recovery did **not match** planned time or cost frame

"Not considered" Improvements needed

- **No frame** for time and costs was given

10 9 8 7 6 5 4 3 2 1

Structural recovery

7.3 To what degree was the funding for structural recovery adequate?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Funding was **absolutely adequate**	• Funding was **quite adequate**	• Funding was **satisfactory**	• Funding was **not satisfactory** at all

10 9 8 7 6 5 4 3 2 1

Recovery learning organisations

8.1 To what extent has the management of the event been debriefed and documented?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Management of event documented by **all target groups**, **all** useful information available • Debriefing of the event with **all** target groups involved	• Management of event documented by **most target groups**, **some** useful information missing • Debriefing of the event with **some** target groups involved	• Management of event documented by **few target groups**, **sparse** information in documentation • **No debriefing** of the event	• **No documentation** of management of event • **No debriefing** of event

10	9	8	7	6	5	4	3	2	1

Recovery learning organisations

8.2 To what degree was the information collected in the debriefing evaluated to identify possible improvements for the future?

Good practice	"Satisfactory" Improvements possible	"Partly satisfactory" Improvements desirable	"Not considered" Improvements needed
• Information of debriefing was evaluated to identify possible improvements for the future • Implementation of identified improvements **strategically planned** and **continuously followed up**	• Information of debriefing was evaluated to identify possible improvements for the future • Implementation of identified improvements **only partially followed up**	• Information of debriefing was **partially evaluated** to identify possible improvements for the future	• Information of debriefing was **not further used** • Debriefing did **not take place**

10 9 8 7 6 5 4 3 2 1

Recovery learning organisations

8.3 To what extent were „lessons learned“ implemented in concrete strategies for future improvement?

Good practice	“Satisfactory” Improvements possible	“Partly satisfactory” Improvements desirable	“Not considered” Improvements needed
• Communication of „lessons learned“ to **all** relevant decision makers and responsibles • **All** „lessons learned“ implemented in concrete strategies	• Communication of „lessons learned“ to **most** decision makers and responsibles • **Some** „lessons learned“ implemented in concrete strategies	• Communication of „lessons learned“ to **some** decision makers and responsibles • **No** implementation in concrete strategies	• **No** communication or implementation of „lessons learned“ in concrete strategies

10 9 8 7 6 5 4 3 2 1

ANNEX 6

X-RISK-CC Climate Risk Storyline – Wipptal (IT)

In the year 2040....

[knowledge sources are indicated by footnotes]

Scope	Geographical setting: Upper Eisack / Isarco valley (Wipptal) with its side valleys (Pflersch / Fleres, Ridnaun / Ridanna, Pfitsch / Vizze). Temporal setting: from August 2040 (event) to December 2045 (long-term consequences / recovery phase) Intended purpose: Stress testing and appraisal of risk management for extreme (compound) hydrometeorological events.
General climate situation (normal conditions in year 2040)	South Tyrol is in a warmer climate with new temperature records in the city of Bolzano exceeding 40°C. The mountainous regions such as Wipptal are still relatively cool with summer temperatures not exceeding 35°C in the side valleys. Winters are getting mild and wet with more rain and less snow. Summers are getting warmer and temperatures at high altitudes above 3000m are frequently not falling below 0°C. Precipitation shows high variability with dry periods up to several months interrupted by intense precipitation events. Thunderstorms in summer can get very frequent and intense with precipitation above 10mm/hour[1]. In addition, autumn brings frequently stormy and rainy weather with higher intensity and a longer duration over several days in short sequence, mainly driven by the warm Mediterranean Sea ("Genua-Tief"). [2]
General effects of climate change	Glacier retreat and melting permafrost above 2500m lead to higher amounts of material that can be mobilized and to decreasing slope stability at these altitudes. Due to the increased intensity and frequency of storm events, some mountain basins are more active than the past (2025), thus also the occurrence of flash floods and debris flow has increased.
General non-climatic situation / non-climatic risk drivers	Tourism in South Tyrol has been steadily rising since 2025. Summer tourism in the area has particularly expanded, since the classical summer destinations (e.g. the Mediterranean Sea) have become too hot and remote destinations too expensive and insecure. Despite plans to limit soil sealing, touristic infrastructure (hotels, parking lots, new campsites) has expanded and upgraded with high investments, and the roads have been extended to adapt to the heavy traffic load. Some of the new buildings are in zones classified as blue in the hazard maps or close to red ones. Forest is still strongly affected by climate-related problems (drought, bark-beetle) and the capacity of protection forest decreased by approximately 20% over South Tyrol. Partly, technical measures (rock fences) had to be installed to compensate for a lost protection function. Forest fires are considered an emergent risk, further enhanced by the sequence of dry years. The resident population has shown only a moderate increase in size with respect to 2025, but with a marked decrease of younger people and a significant increase of the elderly (80+) that are more vulnerable, less active and less mobile (for evacuation, voluntary organizations, ...). The number of volunteers in response organizations is also decreasing. The fact that tourists and local population are getting more and

