

Deliverable D1.4

Guidelines on the actionable assessment of hazard interactions in compound / cascading events.

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Abstract

This Deliverable D1.4 provides an overview on the assessment of hazard interactions in compounding events as well as the applicability of existing guidelines, their advantages and disadvantages in different circumstances. It is part of Work Package 1, *“Learning from the past: understanding the dynamic and interactive conditions of risk”*, which focuses on leveraging historical disaster data to improve multi-hazard impact forecasting. This involves analysing how past hazardous events have impacted various sectors and understanding the complex interactions between hazards.

Different approaches of multi-hazard assessments are presented in a comprehensive framework to evaluate and address the interactions and compounding effects of multiple hazards within a specific geographic and temporal context. Unlike traditional approaches that treat hazards in isolation, contemporary approaches should emphasize the dynamic interplay of hazards and their cascading or compounding impacts, which can exacerbate vulnerabilities and magnify risks. This framework for multi-hazard assessments aims to improve risk-informed decision-making by offering systematic guidelines adaptable to various government levels, risk reduction approaches, data availability, and geographic scales. The framework aims to support sustainable knowledge generation, enhance inter-institutional collaboration, and address the complexities of hazard interactions through accessible yet robust methodologies for diverse stakeholders.

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Disclosure Statement:

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About PARATUS:

The PARATUS project aims to increase the preparedness of first and second responders in the face of multi-hazard events and to reduce the impacts on various sectors resulting from complex disasters. The outcome is to develop an open-source cloud-based Online Service Platform that offers support in reducing dynamic risk scenarios and systemic vulnerability caused by multi-hazard disasters. To achieve these objectives, the project will perform in-depth assessments of complex interactions between hazards and their resulting impacts on various sectors, analyze the current risk situation and study how alternative future scenarios could change multi-hazard impact chains. Based on these analysis, scenarios of multi-hazard impacts will be co-designed and developed with stakeholders in four case study areas (including the Caribbean, Romania, Istanbul, and Alpine regions).



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List of Acronyms

Acronym	Definition
AFAD	Disaster and Emergency Management Authority
AKOM	Disaster Coordination Center Directorate
BRAGSA	Buildings, Roads and General Services Authorities
CS	Case Study
CWSA	Central Water and Sewage Authority
D	Deliverable
DLR	German Aerospace Center
DOI	Digital Object Identifier
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DSU	Department for Emergency Situations
ENGAGE	Geomorphological Systems and Risk Research
EOC	Emergency Operations Center
ESF	Emergency Support Functions
EURAC	Eurac Research
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
IC	Impact Chain
ICIMOD	International Centre for Integrated Mountain Development
ICU	Intensive Care Unit
IGSU	Romanian General Inspectorate for Emergency Situations
IIASA	International Institute for Applied systems Analysis
IMF	International Monetary Found
IMM	Istanbul Metropolitan Municipality
IPCC	International Panel For Climate Change
ISO	International Organization for Standardization
ISU	Coordination and Implementation of Resilience Requirements Unit
ITU	Istanbul Technical University
JEU	Joint Environment Unit
LU-LC	Land Use and Land Cover
MapN	Operative Centre for Emergency Situations
Mio	Million
mm	Millimetre
Mw	Moment magnitude
NEMO	National Emergency Management Office
NGO	Non-Governmental Organisation
NLRC	Netherland Red Cross
PAHO	Pan American Health Organization
PARATUS	Increasing Preparedness and Resilience of European Communities by Co-Developing Services Using Dynamic Systemic Risk Assessment
PDNA	Post-Disaster Needs Assessment
PGA	Peak Ground Acceleration
RC	Reinforced concrete

RCCC	Red Cross Red Crescent Climate Centre
SME	Small and Medium-sized Enterprises
SVG	St Vincent and the Grenadines
TEM	Trans European Motorway
UB	Universitatea din Bucuresti
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNICEF	United Nations International Children's Emergency Fund
UNIVIE	Universität Wien
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
UNU-EHS	United Nations University- Institute for Environment and Human Security
UNU-GLOMOS	United Nations University- Global Mountain Safeguard Research
UT	University of Twente
UWI-SRC	University of West Indies, Seismic Research Centre
VHF	Very High Frequency
VISES	Vienna International School of Earth and Space Sciences
WP	Work Package
WWF	World Wildlife Fund

Executive Summary

Work Package 1 (WP1), *“Learning from the past: understanding the dynamic and interactive conditions of risk”*, focuses on leveraging historical disaster data to advance risk science and improve multi-hazard impact forecasting. This involves analyzing how past hazardous events have impacted various sectors, including health, cultural heritage, and the environment, and understanding the complex interactions between hazards. Multi-Hazard Risk Assessment (MHRA) emphasizes the holistic evaluation of hazards, recognizing their compounding, cascading, and concurrent effects, which are critical for effective risk management. The framework integrates dynamic vulnerability, encompassing social, economic, environmental, and physical dimensions, and addresses challenges such as inequality and marginalization in disaster contexts. Rooted in international frameworks like Hyogo and Sendai, MHRA aims to provide systematic, scalable, and actionable guidelines for risk assessment and decision-making. This approach highlights the importance of inter-institutional collaboration, dynamic vulnerability analysis, and simplified yet robust methodologies for diverse applications and stakeholders.

Over the past decade, significant advancements have been made in understanding and quantifying multi-hazard events, shifting the focus from single-hazard analysis to integrated assessments. Multi-hazard risk encompasses interactions between various hazards and vulnerabilities, considering their compounding, cascading, or cumulative effects over time. The Sendai Framework for Disaster Risk Reduction emphasizes an all-hazards approach to strengthen risk assessment methodologies, while definitions like compound and cascading hazards have emerged to describe the interconnectedness of disaster impacts across sectors. Recent frameworks, including hazard matrices and event trees, provide tools to model hazard interactions and assess their amplified impacts, offering a holistic perspective for disaster risk reduction and informing global socio-economic resilience strategies.

Environmental settings play a critical role in shaping the occurrence, intensity, and interaction of hazards, necessitating a location-specific approach. Environments, defined by their natural, physical, and human-made characteristics, influence hazardous processes and their impacts. For instance, mountainous regions face unique threats like avalanches, landslides, and torrential floods, exacerbated by human activities such as infrastructure development. Conversely, lowland areas are vulnerable to riverine flooding and soil degradation, while coastal regions contend with storm surges, tsunamis, and sea-level rise. These environmental distinctions highlight the importance of understanding hazard dynamics in context, as interactions between natural processes and human activities can amplify disasters. Multi-hazard events often cross environmental boundaries, producing cascading and compounding effects that demand integrated, adaptive disaster risk management strategies. This nuanced, environment-centered perspective underscores the interconnected nature of hazard processes and the necessity of tailored approaches to reduce human and economic losses.



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1 Introduction

The United Nations defines natural disasters as “the consequence of events brought about by natural hazards that overwhelm the local response capacity of a country and seriously affect its social and economic development.” The term *hazard* refers to potentially dangerous phenomena such as floods, landslides, forest fires, technical or other anthropogenic accidents and earthquakes that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation. Each hazard is characterized by its type, location, magnitude (indicating the severity/energy of the event), intensity (indicating the spatial distribution of the damaging effects), the frequency of the events with the same magnitude/intensity, the time of onset, and their duration (see Figure 1). Hazards and their interactions are an integral part of the *Multi Hazard Risk Assessment* (MHRA), which is comprehensively shown with its different components in Figure 1. However, in this deliverable we focus on the hazard interactions. *Multi-hazard* is defined as multiple hazards that an area faces and the specific contexts where hazardous events may occur simultaneously, with a cascading effect, or cumulatively over time, taking into account the potential interrelated effect.

‘Multi-hazards’ also refer to possible and relevant hazards and their interactions in a given spatial region and time period. When communities are exposed to multiple hazards, management decisions must consider their interactions holistically. Treating hazards as discrete entities distorts management priorities, increases people’s vulnerability due to the potential compounding effects of other hazards, and underestimates the associated risks. Multi-hazard assessments should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also considering the dynamic nature of vulnerability (Gill and Malamud 2014). The *multi-hazard risk assessment* entails the examination of various hazards within a specific context, considering their possible interactions and the resulting potential impacts arising from their compounding, concurrent, or cascading occurrences. The Hyogo Framework for Action (2005–2015) called for an “integrated multi-hazard approach to disaster risk reduction” (UNISDR, 2005, p. 4), while the Sendai Framework for Disaster Risk Reduction (2015–2030) stated that “disaster risk reduction needs to be multi-hazard” (UNISDR, 2015, p. 10). The multi-hazard risk assessments acknowledge the interdependence of hazards and potential hazard interactions that may arise in a location.

Multi-hazard assessment applies methodologies and approaches designed to evaluate and map the potential occurrence of various hazards within a designated geographic region. The current practice in many countries is to consider the impact of different hazards individually. However, in many scenarios, concurrently analyzing two or more hazards becomes crucial but challenging because of their combined impact due to the knock-on effect, where the impact of two events is larger than the summed-up impact of the individual events. Therefore, the analysis of compounding and cascading events is important for risk-informed decision-making. Typically, a community or settlement can be susceptible to diverse hazards arising from multiple triggers, which could be related to environmental (topography, geomorphology, geology, soils, etc.), climatic (heatwave, cold wave etc.), or human activities (deforestation, construction, tourism, vegetation burning etc.) or a combination of all, creating the complexities in assessment.

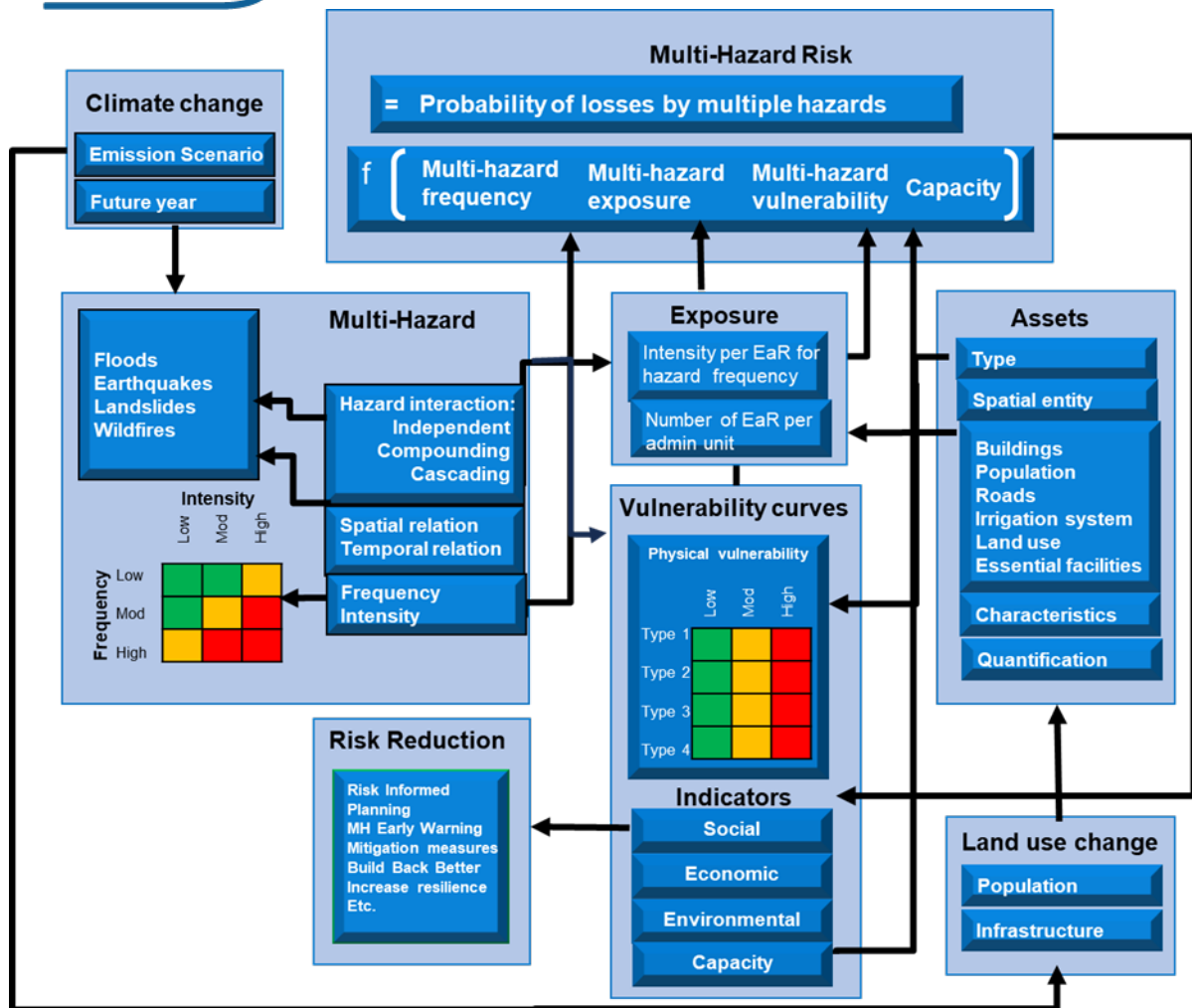


Figure 1: Conceptual framework of multi-hazard risk, with individual risk components of multi-hazards, assets exposure, vulnerability, and output leading to risk reduction planning (Van Westen et al. 2024).

A multi-hazard assessment encompasses a range of dimensions, including social, environmental, economic, and physical aspects. Vulnerability and exposure are also dynamic and change over time (with time scales ranging from hourly to decades) as a result of previous disaster impacts. Capturing these dynamics is a major challenge in MHRA. Vulnerabilities translate into reduced access to entitlements and opportunities, impairing capabilities (UNDRR 2024a) and potentially contributing to fatality, livelihood disruption, or displacement in a hazardous event. The brunt of these impacts is disproportionately borne by the most marginalized communities, intensifying inequality and perpetuating poverty. UNDRR (2024b) defines vulnerability as "The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards." Comprehending the risk landscape and the interplay of social, environmental, and economic systems and their resulting vulnerability remains a cornerstone of multi-hazard risk assessment.

The framework for multi-hazard risk assessment also aims to address the lack of understanding of the concept of multi-hazards and hazard interactions, how these can be defined and conceptualized, and how

the hazard and in the following risk could be calculated. This MHRA framework provides a general guideline that identifies the various approaches that are suited for different levels of government, different applications, and different situations of data availability. It serves as a basis for the future development of detailed guidelines and capacity building (e.g., at the municipal level). It addresses the management policies and actions to support the cumulative building of knowledge in a sustainable and systematic way, highlighting important inter-institutional aspects of data management and sharing. In terms of applicability, there is a necessity for rather simple guidelines which, however, should also convey the complex nature of multi-hazards. Here, the focus is on exploring the existing guidelines on multi-hazard interactions and how these guides are applied in different settings, how they are utilized and how stakeholders perceive them.

This deliverable contributes to Work Package 1 (WP1) “Learning from the past: understanding the dynamic and interactive conditions of risk” of the PARATUS project, which focuses on leveraging historical disaster data through Learning Case Studies and combining it with disaster histories in Application Case Studies. This involves analyzing both the direct and indirect impacts of hazardous events on various sectors, including health, cultural heritage, biodiversity, public finance, and key economic domains. Learning from past events enables advancements in risk science and enhances multi-hazard impact forecasting. Additionally, WP1 integrates satellite remote sensing data to provide critical components for systemic risk assessment.

As part of the PARATUS project, a series of past disaster events (Learning Case Studies, detailed in Deliverable 1.2) and four Application Case Studies (outlined in Deliverables 6.1, 6.2, and 6.3) have been selected for focused analysis. Within WP1, these case studies are examined through the development of Impact Chains, supported by forensic analysis, remote sensing, and disaster databases. The ultimate goal is to achieve a qualitative and quantitative understanding of systemic risk associated with complex disaster scenarios. Deliverable 1.4 is especially focusing on the hazard interactions as a first component leading to multi-hazard risk assessments. One important component here is to not only consider single hazards but consider the complexities of these multi-hazard interactions and how they interact.

2 Review of multi-hazard concepts

Over the past decade, a large number of international concepts and scientific publications has emerged to better understand and quantify multi-hazard events (Marzocchi et al. 2009, 2012; Kappes et al. 2012; Gill and Malamud 2014; Gallina et al. 2016; Gill et al. 2022; Hochrainer-Stigler et al. 2023; Owolabi & Sajjad 2023). Older classification systems often have differing views on the grouping of the individual hazard types. For example, the global EM-DAT disaster database (EMDAT, 2023) used by most international organizations applies a different classification system than the UNDRR. A recent publication by UNDRR & ISC (2020) differentiates a total of 302 hazard types, ordered into eight groups: Environmental, Geohazards, Extraterrestrial, Meteorological and Hydrological, Societal, Technological, Biological, and Chemical. These are further described and characterized in specific hazard information profiles in Murray et al. (2020).

In the past decade, the focus has shifted from analysing single hazards to multiple hazards. Multi-hazards were defined by UNDRR (2016) as “multiple major hazards that an area faces, and the specific contexts where hazardous events may occur simultaneously, in a cascade or cumulatively over time, and taking into account the potential interrelated effects.” The Sendai Framework on Disaster Risk Reduction emphasizes a so-called all-hazards approach “to strengthen technical and scientific capacity to capitalize on and consolidate existing knowledge and to develop and apply methodologies and models to assess disaster risks, vulnerabilities and exposure to all hazards” (UNDRR 2015). Disaster Risk in this context is defined as the “potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period, determined probabilistically as a function of hazard, exposure, vulnerability, and capacity” (UNDRR 2016). This multi-hazard risk assessment is not simply the combination of the probability of expected losses from individual hazards. It is crucial to consider the interrelationships among the different hazards and the interrelationships between the hazards and vulnerabilities, which is also referred to as multi-risk (Zschau 2017). A very useful definition of multi-hazard risk was given by Gill and Malamud (2014): “A *multi-hazard risk assessment should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses.*”

Pescaroli and Alexander (2018) and Alexander and Pescaroli (2019) provide a holistic framework for better understanding of the terms used. The term compound risk came from the climate risk community and was used in IPCC reports as “a special category of climate extremes, which result from the combination of two or more events, and which are again ‘extreme’ either from a statistical perspective or associated with a specific threshold” (IPCC, 2018). These could be two or more simultaneous or successive extremes or events that combine to become an extreme event. Although initially used to describe specific combinations of weather and climate events that contribute to risk (Zscheischler et al. 2020), the term compounding hazard is now also used to indicate the concurrence of several hazardous events from different origins, and it has become a general term to indicate that several hazardous events worsen the impact on society. The term interacting risk is used to highlight the importance of hazard interactions in terms of their causal mechanisms and the effect they have on other hazardous processes. These hazard interactions can be modelled using various numerical modelling approaches, leading to increased hazard intensities as compared to those from individual hazards. The term interconnected hazard is used to highlight the importance of interconnected causality networks that generate and amplify disasters and the interlinkages between human, environmental, and technological components (Helbing 2013), which can be analysed using network analysis.

The term cascading hazards is used to focus specifically on the progressive impact of disaster events, which propagate from one component or sector to another. It uses the analogy of toppling domino stones, where one hazardous event leads to a secondary hazardous event, and primary impacts and damages lead to secondary impacts and losses. Central to this concept is the impact on critical infrastructure, which may lead to indirect impacts in other sectors. This can also include so-called NaTech disasters, where extreme events with a natural origin (e.g., earthquake) cause a secondary technological disaster chain (Krausmann et al. 2011). Serious impacts of climate change, such as extreme drought, tropical storms, forest fires, or floods, may have knock-on effects that impact international socio-economic sectors such as agriculture, finance, international trade, and manufacturing chains. For example, COVID-19 had serious cascading consequences on many sectors and cross-border activities. Finally, another relevant term to mention is emerging hazards, which refers to possible threats that have not manifested themselves in the past or for which the available knowledge is weak. One of the important emerging hazards is related to climate change and the impact of possible tipping points (IPCC, 2018). In terms of hazard interactions, Marzocchi et al. (2009) state that hazard interactions can be named accordingly when impacts of one hazardous event is exacerbated by interaction with other hazards. Such studies examine hazard interactions by starting with information about the primary hazard, which may trigger additional hazards or increase the likelihood of their occurrence. Commonly used methods include hazard matrices and event trees (Liu et al. 2016).

3 Multi-Hazards in Different Environments

Hazards occur case and location-specific, making it crucial to differentiate based on specific environmental settings when assessing them. Environments are here defined from a geographical perspective referring to natural, physical, and man-made surroundings in which certain activities take place. The physical space encompasses natural features such as topography, relief, and water resources, which play a significant role in influencing the hazardous processes and the characteristics that shape their impacts. Depending on how these parameters are linked, natural processes can transform into potentially harmful events based on location and timing. Given this variability, hazard reduction measures must be tailored to the environmental context. Effective plans and responses depend on understanding which hazard interactions are most likely in a given setting. Since not all hazards occur universally, focusing on the most probable processes and their interactions in a particular environment can enhance preparedness and resilience.

Figure 2 illustrates the correlation between specific hazards in different environments where they are most likely to occur and interact. These examples highlight how unique environmental conditions from mountainous, lowland, coastal, sea and lakes influence the dynamics of hazardous processes, enabling a more focused approach to disaster risk management.

Mountain Regions

High relief, steep slopes, large variability in weather patterns, and orographic barriers, combined with extreme weather phenomena, make mountain environments particularly vulnerable to avalanches, torrential floods and gravitationally induced hazards. For example, narrow valleys in mountainous areas often exacerbate flooding and torrential processes due to their confined topography. Even though these processes have been studied intensely, defining mountainous areas can already be challenging, as their characteristics vary significantly based on factors such as elevation, relief, and exposure (Barsch & Caine 1984; Troll 1973).

Case studies frequently focus on specific mountain environments to assess hazards. Froude and Petley (2018) explored landslide risks in the Himalayas, emphasizing how rainfall and seismic activity interact to trigger such events. Similarly, Hewitt (1992) documented a broad range of hazards in mountainous areas, including rockslides, mud and debris flows, avalanches, earthquakes, volcanism-induced landslides, weather-triggered slope failures, and natural dam collapses caused by glaciers or landslide blockages. The occurrence of hazards in mountains is influenced by a wide variety of parameters affecting slope stability, generally described in three stages from stable, marginally stable to active unstable (Crozier 1989). These range from rapid changes, such as extreme precipitation or seismic events, to long-term processes like gradual weathering and climatic shifts that can enhance the progression of slope instabilities (Varnes 1978; Popescu 1994). Forest cover is often regarded as a stabilizing factor that mitigates landslide risks, as noted by Abernethy and Rutherford (2000) and Glade et al. (2005). However, it can also pose a threat in the form of forest fires, which spread particularly rapidly in mountainous regions due to steep slopes, strong valley winds, and a higher incidence of lightning. In mountainous regions hazards can have varying temporal scales, from short-lived, sudden events such as avalanches or flash floods to longer-term vulnerabilities like high-altitude hypoxia or environmental degradation (Hewitt 1992).

Human activities further compound hazard risks in mountainous regions. Constraints on land use and settlement in these areas often force human activities to interact closely with unstable slopes, increasing the likelihood of hazard activation (Ozturk et al. 2022). Infrastructure projects, such as road and railway construction, frequently destabilize slopes, triggering landslides and erosion. About 43% of all landslides

being attributed to anthropogenic causes (Damm and Klose, 2015). Construction and other interventions on unstable slopes have demonstrated the potential to reactivate old landslides or trigger new slope failures. This phenomenon is also evident in lower mountain ranges, such as in Germany's Swabian Alb (Bell et al. 2006), Franconian Alb (Jäger et al. 2013) or Eifel (Hagge-Kubat et al. 2022; Wenzel et al. 2024a), where increased human influence has led to increased hillslope instability.

Areas adjacent to mountainous regions, such as intermontane basins and mountain foothills, often suffer more significant damage than high-altitude regions due to larger populations and the arrival of hazards like flash floods, which originate upstream (Hewitt 1992). These areas function as transport or accumulation zones for hazards, intensifying their erosive force. For instance, natural dams are more likely to form in steeper, narrower valleys, as Costa and Schuster (1991) noted. However, the downstream impacts of their collapse, such as floods, can extend beyond the source area, highlighting the interconnected nature of mountain hazard dynamics.

Lowland areas

Lowland regions, particularly floodplains, represent highly vulnerable landscapes exposed to a complex array of environmental hazards. Riverine flooding, pluvial floods, and soil liquefaction characterise these areas, often triggered by heavy precipitation and influenced by upstream processes originating in mountainous regions. The transport of water and sediment from source areas can accumulate at foothills or lowlands, intensifying flood risks. The flat morphology of these regions, combined with slow drainage capabilities and soil degradation from water erosion and human activities, significantly amplifies the potential negative impacts of flooding.

The complexity of hazard interactions in lowlands becomes particularly evident through compound dry and wet extremes (CWDEs). These interconnected phenomena can simultaneously stress crops and livestock, placing them under severe physiological pressure (Chen et al., 2023). A study conducted by Chen and Wang (2023) revealed that the risk of yield loss from such compound extremes can be twice as high as losses from individual wet or dry events. This finding underscores the importance of understanding and assessing the combined impacts of multiple hazards on agricultural systems.

Human activities further exacerbate hazard impacts in lowland regions. Groundwater extraction and urbanisation significantly exacerbate environmental risks, as demonstrated in regions like the Netherlands (Erkens, G., & Stouthamer, E. 2020) and North-East Italy's Polesine area (Viero et al., 2018). Anthropogenic landscape modifications, such as land subsidence, dramatically alter flood dynamics and hydraulic hazards.

Coastal areas

Coastal regions are unique environments characterized by complex and interconnected hazards arising from their proximity to the ocean. These include hydrometeorological hazards such as storm surges, coastal flooding, tropical cyclones and hurricanes. There are also geological hazards like coastal erosion, earthquakes, tsunamis, as well as climate-related hazards such as sea level rise and heat waves. Many of these events have a multi-hazard nature; for example, hurricanes can lead to storm surges and heavy rainfall, which may cause flooding. A notable example is Hurricane Katrina (USA) in 2005, which intensified vulnerabilities in pre-existing levees and resulted in widespread flooding in New Orleans (Kates et al. 2006).

One of the most critical multi-hazard interactions in coastal regions, due to the severity of their impacts, is the occurrence of tsunamis triggered by earthquakes or other geological hazards. A tsunami is a series of enormous waves generated by an underwater disturbance occurring below or near the ocean (Intergovernmental Oceanographic Commission, 2019). The Tohoku earthquake (Japan) in 2011 exemplifies the catastrophic potential of such events, causing not only a massive tsunami but also resulting in over 18,000

fatalities, destroying 400,000 homes, and triggering a nuclear meltdown at the Fukushima Daiichi Nuclear Power Plant (UNDRR, 2021).

The complexity of coastal hazards is further amplified by anthropogenic climate change, which is increasingly producing more intricate and interconnected environmental challenges. The IPCC AR6 report highlights that in coastal areas, the interaction of rising sea levels combined with storm surge and heavy rainfall will increase the risks of compound flooding (IPCC(b), 2022). Sea-level rise amplifies storm impacts by increasing the baseline water levels, especially in deltaic systems, thus intensifying inundation risks (Nicholls & Cazenave, 2010). The projected increase in sea levels will have a detrimental impact on coastal ecosystems and their services. These impacts include groundwater salinization, flooding, and damage to coastal infrastructure (IPCC(b), 2022).

The hazard interactions become even more complex when considering the interface between mountain and coastal environments. The combination of these two environments is particularly dangerous when processes from both regions occur. Seismic event triggered landslides in mountainous areas that cascaded into the sea can generate large waves and contribute to devastating tsunamis. Similar hazard interactions are observed in other coastal mountain ranges, where landslides or rockfalls into the ocean can trigger tsunamis. For example, potential collapse scenarios in the Canary Islands, such as a massive landslide at La Palma, could lead to catastrophic wave generation, posing significant risks to nearby coastal populations (McGuire, 2006).

Lakes

Lakes represent unique aquatic ecosystems distinguished from seas by their confined nature and typically defined inflow and outflow patterns. Despite their enclosed characteristics, larger lakes can experience processes similar to small seas, including seiches (standing waves triggered by seismic or meteorological activities) and flooding resulting from storm-driven water level fluctuations.

One of the most significant hazards in mountain lakes is the Glacial Lake Outburst Flood (GLOF), a phenomenon with multiple potential trigger mechanisms. These include dam breaks caused by mass movement-induced impulse waves, lake overfilling from pluvial and glacial runoff, and the degradation of moraine or ice dams (Taylor et al. 2023). The complexity of GLOFs triggers underscores the intricate interplay between geological, meteorological, and hydrological processes in mountain environments. Additionally, lakes face hazards such as algal blooms exacerbated by nutrient runoff, coupled with droughts or storms that reduce oxygen levels, threatening aquatic life (Paerl & Huisman 2008).

Overall, the combination of natural processes and human impacts, necessitates a detailed, context-specific understanding of hazard interactions. These interactions are shaped by environmental factors, human activities, and the surrounding landscapes, emphasizing the importance of integrated disaster risk management strategies. For example, reinforcing coastal infrastructure may be essential for seaside towns, while slope stabilization and afforestation are crucial for reducing landslide risks in hilly regions (Petley 2012). Understanding the environmental context is key to developing targeted, location-specific hazard planning and response strategies that can reduce both human and economic losses. Shifts in hazard patterns should not be overlooked, as they highlight the potential for hazards to affect areas that were previously thought to be not a problem zone. Such developments underscore the need for flexible, adaptive approaches to disaster risk management that account for evolving hazard trends across diverse environments and latitudes.

While it seems logical to classify hazards based on their environmental settings, the reality is more complex when multiple hazards interact, particularly during large-scale events. These events can have far-reaching impacts, extending beyond their immediate sources to affect multiple environments

	Extreme Precipitation	Extreme Temperature	Strong wind	Earthquakes	Volcanoes	Biological	Technological	Extraterrestrial
Land area in general	Snow fall Wild fire Drought Pluvial Floods River Floods	Cold wave Heat wave Wild fire Drought	Snow storm Tropical Storm Tornado Wind storm	Fault rupture Ground shaking Liquefaction	Ash Fall Ash clouds Gas emission	Epidemic Insect infestation Animal disease Plant diseases	Nuclear accidents Pollution Hydropower accidents Water extraction Industrial accidents Transport accidents Agriculture malpractice Mining related	Meteorite impact Geomagnetic storm
Hills and Mountains	Snow avalanche Flash Floods Outburst Floods Mass movements	Permafrost decline Mass movements	Mass movements	Mass movements Outburst Floods	Lahar Pyroclastic flow Lava flow Volcanic explosion		Dam failure Subsidence Coal fire	
Lowlands	River Floods Pluvial Floods							
Coastal areas	Coastal flooding		Coastal erosion Storm Surge	Tsunamis	Tsunamis		Subsidence & flooding	Tsunamis
Sea		Eutrophication	Waves	Tsunamis	Tsunamis	Algal bloom Coral bleaching	Oil spills Plastic soup	
Lakes		Eutrophication		Seiches	Seiches CO emission	Algal bloom	Pollution Dry up	

Figure 2: Hazard types that are specific for certain triggering events and environments (Van Westen, pers. com).