[1] See WP1 pilot reports for Wipptal/Stubaital and Garmisch – analysis of future sub-daily precipitation
[2] See WP1 pilot report for Vaia – more frequent GWT 7 gross weather type (Vaia type)

	more international, the language used for risk communication and the sharing of a common risk culture is becoming a challenge.
Event – meteorological event	After a dry spring and warmer than average June and July, August has been rather humid and hot. A low-pressure system developed and persisted over Central Europe leading to a series of rain events, locally up to 50mm per day[3], in the beginning of August. An orange warning is issued by the Civil Protection Agency. On 16th August, a series of intense rain events of convective type, develops and affects also the Wipptal area with very intense phenomena of up to 120mm per day[4] and a total amount of 300mm in three days[5]. In addition, heavy wind with gusts up to 100 km/h is affecting the region.
Event – hazards	Due to the intense rainfall (trigger) and the critical preparatory conditions (high saturation of soils from pre-events) and pre-conditions (poor health of protection forest, high amount of material that can be mobilized) the rainfall triggers not only flash floods in rivers, but also landslides on steep slopes with missing or disturbed protection forest. The high amount of material (sediment, debris, soil) and additional load of wood, partly triggered by falling trees due the heavy wind gusts, is transported by the rivers to the main valley. Specifically, the Kogbach/ rio Covolo produces a debris flow affecting the Pflerscherstrasse and thus isolating part of the fraction of San Antonio and two hotels upstream, which are fully booked, since we are in the high touristic season. Unexpectedly, the Allrissbach / rio Alberes also produces a big debris flow, depositing in the main valley the sediments produced by the glacier retreat and by the complete destruction of the first wooden bridge encountered in its downstream flow. The deposited material causes the blockage of the main road and of the confluence with the Fernerbach / rio Ferner. Consequently, the Fernerbach floods in its left orographic side. The main road and the forestry road (used in winter as sledge track) are damaged and the water intake of the mountain huts upstream is compromised. Downstream, the Toverino river produces a debris-flow event with a 100-year recurrence interval: part of the material is captured by the new protection structures realized after the 2021 debris flow. However, the retention basin cannot contain all the material, which partially floods the main road (Pflerscher strasse). The main road remains closed for two hours for the cleaning operations. At the same time, in Pfitschtal / val di Vizze the Riederbach / rio di Novale produces a debris flow causing the further flooding of the Pfitschbach towards the biotope located on the orographic left. The bridge and the main road are not affected for now, but they must be set under control for the next 24 hours.
Event –impacts	Tourists and local inhabitants cannot leave the valleys and must be evacuated. Due to high season, more than 2000 tourists are affected.

[3] Considering the projected increase of 1-day precipitation maxima under GWL2 with respect to observed average values in 1991-2020 in Wipptal station sites.

[4] A 100-year event in the year 2040, about 10-15% more intense than a 100-year event today at the Fleres station, according to WP1 pilot report for Wipptal/Stubaital.

[5] As happened in Slovenia in August 2023 (Porocilo_visoke_vode_in_poplave_avg2023.pdf (gov.si)) or during Vaia event 2018 in South Tyrol (Pubblicazioni | Meteo | Provincia autonoma di Bolzano - Alto Adige)

	Damages to a transformer house close to the river causes an electric black-out that is affecting the region for two days with consequent problems for cooking, access to houses with “smart” doors, gates, roller blinds, cooling in supermarkets, hotels and restaurants. Some buildings and infrastructure outside hazard zones are also affected. Cell phone network is getting unstable, and the emergency lines are partly overloaded. Not all affected people are able to indicate their emergency. Due to the damage to the water intake, few huts remain without drinkable water.
Post-event (post emergency)	Effects of this event last over the next months and years, with buildings, roads and bridges damaged in three side valleys in the Wipptal region. Furthermore, landslides have led to heavy erosion on already affected slopes and further reduced the slope stability and destroyed further parcels of protection forest. Sediment is accumulated at critical locations that could increase the risk of future flood situations. The population is very concerned about the future. The tourism sector has been heavily affected and had a high economic damage from direct damage to infrastructure but also by the fact that they could not continue with their touristic activities until recovery. After the cleaning operations of the main roads, the secondary and forestry roads remain to clean and new bridges are necessary. Some mountain huts are still without water and cannot open for the winter touristic season.