4 Data availability and acquisition techniques for Multi-Hazard Assessments

Multi-hazard risk assessments require a wide array of data, including historical data, inventories of hazard events, frequency, possible interactions between hazards, aggregated and disaggregated population information, critical infrastructures and their vulnerabilities, and much more. There are various methods for assessing multi-hazard risk, namely quantitative, qualitative, and semi-quantitative. These methods are data-dependent and context-specific, and the reliability depends on the models' performance, which inherits some uncertainties and assumptions. Adoption of contextual methodologies complemented by field verifications is often required for various scales of assessment (i.e., national, regional, local, municipal, basin, etc.). As the first step it is necessary to understand the hazard interactions and choose datasets appropriate to model these interactions.

Data is collected and generated from various sources, resulting in heterogeneous data quality. In the past few decades, many collaborative projects such as have been conducted in the field of disaster risk reduction and management, hence compiling the necessary data required for risk assessment (UNDRR, 2022).

To ensure the interoperability, storage, and distribution of any dataset, a set of information describing the dataset is mandatory, known as metadata. Metadata defines the content, the creation process, the data quality and type. It also provides an overview of how and for which purpose a data set can be used. For spatial data, it is essential to provide the spatial and coordinate reference systems (CRS) and the scale of capture or resolution for raster data. These metadata can be stored in several open and software-specific file formats. However, in order to achieve interoperability, the most common is the XML Format. Given budget constraints in developing countries, it is advisable to utilize open file formats and open-source software as they reduce costs at the government level, enhance traceability, and promote wider usage of the data and models created by professionals and the public.

Enhancing multi-hazard risk assessment through technological innovation is inevitable, where threats from natural hazards and the occurrence of disasters increase in frequency and intensity. With climate change driving more extreme weather events and urbanization exacerbating vulnerabilities, traditional risk assessment methods are no longer sufficient to address the complex challenges that we face nowadays. Through the integration of advanced technologies in acquisition, such as remote sensing, and sensor networks, or in data management such as, artificial intelligence (AI), machine learning and big data, we can gather up-to-date data and derive insights to better understand the dynamics of hazards and multi-hazards. Furthermore, embracing technological innovation in multi-hazard risk assessment improves our capacity to mitigate the impact of disasters. It fosters a more proactive and adaptive approach to managing complex and interconnected hazards.

Remote sensing technology has been widely used across various domains, and it serves as an important data source for multi-hazard, vulnerability, and risk assessment (Van Westen 2013). It involves collecting data about the Earth's surface from a distance, typically using satellites, aircraft, or drones. One of the primary advantages of remote sensing is its ability to acquire data over large spatial extents, making it particularly

useful for assessing hazards and vulnerabilities across expansive territories, including remote and inaccessible regions. Furthermore, remote sensing offers multi-temporal capabilities, allowing for the observation of changes over time. By analyzing historical imagery and time-series data, we can identify trends, detect anomalies, and assess the evolving nature of hazards and vulnerabilities, enabling stakeholders to anticipate future challenges and implement proactive measures. For example, satellite radar altimetry can provide consistent and up-to-date river discharge datasets to perform a trend analysis towards the continuous monitoring of extreme events (Belloni et al. 2021). In addition to its broad coverage and multi-temporal capabilities, LIDAR, photogrammetry and remote sensing provide varying levels of resolution, ranging from coarse to high spatial detail (Lombardo et al. 2021). High-resolution imagery enables the identification of fine-scale features such as building footprints, transportation networks, critical infrastructure, etc., enhancing the accuracy and granularity of risk assessments and decision-making processes.

Regarding the data availability several remote sensing sources are freely available and can be integrated in the further analysis regarding multi-hazards. One example is the Copernicus Sentinel mission including among others publicly available optical and radar satellite data at a 10 m resolution and temporal resolution up to 6 days (Berger et al. 2012).

While remote sensing is particularly useful in providing information on wide-scale hydrological parameters such as water discharge, detailed data from hydrological stations is often still required. In such cases, a regionalization approach can be considered that aggregates data from available locations to estimate data of ungauged locations from hydrologically similar catchments. This approach of combining remote sensing data with additional more detailed regional information and disaggregate it spatially is used for different fields. For instance, to project census information, as it is done for the Global Human Settlement Layer POP (European Commission 2023) and the WorldPop (Stevens et al. 2015) dataset. Another approach that has been used to generate spatial building information related to earthquakes uses statistical building type data on communal level and disaggregates it spatially by combining it with Sentinel-2 and TanDEM-X remote sensing datasets (Geiß et al. 2023).

AI, machine learning (Linardos et al. 2022), and big data analytics (Yu et al. 2018) are revolutionizing multi-hazard risk assessment methodologies by offering sophisticated tools for analyzing complex datasets, identifying patterns, and making informed decisions in diverse domains of disaster risk management. AI and machine learning algorithms are instrumental in processing vast amounts of data generated by various sources, including historical records, sensor networks, and remote sensing data. These algorithms can extract valuable insights, detect trends, and predict potential risks with a level of accuracy and efficiency that was previously unattainable. Moreover, big data analytics enables the integration and analysis of heterogeneous datasets, combining structured and unstructured data from multiple sources to uncover hidden relationships and correlations. In the context of multi-hazard risk assessment, AI and machine learning techniques facilitate the development of predictive models that can forecast the likelihood and magnitude of future events based on historical data and real-time inputs. AI and machine learning are also instrumental in the development of automated elements-at-risk databases, such as the large-scale Microsoft (2023) and Google (2023) open building footprints datasets, and in mapping and characterizing buildings for flood exposure analysis using

deep learning techniques (Bhuyan et al. 2023), which is the essential step forward from the hazard interaction assessment towards a multi-hazard risk assessment.

The integration of remote sensing, AI, machine learning, and big data analytics in multi-hazard assessment transforms it from a static, reactive process to a dynamic, proactive endeavor. By continuously analyzing data, monitoring trends, and adapting to changing conditions, organizations can stay ahead of emerging risks, minimize uncertainties, and enhance resilience in the face of evolving threats. Moreover, leveraging innovative approaches like crowdsourcing (Poblet et al. 2018), citizen science (Hicks et al. 2019), and participatory mapping (Partidário et al. 2022) fosters community engagement and empowers local stakeholders to contribute valuable information and perspectives. This collaborative effort enhances the accuracy and relevance of risk assessments, ensuring that preparedness and mitigation efforts are tailored to meet the specific needs of affected communities.

Data is often scattered in different departments and agencies across a country. One of the major challenges in inter-agency data sharing is the perceived loss of authority and power over the data, making it an arduous process. Even if the data is available freely, its quality might be poor. Inconsistent, inaccurate, incomplete, and outdated data misinterprets the context, resulting in poor planning and decision-making. Many countries are implementing the Spatial Data Infrastructure (SDI) in their development policies, following the OGC (Open Geospatial Consortium) standards or the INSPIRE Directive. SDI provides a platform to collaborate and link services across and between national, state and local jurisdictions, organizations, and disciplines. SDI aims to facilitate information with known precision and accuracy, avoid duplication in the effort to collect data, reuse existing data, reduce human and financial resources, and improve data quality, as well as data accessibility.

The use of metadata allows us to find datasets with relevant information for MHRA. An example are the reference data from the Annex 1 and 2 of the INSPIRE Directive for European countries (EU Commission 2024) with information regarding hydrology, protected sites, geology, land cover etc. and especially the theme in Annex 3 “Natural risk zones” (EU Commission 2024). Moreover, with the European regulation about the High Value Data more information will be available in the different countries with an interoperable format (EU REGULATION 2023/138). This information is also available beyond Europe, in other countries that have a SDI implemented.

5 Multi-hazard Interactions

The choice of appropriate multi-hazard risk assessment methods is governed by the interrelations between the hazardous events that should be considered. We are referring here to hazard interrelations, and not hazard interactions, because the hazards might not actually interact with each other while still having an important influence on the resulting impact. The hazard interrelation is determined by a combination of three components:

- Type interaction: how different hazard types can have an influence on the expected losses.
- Spatial interactions: how the spatial extents of hazards have influence.
- Temporal interactions: how the timing of events relate to each other is important for losses.

Table 1 provides an overview of the interrelations between different **hazard types**. Independent hazards are those that do not have the same trigger and where the occurrence of a hazard is not related to the occurrence of the other hazards. The triggering relationship considers if the hazards are caused by the same external triggering event (e.g., precipitation and/or temperature extremes, earthquakes). The cascading relationship considers whether one hazard causes other hazards in a cascading relationship, where primary hazard events generate secondary hazard events. The conditioning (or amplifying) relationship considers if the occurrence of one hazard could amplify the frequency or intensity of a second hazard. The conditioning relationship determines whether the occurrence of one hazard might modify the conditions that make the occurrence of a second hazard more likely. Note that we do not consider the term compounding here as a separate class because this term is a general term that indicates that multi-hazard events might lead to larger losses than if we consider individual events.

The **spatial relationship** considers if the hazards occur in the same area, adjacent areas, or far away (Table 2). *Overlapping* events have areas that (partly) overlap and where two or more hazard types have an impact. The *source and spread* events relate to those multi-hazards where one event is the source, and another event is the area from which a hazard spreads out (e.g., a glacial collapse leading to a flood downstream). The *cross-boundary* relationship is relevant for hazards that cross administrative boundaries, where the information might not be shared, or where two or more authorities need to act and coordinate efforts.

The **temporal relationship** considers how events occur in time, which could be simultaneous or concurrent, close to each other, or a long time after each other (Table 3). Consecutive disasters are two or more disasters that occur in succession. It should be noted that these could also be two events of the same hazard type. Hazardous events may be slow-onset events such as droughts or pandemics, which may cover months or years, or fast-onset events such as earthquakes, storms, or flash floods.

Table 4 gives 15 examples of the combinations of these hazard interrelations.

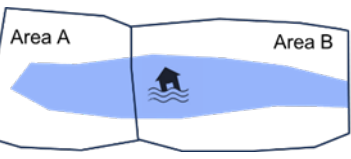
Table 1: Subdivision of the main types of hazard type interrelations. The codes are used in table 4 (Van Westen et al. 2024)

Hazard type interrelations	Description	Example	
Independent (HIN)	Hazardous events that have no direct causal relationship and for which the hazard assessment can be carried out independently	An earthquake and a flood happen at different times.	
Triggering (HTR)	Hazardous events might share the same trigger, occur simultaneously, and affect the same area.	Landslides and floods occur as a result of the same triggering rainfall event.	
Cascading (HCA)	These hazardous processes occur in sequence, where one process triggers the second and the second the third	An earthquake may trigger a landslide that dams a river, and the eventual break of the landslide dam can lead to flooding.	
Conditioning (HCO)	These hazardous events change the conditions of the landscape in such a way that the susceptibility/ likelihood and/or intensity of other hazardous processes increases substantially	Forest fires change the soil conditions, increasing the susceptibility to floods and landslides.	

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. To simplify the above-mentioned classification for applicability in practice, we propose the following three-class classification:

- Individual Independent events: hazardous events that have no direct causal relationship and for which the hazard assessment can be carried out independently.
- Compounding events is used to indicate the concurrence of several hazardous events, and it has become a general term to indicate that several hazardous events worsen the impact on society.
- Cascading events are used to focus specifically on the progressive impact of disaster events, which propagate from one component or sector to another. It uses the analogy of toppling domino stones, where one hazardous event leads to a secondary hazardous event, and primary impacts and damages lead to secondary impacts and losses.

Table 2: Subdivision of the main types of spatial multi-hazard interrelations. The codes are used in table 4 (Van Westen et al., 2024)

Spatial hazard interrelations	Description	Example	Implications for the risk assessment
Overlapping (SOH)	The areas that might be affected by several types of hazards might overlap or partly overlap. Several types of hazards impact the assets.	A flood might affect the same area as an earthquake, so two events impact the same assets.	
Source and spread (SSS)	Hazardous events are spatially connected through a source and spread relation, where one hazardous event is the source, and the other is the area where a hazardous process or phenomenon spreads out to	A landslide dam is a river, and after the breaking of the landslide dam, the resulting flood spreads out in the downstream area, impacting assets that were not affected by the flood.	
Cross-border (SCB)	Hazardous events that cross different administrative borders. These can be within a country but can also be across different countries	Major flooding originated in one country and reached another, crossing different administrative borders and reaching into neighboring countries.	
Not-overlapping (SNO)	The areas of different hazardous events do not overlap	A flood event in one part of the country occurs simultaneously with an earthquake event in another part of the country. This will put stress on the emergency response system and will create more impact than a single event	

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. Table 4 gives examples of these hazard interactions with their spatial and temporal parameters. To simplify the above-mentioned classification for applicability in practice, we propose the following three-class classification:

Table 3: Subdivision of the main types of temporal multi-hazard interrelations. The codes are used in table 4 (Van Westen et al., 2024)

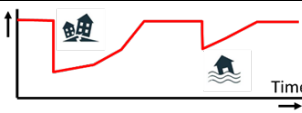
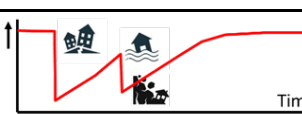
Temporal interrelations	Description	Example	
Events occur after a long time (TDI)	the time-period between two events is long enough so that the society or territorial system has fully recovered from the previous event	An earthquake which damage is repaired within several years, followed by a flood after five years	
Consecutive events (TCO)	Hazardous events may occur close to each other so that the damage of one is worsened by the damage of the other. Events occur in succession.	Flash floods and landslides follow an earthquake in mountainous regions. The impact is larger, as the region is still recovering from the impact of the previous event.	
Simultaneous/ Concurrent events (TSI)	Independent events that are unrelated may occur simultaneously or very close to each other, belonging to the same sequence, so the damage is due to the combined intensity of the hazard events.	The occurrence of a flood event during the COVID pandemic resulted in large migration and pressure on hospitals	
Onset speed	Hazardous events may be slow-onset events, which may cover months or years, or fast-onset events, such as earthquakes, storms, or flash floods.	Slow-onset: droughts or pandemics, Fast-onset ones: flash floods, earthquakes.	

Table 4: Fifteen examples of hazard interactions with their spatial and temporal components. **Hazard types:** EQ = earthquake, FL= flood, TA = Technological accident, LS = Landslide, DB = Debris flow, VE = Volcanic eruption, FF = Forest Fires, WS = Windstorm, ER = Extreme rainfall, TE = Temperature increase, DR= Drought, HW = Heat Wave. **Hazard Interaction:** Independent events (HIN), Trigger-coupled events (HTC), Cascading events (HCA), Pre-conditioning events (HPC), Compound events (HCO). **Spatial relation:** (partly) Overlapping hazard footprints (SOH), Source and spread relation (SSP), Not-overlapping hazard footprints (SNO). **Temporal relation:** Distant events in time (TDI), Consecutive events (TCO), Simultaneous events (TSI). Source: Van Westen et al. (2024).

Case	Hazardous events			Hazard interaction	Spatial relation	Temporal relation	Comments
	First event	Second event	After				
1	EQ	FL	1ye	HIN	SOH	TDI	An earthquake causes damage to infrastructure, which is repaired within one year. One year later the same area is impacted by a flood. Example: Japan

2	EQ	ER - FL	1mo	HIN	SOH	TCO	One month after an earthquake which weakened river embankments, an extreme rainfall causes a high discharge and the embankment fails, leading to a flood event. Example: Po River, Italy
3	EQ	FL	1ho	HCA	SOH	TSI	An earthquake damages a dam of a water reservoir, which ruptures and results in a dam break flood. Example: Bucharest, Romania
4	VE	AC	1we	HCA	SNO	TSI	A major volcanic eruption can trigger multiple hazards near the volcano and impact broader areas, such as volcanic ash clouds disrupting air traffic: The Eyjafjallajökull Eruption in 2010
5	EQ	WS - FL	4da	HIN	SOH	TCO	The occurrence of an earthquake in an area, followed by a storm that produces floods which impact a society already impacted by a previous event. Example: the 2021 7.2 Haiti earthquake was followed four days later by Tropical Depression Grace.
6	EA- TS	TA	1ho	HCA	SNO	TSI	NaTech example. An earthquake caused a major tsunami, which resulted in electrical grid failure backup energy supply of a nuclear power plant. The inability to cool the reactors resulted in a nuclear accident. Example: Fukushima disaster 2011
7	EQ	LS	1mi	HTC	SOH	TSI	An earthquake in a mountainous region triggers many landslides, which also damage the built environment at the same time as the earthquake damage. Example: Turkey 2023
8	EQ - LS	FL	1mo	HCA	SSP	TCO	Earthquake-triggered landslides might be so large that they dam a river and cause temporary lakes, which might grow within a short period of time, before a dam break occurs and a massive flood affects areas that were not heavily impacted by the earthquake. Example: 2018 Wenchuan earthquake, China.
9	WS -- ER	LS DF FL	1da	HTC	SOH	TSI	Tropical storms can cause extreme wind, and rainfall. The extreme wind can cause a storm surge in a coastal area, and uproot trees. Extreme rainfall can cause pluvial flooding and flash flooding, which may interact with the storm surge, causing more extreme flooding. Extreme rainfall might also trigger landslides, which can mix with the rainfall runoff causing debris flows. The resulting debris might be transported downslope and cause blockage of culverts and bridges, leading to even more intense flooding. Example: tropical storms in the Philippines
10	TS -LS FL- WI	TS -- LS FL - WI	1ye	HIN- HTC	SOH	TCO	One year after the impact from tropical storm Erika, which caused extensive flooding and landslides, that impacted on the transportation network, the area is impacted again by a hurricane. Example: Erika (2015) and Maria (2017) in Dominica
11	FF	LS -- DF - FL	0.5ye	HPC	SOH	TCO	Forest fires, windstorms, or insect infestations might have a large impact on the vegetation cover within hilly and mountainous regions, making the soil more exposed and changing the soil characteristics, so that the likelihood of flash floods and landslides is increased. Example: 2022 California Forest fires followed by debris flows and floods.
12	ER	FL	1we	HCO	SNO	TSI	Extreme rainfall caused flooding in several countries in Europe during the same period, such as United Kingdom, Austria, Belgium, Croatia, Germany, Italy, Luxembourg, the Netherlands, and Switzerland. Example: 2021 European Floods
13	HE - DR	FL	1mo	HCO	SOH	TCO	The combination of hot and dry events followed by extreme rainfall is a phenomenon that is linked to the rapid onset of the summer monsoon. Example: Damage to crops by drought and floods in Pakistan in 2022
14	TE - ER	FL	1da	HCO	SOH	TSI	Rain-on-snow (ROS) flood events. Example: June 2013 flood in Alberta, Canada, that was the costliest natural disaster in Canadian history.
15	EQ WS	LS FL	100y	HCO	SOH	TDI	Multi-hazard assessment for all districts considering all hazard types, frequencies and elements-at-risk. Example: Tajikistan Multi-Hazard Risk Assessment

6 Outliers – The importance of low frequency and high impact events

High Impact Low Probability (HILP) events, often referred to as "Black Swan" events (Taleb 2007) or "Dragon Kings" (Sornette 2009), represent rare occurrences with potentially catastrophic consequences. These events are difficult to predict due to their low occurrence rate and complex causation, yet their environmental, and socio-economic impacts can be profound. Understanding the mechanisms behind HILPs is essential for developing robust disaster management and resilience strategies. Stratigraphical information and dating or other records, such as geological cross-sections or sediment deposits can provide valuable insights into the frequency and magnitude of HILP events like large landslides, glacial lake outburst floods, volcanic eruptions, hurricanes or extensive wildfires.

HILPs are characterized by their rarity, catastrophic societal impacts, and unpredictability, often resulting from complex interactions between multiple hazards. These events often involve cascading failures, compounding hazards, or the confluence of multiple smaller hazards that can escalate into a catastrophic outcome. Traditional disaster preparedness frameworks focus on likelihood and cost-effectiveness, creating a challenge when facing HILPs, where the probability of occurrence is highly uncertain. The challenge lies in justifying investments in prevention and mitigation for events that are both uncertain and unprecedented.

As described by the AGILE project (www.project-agile.eu/), HILPs often involve unforeseen risks that exceed conventional preparedness frameworks. These include cascading or compounding events, where multiple hazards interact to amplify impacts. Examples include large-scale disasters, such as the 2004 Indian Ocean tsunami, and anthropogenic crises, such as the 2008 global financial collapse. These events underscore the importance of considering not just individual hazards but also the interactions and feedback loops between them. For instance, a small-scale landslide, coupled with heavy rainfall and a poorly maintained dam, could escalate into a glacial lake outburst flood in a respective environment (Peng et al. 2023). Similarly, a cyberattack on critical infrastructure could cascade into widespread economic and social disruption.

The socio-cultural context and historical memory of past events significantly influence societal vulnerability to HILPs. As Pidot (2013) emphasizes, risk perception diminishes over time, leading to inadequate preparedness. This is particularly evident in regions with long intervals between events. For instance, the Ahr Valley floods in Germany (2021) highlighted how communities struggled to cope with the extreme rainfall, despite the event being theoretically predictable.

Considering this, impact chains can guide future disaster management strategies by showing hazard interactions and vulnerabilities encompassing societal factors of past events. Focusing on the details of some large-scale events such as the Valencia floods Spain 2024 (ESA 2024), Wildfires Hawaii 2023 (Rowan et al. 2023), Ahr valley flood Germany 2021 (Wenzel et al. 2024), Fukushima 2011 or the Katla eruption 1755 shows that also small events, when occurring in combination or sequence, can magnify risks and lead to HILPs. The 2011 Tōhoku earthquake in Japan triggered a tsunami, leading to the Fukushima nuclear disaster (Pescaroli & Alexander 2016). Urban flooding in areas with inadequate drainage systems can exacerbate public health crises by spreading waterborne diseases (Di Baldassarre et al. 2015). Financial market collapses, such as the 2008 subprime mortgage crisis, demonstrate how small-scale imbalances can cascade into global economic turmoil (Bussière & Fratzscher 2008).

Time and space of occurrence matters, as we see examples such as a recent (June 2023) rock avalanche collapse of the Fluchthorn mountain in the Austrian Alps, where 100.000 m³ of material were displaced and lowered the mountain peak for several meters (Krautblatter et al. 2024; Land Tirol 2023). These events highlight the importance of developing scenarios that account for low-probability but high-impact events considering the “what if” in another area, at a different time.

Such interconnected risks necessitate a systems-based approach to understanding and preparing for HILPs. However, the reliance on historical data alone may lead to a false sense of security, as emerging risks—such as cybercrime and advanced technological failures—do not have historical precedents. Emerging risks, such as solar storms and cyberattacks, present new challenges for disaster management. A severe solar storm, while historically rare, could now cause widespread technological and economic disruption due to societal dependence on electricity and communication networks (Pescaroli et al. 2024; AGILE).

Traditional risk matrices struggle to account for the dynamic and systemic nature of HILPs, particularly in the "medium risk" category, where preparedness is often insufficient (AGILE Project; Taleb 2007). Now the challenge is to keep guidelines, frameworks and assessments usable for practitioners in decision making positions. As described by Cohen et al. (2021) it is possible to calculate the probability of very unlikely events by using the semi variance and the average. However, this is far from practical. Therefore, we propose a shift from quantitative to semi-quantitative approaches with tools such as scenario-building in form of impact chains, based on past experiences and additional future prognoses to help visualize potential outcomes and inform decision-making ([PARATUS Deliverable 1.1](#)). For example, the federal office of civil protection and disaster assistance in Germany prepares for mass casualty incidents through scenario-based exercises (BBK 2024), while the financial sector employs early warning systems to mitigate market imbalances (Bussière & Fratzscher 2008). Systemic risk assessment tools such as Bayesian networks and agent-based modelling can simulate cascading failures and compounding risks (Pescaroli & Alexander 2016).

HILPs are increasingly recognized in international policy and legislation. European legislation emphasizes the need for proactive measures to address low-probability, high-impact risks. Similarly, the IPCC (2018) highlights the role of compounding and cascading hazards in shaping HILP outcomes. Addressing such risks requires forward-looking policies and investments in resilience.

HILPs pose unique challenges that demand a proportional assessment that considers contextual factors, rather than relying solely on traditional metrics like economic costs or fatalities. By including historical insights, addressing emerging risks, and adopting innovative assessment methodologies, resilience can be enhanced to these rare but catastrophic events. Improved collaboration between policymakers, practitioners, and researchers will be essential in navigating the uncertainties and complexities of HILPs (see Section 9 referring to Stakeholders).

7 Examples of hazard interaction assessments

Hazard interrelations are profoundly influenced by environmental contexts, with different settings showcasing unique patterns of interaction. This chapter explores examples of hazard interrelations and their assessment in urban, island, and mountainous environments, providing a comprehensive view of how these dynamics can manifest. Each example highlights key hazard in specific settings, their potential interactions, and available frameworks or guidelines for documenting and analysing these relationships. Specific topics within each study site are examined in depth, shedding light on the practical challenges and solutions in understanding hazard interactions.

a. Bucharest

In the Bucharest Case Study, earthquakes, earthquake-triggered fires, and dam-break floods are the main hazards expected to interact within a cascading hazard framework. Considering the significant impact of earthquake-flood interactions, we aim to model the potential effects of a flood caused by the failure of the Ciurel Dam at the Morii Lake in the event of an earthquake over 7 M_w . In addition, we acknowledge the need to further investigate potential interactions between earthquakes and fires, and earthquakes and future pandemics or pandemic waves of COVID-19.

By damaging lifelines and buildings, earthquakes can trigger fires in various locations in the capital city of Romania, leading to a hazard interaction that is typical of major seismic events. Historical records document such instances in Bucharest, with fires reported during historical periods (1100-1900), and in the aftermath of more recent major earthquakes, like the ones in 1977 (7.4 M_w) and 1940 (7.7 M_w). Prior to the 20th century, most buildings in the capital were wooden-made and used stove heating. These particularities of the building stocks represent physical vulnerabilities that contributed to the impacts of the fires triggered by the collapse or damage of chimneys or stoves. In the case of winter earthquakes, a notable impact of such damages was the CO₂ poisoning, which mainly affected the poor population living in one room. The frequent occurrence of fires in Bucharest motivated the establishment of fire protection services in the 17th century, with the first military fire department created in 1845. More recent earthquakes are associated with greater tragedies: in 1940, the collapse of the Carlton building was followed by a major fire caused by the ignition of a fuel spill from a damaged reservoir. The fire killed the survivors trapped under debris in the building basement, who had been communicating with rescuers by telephone and were expecting salvation (Sima, 1982). Another example refers to the thermo-electric Bucharest West plant, where an explosion was prevented after the roof collapsed during the 1977 earthquake (Buhoiu, 1977).

Although no earthquake-flood interactions have been reported in Bucharest in the past, such cascading mechanisms can unfold and cause major destruction. A powerful earthquake can damage the water infrastructure in Bucharest (PAAR, 2024), which would result in the flooding of a significant area of the city. The Morii Lake lies in the Northwest of Bucharest, on the Dâmbovița River. It was built in 1985, as part of the hard engineering infrastructure that aimed to control river floods. Approximately 18.7 million m³ of water are held back by the 15 m-high Ciurel Dam, and releasing such a large volume would lead to massive flooding.

To develop scenarios for the earthquake-flood interactions, the PARATUS team at the University of Bucharest considers an earthquake-triggered 1) failure of the Ciurel Dam, and 2) breach in the levee surrounding the

Morii Lake. The hydraulic modelling was implemented in the HEC-RAS 6.4.1. software, employing a LiDAR digital terrain model, bathymetric data from the reservoir, surveyed critical cross-sections of the Dâmbovița River, as well as exposure data (e.g., footprints of the buildings in the floodplain). A full 2D model was used to accurately represent overbank flows and flooding extents in the urban area, covering the river from upstream of the Morii Lake to the South-eastern boundary of the city. Key hydraulic structures (e.g., the Ciurel Dam, the Unirii Underpass, and levee infrastructure) were considered in the model: a simulation of seepage failure triggered by piping and followed by the collapse of the Ciurel Dam; the reduction of the flow capacity of the Unirii Underpass and water diversion above ground; and a 300-meter-long breach in a levee surrounding the Morii Lake, nearby the Giulești neighbourhood.

It is worth noting that the Bucharest Plan for Analysis and Coverage of Risks (ISU-BIF, 2024) mentions multiple similar scenarios for the Ciurel Dam failure and breach in the levee (acknowledging the potential problem) but does not explain the hazards that could contribute to its damage.

Another shortcoming refers to the fact that the seismic risk often encompasses only the dimension of losses due to direct damage to buildings, but even here, too, non-structural damage and indirect damage have not been taken into account so far in the scenarios focusing on Bucharest, and in economic terms, reconstruction costs have often been considered.

An additional disaster scenario involving hazard interaction is the occurrence of a major earthquake (similar to the one in March 1977) during a pandemic wave (similar to the one in March 2021). To investigate this seismic-epidemiological hazard interaction, we have developed an Impact Chain focused on the effects of the COVID-19 pandemic on the hospital network in Bucharest (2020-2022). An additional Impact Chain will be built to account for the pandemic impacts at the level of Fundeni Hospital, which will serve as a case study. This Impact Chain methodology will be integrated with a simulation of the accessibility to the primary hospital units in Bucharest, including the Fundeni Hospital, in the event of an earthquake exceeding 7 M_w . The earthquake is expected to cause the collapse of vulnerable buildings, with debris blocking the streets and restricting the access to both intervention points (i.e., collapsed buildings) and hospitals, ultimately limiting first response. The findings can be used as entry points for designing contingency plans for providing health care to the earthquake victims and for developing disaster management plans at the hospital level.

The combined impact of an earthquake and a flood on contemporary traffic would have significant implications, particularly for accessibility, travel times, and first-response capabilities. Bucharest, ranked as one of Europe's most congested cities (Tom-Tom, 2023, <https://www.tomtom.com/traffic-index/ranking/>) faces heightened vulnerability in such scenarios, as highlighted by recent studies, which is planned to be incorporated into further research (Toma-Danila et al., 2022).

Such hazard interaction assessments are without precedent in the Bucharest Case Study and Romania, positioning the proposed model as pioneering research work. The study of hazard interactions is mainly the job of academics and researchers, on whom emergency management services rely for the provision of the scientific input upon which to build disaster management guidelines.

In the absence of results on earthquake-flood or earthquake-fire interactions, the Disaster Risk Management (DRM) guidelines in Romania currently lack provisions for multi-hazard situations. Instead, each hazard is addressed by its own set of measures outlined in legally binding guidelines. The core organisations in charge of DRM are the Ministry of National Defence, the Ministry of Internal Affairs, the General Inspectorate for Emergency Situations, and the Department for Emergency Situations. Also, the Health Ministry and the Red Cross may provide medical support as part of disaster management.

These institutions collectively coordinate disaster responses within the legal framework that regulates DRM with respect to individual hazards, without considering hazard interactions. Therefore, the presented siloed

approach leaves disaster management services unprepared in the face of multi-hazard situations. A telling example comes from the co-occurrence of powerful river floods across Romania in 2020 and 2021 and the COVID-19 pandemic. In this regard, Albulescu (2023) notes that the flood management procedures did not consider the pandemic context, which may have contributed to the increase in the COVID-19 viral load at county level, 14 days after the flood event, aligning with the SARS-CoV-2 virus' extended incubation period. This was observed in nearly all counties (with a single exception) where the floods necessitated the evacuation of the population. As there is no official information on the COVID-19 preventive measures implemented in temporary emergency shelters where the evacuees were accommodated or during the transportation operations, it is difficult to establish a definite causal link between the flood events and the increases in the number of positive cases (Albulescu, 2023).

The study exposes the limitations in managing the impact of one hazard in a conventional manner that overlooks the added complexity introduced by a co-occurent hazard. Furthermore, the COVID-flood-related example highlights that unforeseen impacts can result from subpar management practices reliant on regulations that disregard evolving contexts, leading to more complex and therefore harder-to-manage crises.

Given the increasingly frequent co-occurrences or cascading progression of multiple hazards, each having particular impacts and underlying vulnerabilities that interact and are constantly changing, a pressing need has emerged related to the development of multi-hazard management guidelines in Romania and other EU countries. These guidelines must consider the distinct yet complementary responsibilities of the emergency management organisations, which, in turn, are called to enhance collaborative capabilities in order to effectively tackle the new challenges imposed by different simultaneous or cascading hazards. Until comprehensive guidelines are elaborated or validated, the expertise of higher-ranking first responders and their on-site presence can compensate for the gaps in the guidelines. The literature has noted the great capacity of emergency intervention services to respond with clever solutions to emerging issues (Fekete et al., 2023; Armaş et al., 2024).

Such advancements are not possible without firstly studying and understanding hazard interactions and their cross-sectoral implications. The research conducted by the PARATUS team at the University of Bucharest addresses these necessities, as its outputs contribute to hazard interactions guidelines and subsequently inform policymaking and decision-making, ultimately supporting the development of scientifically grounded multi-risk management guidelines.

b. Istanbul

Istanbul, situated in a seismically active zone along the North Anatolian Fault, faces complex challenges due to its spatial, economic, and systemic interconnections. With a population exceeding 16 million, the city contributes 31% of Türkiye's GDP, including 40% of the national services, 65% of internet technologies, and 59% of financial activities, while generating 30% of the country's tax revenue. The city's critical infrastructure, dense population, and economic significance amplify the potential for cascading impacts of hazard interactions during a major earthquake. This makes Istanbul's seismic risk management critical not only for the city but also for the entire nation.

Istanbul, as an earthquake-prone megacity, presents significant challenges due to its spatial complexity, sectoral interdependencies, and systemic connectivity. Historical and contemporary seismic events illustrate the interconnected nature of hazards triggered by earthquakes in the region. For instance, a significant earthquake may lead to secondary hazards, such as landslides and tsunamis, which compound the primary

disaster's effects. As part of the PARATUS Project, two learning case studies have been analysed to anticipate the potential impacts of a probable earthquake along the North Anatolian Fault, which could significantly affect Istanbul. The 1999 Kocaeli Earthquake and the 2023 Kahramanmaraş Earthquakes demonstrated how seismic events can cause widespread infrastructure failures and economic disruptions, cascading through transportation networks, energy systems, and communication lines.

The 1999 Kocaeli Earthquake (Mw 7.4), which occurred approximately 90 km east of Istanbul, caused over 17,000 casualties and \$6–11 billion in economic losses. Despite its distance from Istanbul, the earthquake severely impacted the city's infrastructure and raised awareness of its seismic vulnerabilities. At that time, Istanbul's population was under 10 million, whereas today, the city accommodates over 16 million residents, alongside significant numbers of daily commuters, refugees, and tourists. On the other hand, seismic activities in February 2023 resulted in a fault rupture spanning over 300 km along the left-lateral East Anatolian Fault. These seismic events impacted 11 provinces in Türkiye and affected over 14 million people. The devastation caused extensive collapses and damage to various structures, including buildings, bridges, airports, tunnels, hydraulic facilities, lifelines, and network systems. Over 90,000 reinforced concrete structures sustained severe damage, resulting in more than 53,000 casualties (MoEUCC, 2023; SBO, 2023). The region exhibited extensive damage across numerous structures.

With 20–40% of pre-2000 buildings requiring retrofitting, structural collapses could trigger further hazards, such as gas leaks, fires, or blocked evacuation routes. Transportation, water supply, and energy systems are interdependent, meaning failures in one can disrupt the others, complicating emergency responses. Damage to Istanbul's financial and technological hubs could therefore disrupt national services, amplifying the consequences beyond the immediate disaster zone.

Istanbul's seismic history spans over two millennia, with records indicating that the city has experienced at least one moderate-intensity earthquake (I_0 =VII-VIII) approximately every 50 years (Ambrassey & Finkel, 1991). The earliest documented earthquake dates back to 32 B.C., and notable historical events include those in 1509, 1719, 1766, and 1894, all originating along the North Anatolian Fault. The 1509 earthquake caused widespread destruction, particularly along the northeastern coast of the Marmara Sea. In Istanbul, it demolished fortifications, mosques, and over 1,000 houses, resulting in 4,000–5,000 deaths and 10,000 injuries. A tsunami exacerbated the damage, and reconstruction efforts favoured wooden buildings due to their perceived resilience. The 1719 earthquake, centered near Izmit Bay, heavily affected Istanbul and Izmit, killing 6,000 people and destroying numerous buildings, including 40 mosques and 27 towers. Its impacts mirrored those of the 1999 Kocaeli earthquake in the same region. In 1766, a fault segment from Izmit to Gallipoli ruptured, triggering an earthquake followed by aftershocks and a tsunami that devastated the Marmara coastline. The Topkapı Palace sustained severe damage, forcing the Ottoman Sultan to temporarily reside in a tent. The 1894 earthquake, which struck during the day, caused significant damage, including the collapse of the Grand Bazaar while it was crowded with shoppers and workers. The event was felt across a wide area, from the Balkans to parts of Africa, and local authorities classified its impact into five regions based on severity. These recurring events provide critical insights into hazard interactions that can inform modern risk assessments.

In the Istanbul case, the primary hazard has been defined as an earthquake likely to occur on the North Anatolian Fault with a magnitude greater than Mw7.0. To delineate the triggered hazards, impact chain diagrams developed for the 1999 Kocaeli Earthquake and the 2023 Kahramanmaraş Earthquakes have been utilized. Furthermore, to define systemic risk components resulting from these hazard cascades, two stakeholder workshops were conducted in Istanbul in 2023 and 2024, the latter taking place in Avcılar, which

had been the most affected area by the 1999 Kocaeli earthquake. These workshops gathered participants' perspectives on the impact chain of potential earthquake scenarios, enhanced by adjustments for external factors such as time of occurrence and meteorological conditions. The findings from these meetings highlighted the systemic impacts of earthquake-induced failures, emphasizing how interconnected systems amplify vulnerabilities. As a result, local landslides and inundation caused by tsunamis along the shoreline have been included in the multi-hazard assessment. Within the PARATUS Project, six earthquake scenarios were developed to assess these hazard interrelations. The type of relations are in most cases cascades triggered by one event and spatially overlapping. These cascading impacts described by the following scenarios are based on timing, weather, and demographic patterns:

1. Earthquake during an extreme rainfall event in Autumn

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.
- **Context:** The timing coincides with the evening rush hour as people leave work and head home. Additionally, many households are engaged in preparing dinner.
- **Implications:** High traffic congestion is expected, potentially complicating emergency response. Indoor occupancy rates are high, increasing the risk of casualties from building collapses.

2. Earthquake during Night-time in Regular Weather (Weekday, 03:00-05:00)

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.
- **Context:** During these early morning hours, most people are likely at home asleep, and roads are relatively clear due to minimal traffic.
- **Implications:** The risk of immediate casualties is higher for individuals in unsafe buildings. However, clear roads may facilitate faster emergency response.

3. Earthquake on a Sunny Afternoon on a Weekend (14:00-16:00)

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.
- **Context:** Favourable weather encourages outdoor activities, shopping, and social gatherings. A significant portion of the population is present in entertainment and commercial areas.
- **Implications:** Increased human mobility leads to slow-moving traffic, which may hinder evacuation and emergency operations. Crowds in public spaces may experience structural collapses or stampedes.

4. Earthquake on a Snowy Afternoon on a Weekend (14:00-16:00)

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.
- **Context:** Heavy snowfall keeps most people indoors, reducing outdoor activity.
- **Implications:** Although roads may be less crowded, poor weather conditions could delay emergency services. Indoor risks are elevated for residents in substandard housing.

5. Earthquake on a Summer Holiday Season (Weekday, 13:00-16:00, July or August)

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.

- **Context:** A significant portion of city residents is away on summer vacations. Local populations are supplemented by high numbers of domestic and international tourists. The weather is ideal for outdoor activities such as sightseeing and hiking.
- **Implications:** Tourist-heavy areas may see high casualty rates due to unfamiliarity with emergency protocols. Reduced residential population may decrease strain on local emergency services.

6. Morning Routine on a Weekday (09:00-10:00)

- **Event:** An earthquake with a magnitude greater than Mw7.0 occurs along the North Anatolian Fault.
- **Context:** Normal weather conditions prevail. Employees are at workplaces, and students are attending schools. The morning rush hour is starting to ease.
- **Implications:** Crowded office buildings and schools could lead to significant casualties and injuries. Road networks are relatively free, facilitating the movement of emergency services. Schools and offices with good emergency plans might mitigate risks effectively.

These scenarios underline the interplay between both hazard and exposure as well as vulnerability parameters and reveal distinct challenges for emergency preparedness, response, and recovery planning. By accounting for such variations, urban risk assessments and disaster management strategies can be fine-tuned to bolster resilience and reduce losses.

c. Caribbean

The Caribbean region is particularly vulnerable to a wide variety of natural hazards due to its geographical location, climate, and socio-economic conditions. The most important group of hazardous phenomena are hydro-meteorological hazards, and in particular hazards related to tropical storms (Hurricanes). The islands of the Caribbean face risks from tropical storms, coastal erosion, drought, earthquakes, volcanic eruptions, and tsunamis, which often overlap to create complex multi-hazard scenarios. These hazards pose direct threats to human life and result in significant economic and environmental damage, exacerbating existing vulnerabilities in the region.

The frequency and intensity of natural disasters have increased over the past few decades, placing immense pressure on local governments and communities. The region has experienced an average of US\$1.6 billion in direct damage per year due to natural disasters over the last 20 years (World Bank 2018).

The Caribbean's geographic location along active tectonic plate boundaries and within the Atlantic hurricane belt exposes it to a range of geological and meteorological hazards. The region's islands, from the larger Greater Antilles to the smaller Lesser Antilles, are susceptible to tropical cyclones, which bring destructive winds, storm surges, and heavy rainfall. Furthermore, climate change has exacerbated the intensity and frequency of such events, leading to rising sea levels, increasing temperatures, and more severe weather patterns.

The Caribbean also sits near the boundary of the Caribbean and North American tectonic plates, making it prone to significant seismic activity and volcanic eruptions from active volcanoes in the Lesser Antilles. These natural forces and the region's socio-economic vulnerabilities create a complex hazard landscape that requires integrated and comprehensive disaster risk management approaches.

What sets the Caribbean apart is the region's exposure to multiple hazards simultaneously or in rapid succession. For instance, a tropical storm may trigger secondary hazards such as landslides or flooding, while an undersea earthquake could trigger a tsunami and impact volcanic systems. The intersection of these hazards and socio-economic factors like population density, poverty, and inadequate infrastructure increases the overall risk and complicates disaster response efforts.

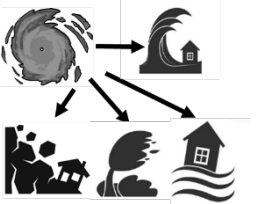
In this multi-hazard context, adopting a holistic risk assessment and management approach is crucial. Effective multi-hazard risk assessment requires a comprehensive understanding of how different hazards interact and compound one another and the vulnerabilities that increase a community's exposure to these hazards. Such an approach allows for more targeted disaster risk reduction (DRR) strategies, better preparedness, and more resilient infrastructure development.

Hydrometeorological and climate related hazards (e.g. tropical cyclones, floods, landslides, droughts, heat waves) have impacted the Caribbean extensively. Given the interrelationships among these hazards, the impact on a whole is expected to surpass that of each hazard. Therefore, it is essential that within the multi-hazard risk framework, these interrelationships are considered with respect to timing and their impact on varying spatial scales. Notwithstanding, it is important to understand the impacts associated with independent events to better appreciate the reality of the expected impact of simultaneous, cascading, consecutive, overlapping and compounding events.

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. To simplify the above-mentioned classification for applicability in the Caribbean, we propose the following three-class classification (See Figure 3).

It is essential that within the multi-hazard risk framework, the hazard interrelationships are considered with respect to timing and their impact on varying spatial scales. It is important to understand the consequences of independent, simultaneous, cascading, consecutive, overlapping and compounding events. Tables 5, 5 and 7 give examples of hazard interrelations from the Caribbean in relation to the types presented in tables 1 to 3.

Table 5: *Examples of the main types of hazard type interrelations in the Caribbean*

Hazard type interrelations	Example	
Independent	Earthquakes and tropical storms have different trigger mechanisms	Haiti: Earthquakes (2010, which killed between 100,000 and 316,000 people) and floods (e.g. 2016 Hurricane Mathew, which killed 580 people and left 35,000 left homeless) 
Triggering	Landslides and floods occur as a result of the same triggering rainfall event.	2017 Hurricane Maria in Dominica caused extensive flooding, storm surge, wind and landslides. 
Cascading	An volcanic eruption may trigger a tsunami which causes coastal flooding	In 1939 an eruption of the submarine volcano Kick-em Jenny 

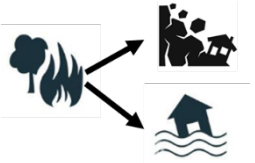
		cased tsunamis in Grenada and Saint Vincent and the Grenadines.	
Conditioning	Forest fires change the soil conditions, increasing the susceptibility to floods and landslides.	Forest fire seasons in 2023 and 2024 in Cuba followed by rainfall events, causing flooding in burned areas.	

Table 6: Examples of the main types of spatial multi-hazard interrelations in the Caribbean

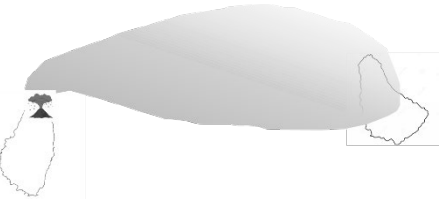
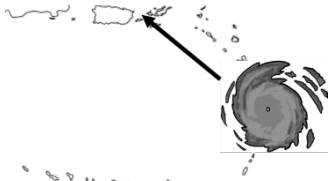
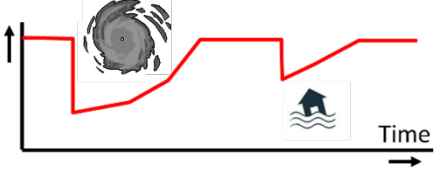
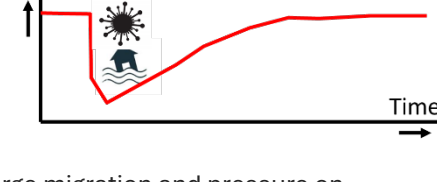
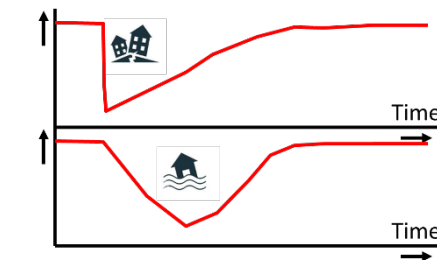
Spatial hazard interrelations	Example		
Overlapping	During a hurricane the same area might be affected by different hazards (e.g. wind, storm surge and flashflood).	For example, hurricane Irma 2017 in Saint Maarten	
Source and spread	A volcanic eruption can cause hazardous processes that reach to areas far away from the volcano.	The 2021 Soufriere eruption in Saint Vincent, causing ash cloud affecting air traffic over Barbados.	
Cross-border	Major hurricanes affect a number of countries and require collaboration for the hazard assessment		
Not-overlapping	Wildfires in one island, floods on another and drought on a third.		

Table 7: Subdivision of the main types of spatial multi-hazard interrelations

Temporal hazard interrelations	Example	
Events occur after a long time	An hurricane of which damage is repaired within several years is followed by a flood after many years	Hurricane David in 1979 and Storm Erika in 2015 
Consecutive events	An earthquake is followed by a tropical storm occurring during the recovery period of the previous event.	The earthquake and tropical storm that affected the Southwest of Haiti in 2021 
Simultaneous/C concurrent events	The occurrence of a flood event during the COVID pandemic resulted in large migration and pressure on hospitals	For example, the impact of the COVID-19 pandemic resulted in large migration and pressure on hospitals, which worsened during the events in June 2021, in Saint Vincent 
Onset speed	Slow-onset: droughts or pandemics, Fast-onset ones: flash floods, earthquakes.	

It is important to consider this combination of the interrelation between the type of hazard, the temporal aspect, and the spatial aspect in order to select the best approach for multi-hazard and risk assessment. In order to simplify the above-mentioned classification for applicability in the Caribbean, we propose the following classification (See Figure 3).

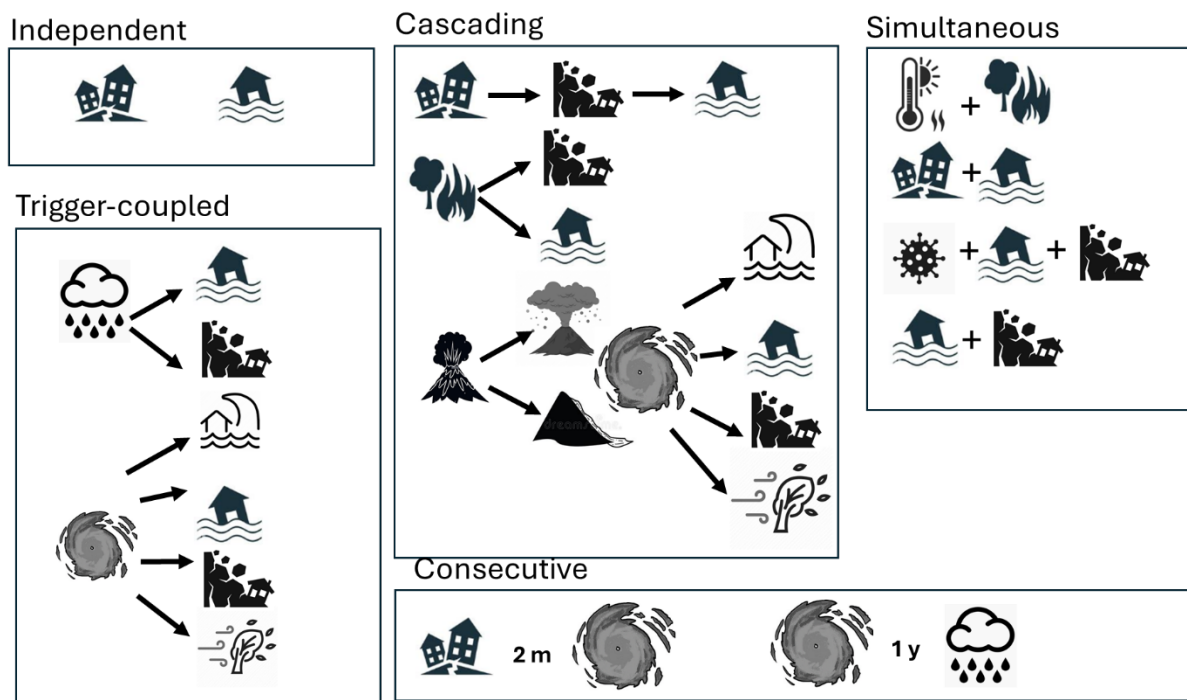


Figure 3: Simplified classification of hazard interactions in independent, compounding, and cascading events (Van Westen et al., 2025).

Cascading volcanic and hydrometeorological hazards : the eruption of the Soufriere volcano in Saint Vincent (See Figure 4). The 2021 event consists of multiple hazards between two events: a volcanic eruption and a tropical cyclone (Hurricane Elsa). Each of the hazard might interact and resulted in secondary hazards. According to eruption processes of La Soufrière and timeline of the 2021 event in Section 3.1, as well the hazard interaction classification mentioned in Section 2.1, the interaction between hazards of the 2021 event are concluded as Independent and Cascading (Domino).

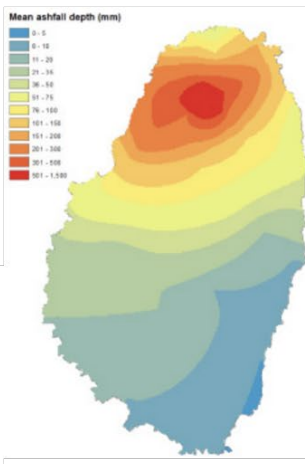
A volcanic eruption and a tropical cyclone both have different trigger factors, which makes them have an independent interaction. However, for some volcanic hazards, their occurrence happened in a certain way by the cause of meteorological component of tropical cyclone. For instance, lahar occurrence and the rainfall associated with the tropical cyclone. Although lahars happen regardless the presence of tropical cyclones, heavy rainfall caused by the tropical cyclone could cause more intense and frequent lahar events.

The identification of hazard interaction defines how an impact occurs or worsened after the event happened. For instance, damage on buildings due to ashes was worsened with the damage from the wind and rain. Another example is the frequency and intensity of lahars that was increased, leading to more damage to the bridges because the bridges are more exposed to heavier load from the lahars. However, a mutual exclusion impact could also happen. According to an interview with an engineering from the Ministry of Transportation and Works of Saint Vincent and the Grenadines, there are houses that were prevented to being destroyed by the strong wind because the combination between ash load and rainfall strengthened the roofs. By identifying the interaction, the impact assessment can be more thorough, and more perspective can be considered.

Ash cloud



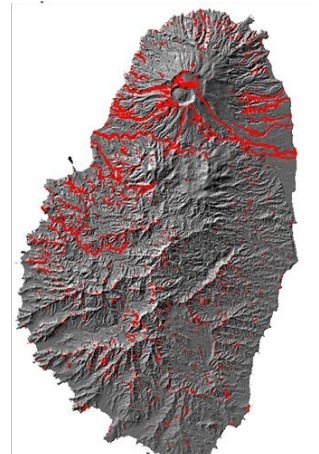
Ash fall deposits



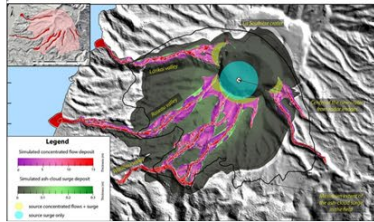
Lahars



Mapping hazardous phenomena from high resolution satellite



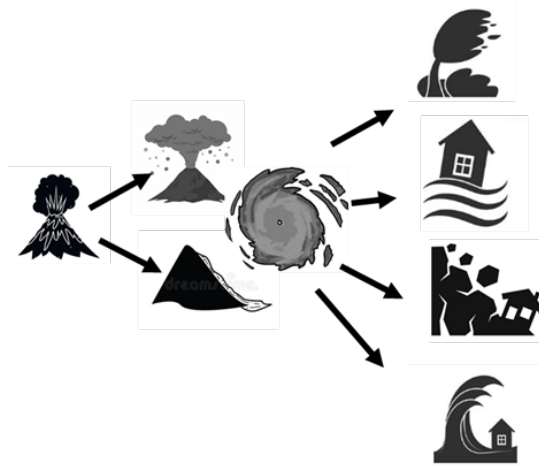
Pyroclastic Density Currents



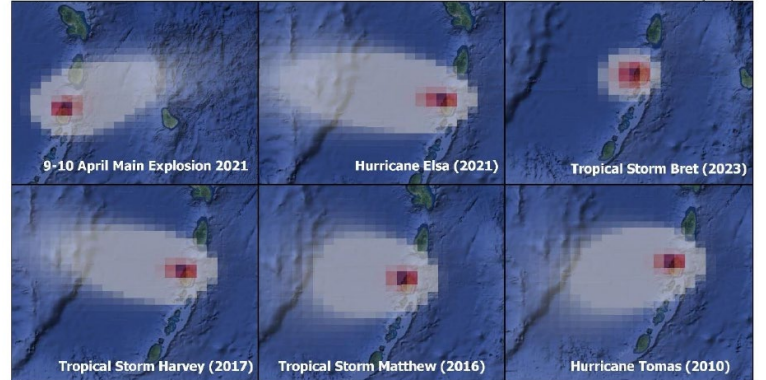
Source: UWI Seismic

Source: World Bank GFDRR

Source: Van Westen et al.



Tephra Mass Loading under Different Scenarios



Lahar Model La Soufriere Comparison with Ground Observation

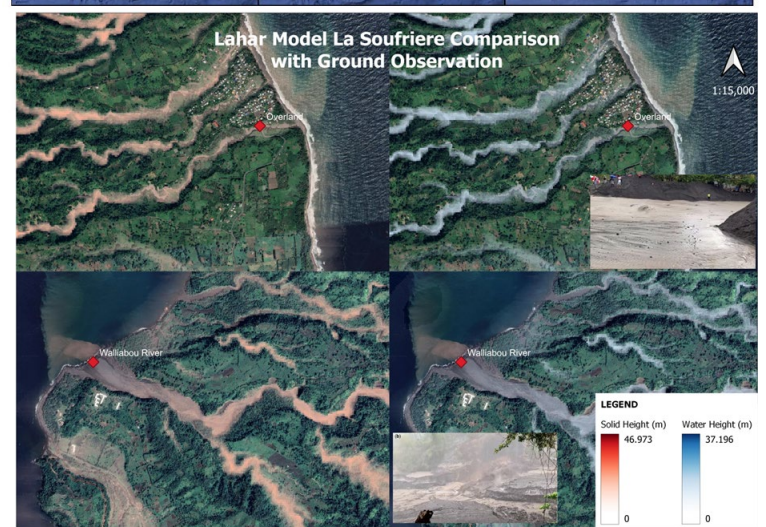
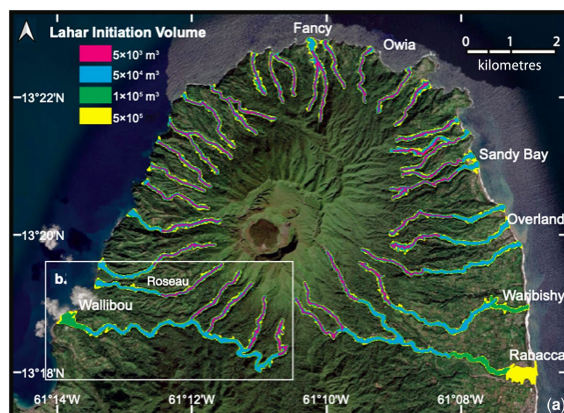


Figure 4 Gives an example of compounding events in Saint Vincent

d. Alps

The Wipptal valley, within the PARATUS application site Alps, connects Bozen (IT) – Innsbruck (AT) and serves as a focal point for examining the complex interactions and interrelations of natural and anthropogenic hazards. This region is particularly susceptible to gravitational movements and flooding, which are compounded by human-induced challenges. A major area of concern is the heavy traffic through the valley, which not only exposes large numbers of people to existing natural hazards but also generates new risks. For instance, in remote areas, traffic congestion can delay the arrival of first responders during emergencies. Adverse weather conditions further exacerbate these challenges. The Wipptal frequently experiences severe weather influenced by Genoa low-pressure systems or föhn winds making helicopter deployments difficult.

One key focus in this application study is the critical transport infrastructure, including railways, roads, and highways, which are managed by operators such as the Austrian Federal Railways (ÖBB), ASFiNAG and the federal state of Tyrol. Given the increasing impact of natural hazards, ASFiNAG, Austria's motor- and expressway operator, places particular emphasis on managing risk arising from such events. Therefore, ASFiNAGs guided by a legal framework that emphasizes its responsibility to minimize risks to life, property, and operational continuity. This framework ensures that risk management decisions are made within established thresholds, reinforcing a structured approach to hazard management. By adhering to this framework, ASFiNAG ensures that safety is prioritized and managed effectively across all operations.

ASFiNAG's natural hazard management practices focus on mitigating risks posed by gravitative mass movements, which could endanger its infrastructure and users. Its "Natural Hazard Management Handbook" serves as the foundational framework, employing a risk-based approach aligned with ISO (International Organization for Standardization), including specific series such as ISO 31000. ISO is a global organization that develops and publishes international standards to ensure quality, safety, efficiency, and consistency across various institutions. ISO 31000, in particular, outlines a systematic and structured approach to risk management, offering comprehensive guidelines for identifying, assessing, and addressing risks across diverse operational contexts (ISO 2018). On a national level, ÖNORM standards, published by the Austrian Standards Institute (ASI), provide Austrian-specific guidelines for various fields, ensuring alignment with the country's unique regulatory and safety requirements. Among these, ÖNORM D4900 plays a key role in complementing international standards, by offering frameworks for integral risk management systems. This series includes practical guidance on implementing structured risk assessments, integrating risk management with existing operational and safety systems, and establishing clear objectives, responsibilities and processes to enhance decision-making and on-term planning (Austrian Standards 2021). Together, the international ISO standards and the Austria-specific ÖNORM guidelines ensure ASFiNAG's natural hazard management approach is both globally informed and locally relevant.

This current approach applied by the ASFiNAG is systematic, involving thorough hazard and risk analysis in phases of prevention, response, and recovery. Hazard indication maps, based on terrain analysis, historical data, and site inspections, help prioritize areas for intervention. Technical solutions, such as rockfall barriers, and organizational strategies, including emergency interventions, form the response strategy. Those protective structures are designed according to ONR 24800, again an Austrian standard that provides guidelines for planning and maintaining mitigation systems. This standard categorizes structures, like rockfall nets and terrain-stabilizing measures, based on their function and impact, ensuring a consistent and effective

approach to risk reduction. Risk assessments use benchmarks like the individual fatality probability of 1×10^{-5} per year (adapted from Swiss models, ASTRA), ensuring effective risk management. Recovery includes post-event analyses that inform future management improvements.

However, despite the robust single-hazard guidelines, the current ASFiNAG framework does not address the diverse range of multi-hazard scenarios. Since the inception of the PARATUS project, however, several incidents have occurred in the Alpine study area that, upon closer examination, reveal clear interconnections between different hazard types. The following two examples serve to illustrate such multi-hazard dynamics in greater detail.

Flooding and Debris Mobilization in Tyrol: August 27-29, 2023

In this case, the occurrence of a Genoa low-pressure system led to intense rainfall in Tyrol, directly triggering two distinct natural hazards that ASFiNAG was compelled to address. These events underscored the differing risk profiles of the Inn Valley and the Wipptal Valley, the two key sub-sections of the Brenner Corridor.

In the Tyrolean Oberland, situated to the west of Innsbruck, the heavy precipitation resulted in significant flooding, with the Ötztaler Ache representing the primary hotspot, reaching a 100-year flood level (HQ100). Consequently, the water levels of the Inn River downstream were also rising, resulting in an elevated probability of flooding in the Tyrolean Unterland region, spanning from Innsbruck to Kufstein. Here, the Inn reached a flood level that has been observed to occur on average once every 30 years (HQ30), which presented the most significant challenges in the vicinity of Wörgl (Figure 5), where mobile flood protection measures had been deployed. The installation of these required the closure of one traffic lane in the direction of Innsbruck, which resulted in congestion reaching 11 kilometres.

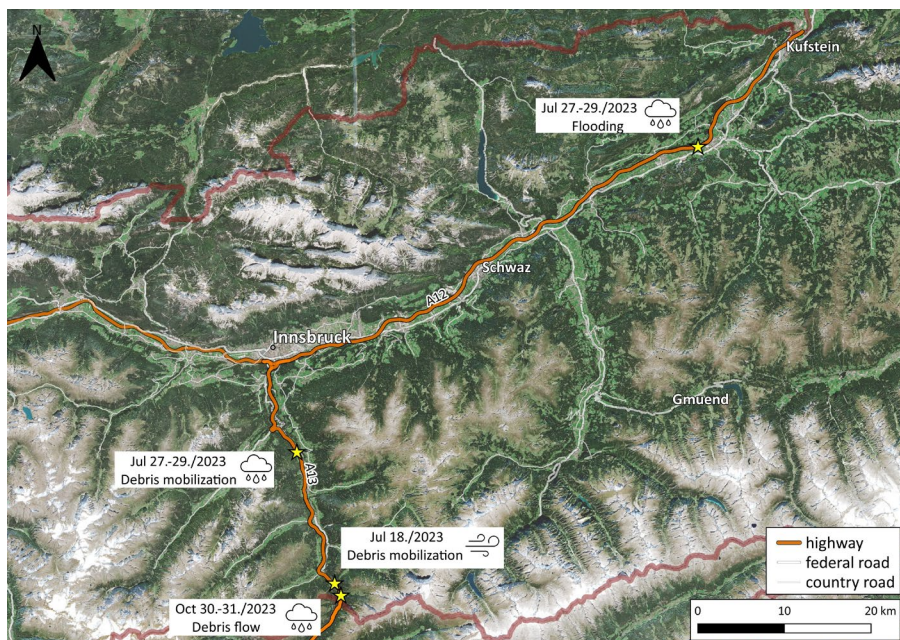


Figure 5: Overview of exemplary cases of events impacting the highway over the past year (2023). The yellow stars indicate the corresponding locations. The red line visualizes to the national border of Austria (Source: BKG 2018, ASFiNAG 2024).

Concurrently, in the Wipptal, the precipitation resulted in the widespread mobilisation of debris across multiple retention basins. ASFiNAG's road patrol teams promptly conducted inspections of critical areas and initiated clearance operations to prevent blockages. In the Matreiwald area (Figure 6), a cascading effect was observed: an upstream debris basin managed by the municipality reached its maximum capacity and overtopped, releasing a significant volume of material downstream. This debris then flowed into a secondary retention basin operated by ASFiNAG, which also required clearing to maintain its protective function. Effective response measures require therefore an understanding of the differing hazards in the region, addressing cascading effects, and coordinating efforts to minimize disruption.

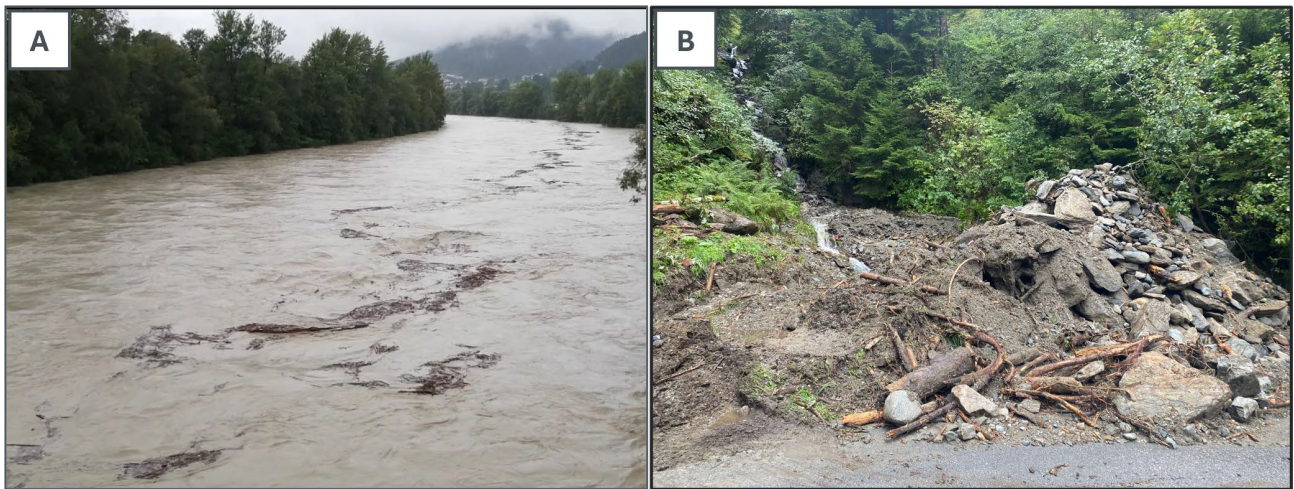


Figure 6: (A) The Inn River during an HQ30 flood event near Wörgl, with large pieces of wood carried by the current, and (B) material cleared from the retention basin after the event.

Debris Flows in the Brenner Region: October 30-31, 2023

On the night of 30–31 October 2023, a series of debris flows occurred in the Brenner region, triggered by intense precipitation. One such event took place on an easterly slope near the Brenner Pass (Figure 7), close to the Austrian-Italian border, directly impacting the highway. Both traffic lanes were initially obstructed by debris (Figure 8), resulting in a full closure of the Brenner highway between 2:50 a.m. and 4:26 a.m. Following this initial closure, extensive clearance operations and field surveys were conducted by federal geologists and ASFiNAG employees to better understand the mechanisms behind the event and ensure road safety. However, one lane in the direction of Innsbruck remained closed until 26 November 2023, reducing capacity on this critical cross-border route.

The analyses revealed that long-term predisposing factors had created the optimal conditions for the debris flow, while the intense precipitation served as the final trigger. An important contributing factor was the extensive windthrow area above the detachment zone, where the loss of protective forest significantly affected rainfall infiltration. The absence of root structures intensified surface runoff, saturating the slope material and increasing instability. Furthermore, two slope failures along a forest road were identified: one with a detachment edge of 20 meters and another with a 5-meter edge, which converged into a single debris flow. These findings suggest that anthropogenic factors, particularly the forest road construction, also played a role in slope destabilisation.

Interestingly, the impact on traffic was relatively low due to the timing of the event. October typically experiences the lowest traffic volumes along the Brenner Corridor, which meant the reduction to a single lane in one direction caused minimal disruption. However, if this event occurred during the peak summer travel season, the cross-border implications and traffic disruptions would have been far more significant. This highlights the critical influence of timing in determining the broader impacts of such events on infrastructure and transnational mobility.



Figure 7: (A) View of the debris flow path (B) Material buried the A13 motorway (C) View of the debris flow path one year after the event (Photos: ASFiNAG 2023, Till Wenzel 2024).

The preceding examples illustrate the necessity of comprehending the underlying causes and the complex interplay of contributing factors to accurately assess potential hazards. It is evident that integrating diverse factors into hazard assessments and especially account for multi hazard interactions is of paramount importance. In particular, the conditioning factors, as discussed in the context of the debris flow above, can be regarded as a case study in learning, whereby the experiences gained are incorporated into future management strategies for natural hazards. In this regard, the severe windstorm that occurred on 18 July 2023 serves as an illustrative example of how these learnings can be applied. During that event, wind records were measured and reached, for instance, 161 km/h at Innsbruck's airport. State-wide, the storm caused damage to approximately 400,000 cubic meters of timber, with the Wipptal being one of the hardest-hit areas. It is of relevance to ASFiNAG that the protective forest above the Lueg Bridge was also impacted, with thousands of trees being felled in a matter of seconds. Fortunately, no trees reached the roadway, and no injuries or damage to vehicles occurred. However, it is evident that ongoing monitoring of this area is imperative. The destabilisation of slopes due to the loss of protective forest markedly elevates the risk of future events, underscoring the significance of integrating such observations into long-term hazard management strategies. While these cascading and compounding events in the Wipptal are not yet extensively described in scientific literature, they are integral to future scenario planning, particularly within PARATUS, WP2.



Figure 9: The image depicts the windthrow area situated above the Lueg bridge. The damaged wood was removed during the previous year in order to prevent the introduction of the bark beetle (Photo: Flora Höfler).

The incidents described underscore the critical need to account for the interrelation of triggering and conditioning hazards in future risk management strategies. Particularly in this region, where steep terrain and varying climatic influences frequently intersect, the boundary between immediate triggers and predisposing factors is often blurred. For instance, long-term slope destabilisation, windthrow events, and intense rainfall have demonstrated how these elements can interact in complex ways to amplify hazard outcomes. Furthermore, the spatial dimension plays a pivotal role, particularly in the context of cross-border challenges along the Brenner Corridor. This critical infrastructure, connecting northern and southern Europe, exemplifies the importance of transnational coordination in addressing hazards that may originate in one region but exert significant influence across borders. The integration of such considerations into hazard assessments and planning is essential to enhance resilience in this vulnerable yet vital Alpine region.

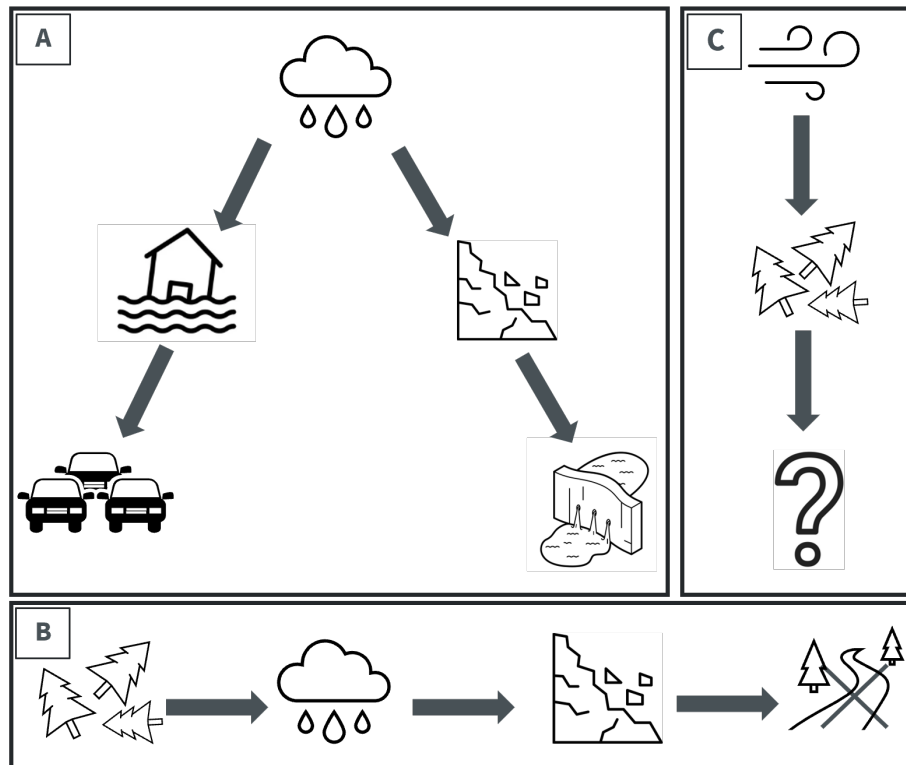


Figure 10: Hazard interactions of the events described in the Alpine case study area (A) heavy precipitation triggering two cascading events in the different sub-regions of the Brenner corridor, (B) loss of protective forest as a precondition followed by heavy precipitation triggering a debris flow and leading to the temporary closure of the A13 motorway, and (3) a wind-throw event above the Lueg bridge which did not yet have a direct impact on the road asset.

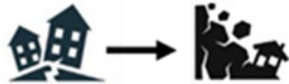
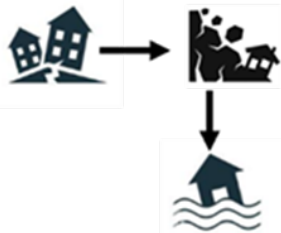
8 Multi-hazard assessment approaches

After the identification of the hazard interaction types and the temporal and spatial relation of the hazards, the next step is to carry out the actual hazard modelling (De Angeli et al. 2022). Each type of hazard has its own modelling approach, depending on the scale of analysis, availability of data, and purpose of the study. Models range from empirical to physically based and probabilistic approaches. In general, there are four main types of hazard modelling approaches that can be applied to the respective classes:

- **Independent hazard modelling.** The standard practice in most multi-hazard risk assessment projects is modelling hazards separately, without considering their interactions, and treating them independently in the risk assessment. The combined effect of different interacting hazards is then often only considered in the loss estimation (Tilloy et al. 2019)
- **Empirical interaction modelling.** A common approach is the application of simplified hazard interaction models, which are based on empirical relations or machine learning utilizing historical data and statistical relationships. For instance, empirical relationships linked to storm severity are applied to model wind fields and rainfall amounts in tropical storms (Kropf et al., 2022). Similarly, machine learning methods are utilized to analyse and model the connections between earthquakes and landslides (Dahal et al., 2023).
- **Joint physically based modelling.** This approach involves simultaneously modelling multiple hazards that directly influence each other during the same event by considering the physical principles governing the hazard processes. For example, a storm can generate extreme wind and rainfall. Extreme wind may cause storm surges in coastal areas and uproot trees, while extreme rainfall can lead to pluvial and flash flooding. These floods may interact with the storm surge, amplifying the flooding. In hilly terrain, heavy rain can trigger landslides and soil erosion, with sediments contributing to hyper-concentrated or debris flows. Uprooted vegetation can exacerbate landslides, and tree debris transported downslope may block culverts and bridges, intensifying flooding. While such models capture complex interactions, they are relatively rare and require substantial data inputs (Van den Bout et al., 2018).
- **Sequential hazard modelling.** This is done when one event has an influence on the hazard intensity of a second event. The output of one model should then be used as input for the next model. This could be the direct output, e.g., the results of sedimentation by debris flows raise the bed and will cause more flooding in the next event, or indirect. For example, when an earthquake in an urban environment causes a dam to fail, the earthquake loss estimation should be done, resulting in an evaluation of the debris blockage in streets caused by collapsed buildings. The changes in elevation should then be added to the Digital Elevation Model as the basis for the subsequent flood model.

Each combination of hazard types, hazard interactions, spatial and temporal relations, and scales of analysis requires a specific approach for frequency assessment and hazard modeling. Table 8 gives a summary of the hazard modelling approaches for several examples of independent, compounding, and cascading events.

Table 8: Implications of hazard interrelations for hazard assessment

Hazard sequence		Frequency assessment	Hazard modelling
	Combination of single hazards. An earthquake causes damage. Several years later, the same area is again impacted by a flood.	Separate frequency analyses are done for earthquakes and floods using distinct methods.	Model earthquakes and floods using specific data, tailored to represent different return periods.
	Cascading hazards In mountainous regions, an earthquake can trigger many landslides, compounding the damage to the built environment already caused by the earthquake itself.	Determine a number of earthquake scenarios and analyze the probability of an earthquake event, which is used as a proxy for landslide.	AI-based modeling of earthquake-induced landslide for a number of earthquake scenarios. Estimate landslide density per slope unit (Dahal & Lombardo 2023)
	Cascading hazards Earthquake-triggered landslides dam up a river and cause temporary lakes, which break after some time, and a massive flood affects areas that were not heavily impacted by the earthquake.	The probability of nodes in the hazard cascade is estimated in an event tree and done spatially	Model earthquake acceleration, use this for modeling damming landslide, use this for flood modeling (Fan et al. 2019)
	Compounding hazards Extreme rainfall will cause pluvial and flash flooding and may trigger landslides, which might mix with the rainfall-runoff to cause debris flows.	The probability of the triggering event (WS) and Extreme Rainfall is used as a proxy for other coupled hazards	Joint physically based modeling of flood, landslide, and debris flow processes and their interactions — separate modeling of WS. (Van den Bout et al. 2022)
	Compounding events Forest fires in mountainous regions make the soil more exposed and change the soil characteristics, leading to increased flash floods and landslides.	Probability of climate conditions, followed by high precipitation from climate data.	Model flash flood events. Update factor maps after a flash flood event. Model flood or debris flow event (Rengers et al. 2020)

9 Stakeholder involvement

Involving stakeholders and practitioners across different sectors in hazard interaction assessments is crucial for developing effective, context-sensitive and applicable approaches to managing multi-hazard risks. One way is through co-development or co-design, a collaborative process where researchers, practitioners, and stakeholders from different fields work together from the very beginning of the process. This approach encompasses everything from identifying research gaps to co-creating methods, and mitigation options for complex hazard scenarios. This collaborative approach is vital in understanding and addressing multi-hazard risks, within and across different sectors, especially when multiple hazards occur concurrently or sequentially, often intensifying their impacts.

Co-development is particularly effective for several reasons. It fosters iterative collaboration, shared decision-making, and the integration of diverse perspectives, ensuring that the solutions are both actionable, practical and based on a sound theoretical basis. This process offers the opportunity to include often-overlooked sectors impacted by hazardous events, but usually not integrated in the process of hazard and risk management. However, one significant challenge is to translate findings into clear, actionable guidelines that stakeholders across different levels can practically implement. The guidelines for hazard interactions presented above represent an important first step toward creating actionable and practical recommendations that are clear and accessible. Early engagement with practitioners is crucial to understanding their needs, tailoring the guidelines to the specific contexts and sectors they work in, and establishing feedback mechanisms to enable continuous improvement and adaptation.

Increasingly, disaster risk management (DRM) and hazard research have embraced co-design and development practices. Examples include initiatives by the United Nations Office for Disaster Risk Reduction (UNDRR) and multinational projects such as PLACARD, PARATUS, MYRIAD, RISK-CC Interreg, or AGILE, which promote participatory approaches to risk reduction. This growing trend reflects a broader recognition of the importance of stakeholder engagement. Major contributions have come from the climate change and adaptation community, advocating collaborative approaches to work on solutions with local communities reducing their vulnerability and building up resilience (Pelling, 2010; Kelman, 2019; Gaillard, 2007). In DRM, participatory approaches help ensure that disaster strategies are designed with community input, strengthening risk informed decision-making and resilience at the local level. Resilience and climate change adaptation often rely on co-production strategies, as highlighted by Boyd (2015), which help communities build capacity to manage their own risks. These strategies support adaptive measures, allowing for adjustments to respond to emerging hazards or changing environmental conditions (Schipper, 2009; Shaw, 2012).

Co-designing for hazard interaction assessments involves bringing together a diverse range of stakeholders—scientists, policymakers, local communities, and others—to create research frameworks, tools, and intervention methods. It brings numerous benefits to hazard studies, especially in multi-hazard contexts:

1. **Contextual Relevance:** By engaging stakeholders from affected communities, co-design grounds research in the specific social, cultural, and environmental contexts that shape local hazards. This is particularly important when hazards interact, as the dynamics can vary significantly based on local conditions.
2. **Inclusive Knowledge Integration:** Co-design encourages the blending of scientific, local, and indigenous knowledge, leading to a comprehensive understanding of hazard interactions. This

integration uncovers unique vulnerabilities and resilience factors that might be overlooked in traditional research models.

3. **Enhanced Engagement and Ownership:** Involving stakeholders in co-design fosters “agency,” where participants are more likely to engage with and support the resulting interventions, promoting long-term sustainability.

These three parameters have been clearly observed within the EU-Horizon project PARATUS through various application case studies, each involving stakeholders in different ways. This highlights the relevance of context, the importance of inclusive knowledge transfer—demonstrating that different sectors have varying approaches and ideas for the effective hazard management—and the critical role of early on engagement for successful implementation.

The need for effective stakeholder involvement was clearly shown e.g. in a recent workshop within the PARATUS Application Site Alps on November 5–6, 2024. Forty participants discussed challenges in MHRA, tried innovative engagement methods (e.g., serious game/social simulation), and reviewed hazard interactions potentially leading to high-impact, low-probability (HILP) events. A notable session involved hazard interaction guidelines, where stakeholders explored ways to communicate and describe complex hazard dynamics in a practical, usable format. Examples of HILP events such as the 2021 Ahr Valley flood, the 2023 Kahramanmaraş earthquake, and the 2024 floods in Brazil as well as the 2024 flash floods in Valencia illustrated the profound societal impacts of such events. These examples have already illustrated that HILPs are context-dependent rather than defined by a specific threshold of fatalities or damage. Following this, stakeholders were invited to share their ideas and perspectives on hazard interactions and HILP events, with a particular focus on applying these insights to the Alps Application Case Study. Until this point in the workshop, the emphasis had been on individual events and hazards. The discussion then shifted toward a multi-hazard perspective, addressing site-specific challenges such as the area's high traffic volume and its cross-border dynamics.

In the example of the Alps workshop, activities included a brainstorming session where stakeholders used coloured pens and paper to document insights on various hazard interaction types (e.g., temporal, spatial, and type-based interactions). Following an initial five-minutes individual exercise, the discussions evolved into group conversations, culminating in a 15-minutes collaborative session where ideas were clustered and analysed for underrepresented or overrepresented aspects. A subsequent survey allowed participants to share additional insights on hazard interactions, HILP events, and multi-hazard risk assessment priorities. Surveys especially in context of sensitive topics such as DRM can help get critical insight into problems of organisational structures where the necessity for changes is more openly discussed compared to non-anonymous input. This was shown in the survey organised by Fekete et al. (2023) to understand better the preparedness, coordination and experience by first responders to get ideas on how to follow this up with improved risk management structures for the case study Germany and Romania.

The aim of the survey performed in the Alps workshop was to get feedback on the hazard-interaction classification presented above, evaluate the importance of hazard interaction in the specific sectors and if stakeholders have high impact low probability events in mind (see Figure 11). Twenty participants answered questions from their professional backgrounds, hazard interaction experiences, and perspectives on HILP events. These insights are intended to refine multi-hazard risk assessment guidelines and will contribute to the design of user-oriented guidelines within the DRM community. Feedback also pointed to the inherent

difficulty in conceptualizing low-probability, high-impact scenarios, as the uncertainty and potential severity of such events are challenging to fully envision.

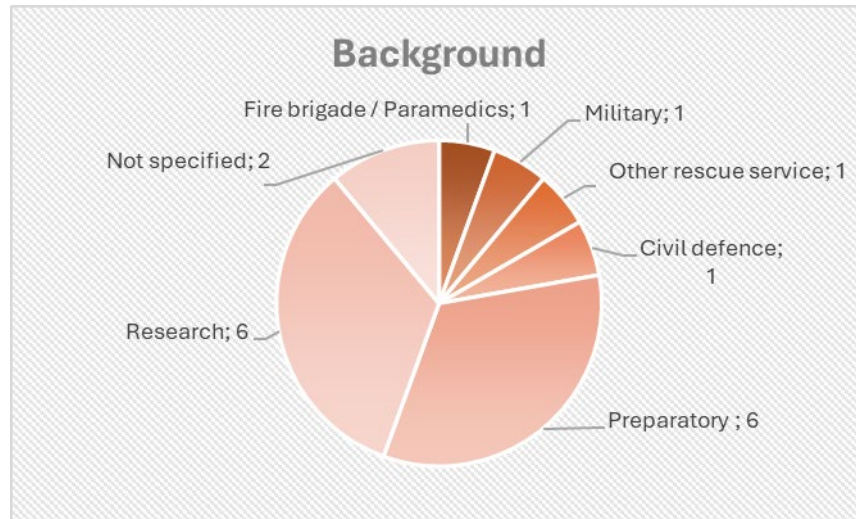


Figure 11 Professional background of the stakeholders involved in the Alps workshop (Nov. 2024).

The results of the survey show that the participants agreed mostly that a better understanding of the interaction between hazards will be helpful and will enable to easier estimate the impacts and work out different crisis scenarios with additional dynamic parts. When comprehending complex interactions better it can lead also to a better understanding of recovery and return periods, therefore raising awareness for both theory and practice helping capacity building. Targeted quick action after windthrow, can reduce for example bark beetle mass propagation. However, it is also doubted that society as a whole is in a position to grasp this complexity. The survey answers concerning the role of High Impact Low Probability (HILP) events show that the majority respondents were already considering HILPs, the other half either did not answer or had not considered these processes before. This shows the need for better communication of these phenomena.

Concerning the applicability and availability of guidelines, stakeholders indicated that an inclusion of multiple instead of single hazards as well as an implementation into the planning tools is mentioned as a help. Other views are that this is already implemented in certain institutions. In general, stakeholders agree that there is a need for more coherent and comparable guidelines as well as that hazard interactions should be included (Figure 6). An important input was also, to keep those guidelines practicable in the daily life of the practitioners.

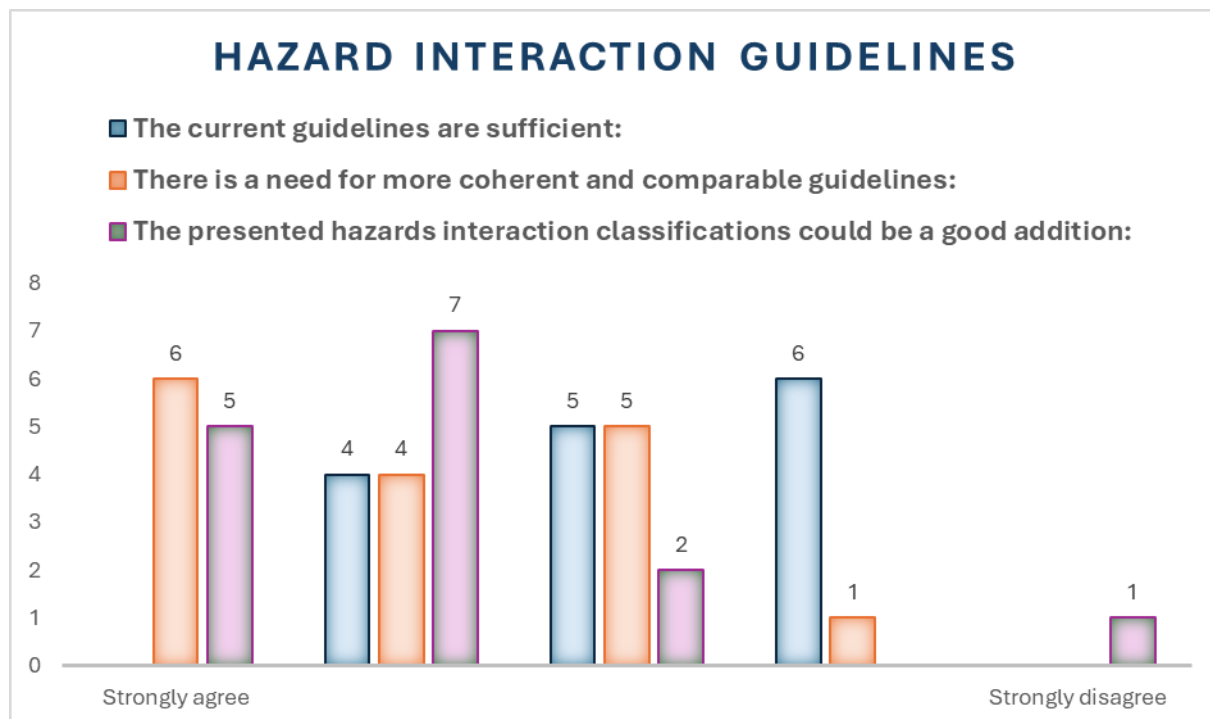


Figure 12: Feedback of the stakeholders from the Alps workshop 2024 concerning their opinion on existing guidelines.

Examples given are major events such as bridge collapses, prolonged blockage of transport infrastructure and the co-occurrence of hazard events such as avalanches + floods / floods + earthquakes leading to landslides. Examples were mentioned in East Tyrol, where a storm event led to snow damage to trees and an unprecedented bark beetle infestation. These scenarios are partly implemented in emergency plans. Other examples are given in the following Table 9:

Table 9: Examples of events from the past where multiple single events interacted from the stakeholder survey on guidelines.

Specific case examples from the Alps	Non-specific Examples
European Floods of 1997, 2010, 2024	Landslide + Covid, Strong wind / intense precipitation -> drought / avalanches
Rigopiano event (avalanche) 2017	Drought / heat -> Wildfire, pest infestation, human stress (accidents, health). Precipitation / cold -> avalanches and blockage of critical transport way (e.g. to hospitals)
Sellraintal flooding, landslides 2015, 2016, 2019, 2021, 2024,	Weather / frost, oversaturation, landslide
Brenner Landslide	Heavy precipitation, landslide -> road closure, strong snowfall -> road closure, detours closed due to avalanche danger

Lower Austria floods 2024	Wet snow, heat, bark beetle infestation
Cascade: storm + snow, bark beetle, less protection function from forest in Eastern Tyrol	Drought, landslide, avalanche, tree damage, landslide
	Heavy precipitation, wind, traffic accidents
	Forest fire, rainfall -> landslides - flooding
	Drought, Heat -> conflicts

Looking ahead, future work will focus on enhancing these guidelines for broader application, including their integration into the disaster risk stakeholder hub. This platform aims to reach a wider audience, making hazard interaction strategies accessible and practical for varied DRM stakeholders across different regions.

10 Conclusions

This deliverable underlines the critical importance of accounting for hazard interactions and interrelations in multi-hazard assessments. It highlights different multi-hazard concepts, the data requirements for these analyses, and the diverse environmental conditions where such interactions can occur. The examples demonstrate that even minor hazard events, when combined or interrelated, can lead to significantly greater impacts across varying scales.

It was hypothesized that no globally applicable guidelines currently exist, with hazard-specific or country-specific frameworks often serving as substitutes for addressing multiple hazards. The reviewed literature showcases various approaches to multi-hazard assessment, employing methodologies like machine learning and spatial analysis tools. However, significant challenges remain, and further advancements are needed to fully integrate hazard interactions into these studies.

- There is still no uniform understanding on the concept of multi-hazards: what they are in terms of hazard interactions, and spatial/temporal evaluation.
- There is no standard methodology which has been tested in different environments and scales of analysis. Most of the papers on the topic remain at a rather conceptual level, although there are some good examples with applications.
- Although the number of publications on multi-hazard risk assessment has greatly increased over the past decades, there is still a bias towards landslide-related applications in Europe (Owolabi & Sajjad 2023).
- Applications of multi-hazard risk assessment, that go beyond the combination of single hazard losses in data scarce regions are still rather rare (Barrantes 2018)
- It is still very difficult to model possible hazard interactions at the local level, due to the lack of appropriate hazard models that take these hazards into consideration. Although there is a rapid development in the use of Artificial Intelligence in the field of hazard and risk assessment, the number of training samples needed to properly model the specific interactions are a limitation. The application of physically-based multi-hazard models is hampered by the large number of input parameters needed for such models and the difficulty to calibrate them. Rapid multi-hazard modelling tools are needed that can be used in combination with other tools representing the uncertainty of the input data.
- The probability of multi-hazard events occurring across space and time remains a major uncertainty. For many hazard types, historical records are too limited to provide a reliable basis for analysis. For hydro-meteorological events the use of climate models (e.g. CMIP6) offers a good alternative for regional scale analysis, but for local scale analysis this remains problematic.



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