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Analysed Case Studies of the Brenner Corridor and the Noto Satoyama Kaido: Application of Partial Impact Chains in a Multi-Hazard Context

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List of Abbreviations

ASFiNAG	Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft (Austrian federal motorway operator)
DRR	Disaster Risk Reduction
EC	European Commission
EU	European Union
FF	Freiwilige Feuerwehr (voluntary fire brigade)
IC	Impact Chain
IPCC	International Panel for Climate Change
MLIT	Ministry of Land, Infrastructure, Transport and Tourism (Japan)
mm	Millimetre
Mw	Moment magnitude
PARATUS	Promoting Preparedness and Resilience of European Communities by Co-Developing Services Using Dynamic Systemic Risk Assessment (EU funded international project)
Scan-Med Corridor	Scandinavian-Mediterranean Core Network Corridor
TEN-T	Trans-European Transport Network

Abstract

Mountain transport corridors serve as critical regional and international lifelines. However, increasing climatic volatility and complex topographical conditions expose these corridors to multi-hazard threats, where cascading and compounding events often result in disproportionate disruptions. This thesis investigates the transferability of the “Impact Chain” framework, originally developed within the European PARATUS project, including the Brenner Corridor as one of the study areas, by applying it to the geographically and climatically distinct context of the Noto Peninsula, Japan. Using a semi-systematic literature review and qualitative comparative analysis, this study reconstructs historical hazard cascades along the Brenner Corridor (A13, Austria) and the Noto Satoyama Kaido (Japan). By synthesising existing documentation, “Partial Impact Chains” were developed to trace the causal links between hazard sequences and their consequences. The results demonstrate that even literature-based, simplified “Partial Impact Chains” serve as effective tools for visualising complex hazard interrelationships and enabling cross-regional comparisons. To bridge the significant differences in hazard profiles and spatial scales between the two corridors, the study incorporated an evaluation of slope protection measures as a consistent comparative metric. The comparative analysis reveals that while the Brenner Corridor relies on protection nets and the Noto corridor on embankments and drainage systems, both approaches contributed to mitigating cascades to a certain degree. However, these measures remain insufficient to fully prevent bottlenecks and major disruptions at critical mountain passes under multi-hazard cascades. The analysis further identifies a significant data gap and asymmetry in documentation practices between the two study areas, which may act as a barrier to the cross-sectoral and trans-regional collaboration required to effectively tackle potential multi-hazards. Nevertheless, the study concludes that Impact Chains possess high potential as a “common language” to facilitate knowledge sharing between distant regions. This research represents a significant step toward future collaborative multi-hazard mitigation efforts, proving that even partial adaptations of complex frameworks can yield actionable insights.

Kurzzusammenfassung

Verkehrskorridore im Gebirge dienen als essentielles regionales und internationales Rückgrat. Aufgrund der klimatischen Volatilität und herausfordernder topografischer Bedingungen sind diese Korridore Mehrfachgefährdungen ausgesetzt, was oft mit Kaskaden- und Verbundereignissen einhergeht, die zu unverhältnismäßigen Ausfällen führen können. Die vorliegende Arbeit untersucht die Übertragbarkeit des "Impact Chain"-Frameworks, das ursprünglich im Rahmen des europäischen PARATUS-Projekts entwickelt wurde. Dabei wird der Brennerkorridor (Österreich) dem geografisch und klimatisch differenzierten Umfeld der Noto-Halbinsel (Japan) als Fallstudie gegenübergestellt. Mithilfe einer semi-systematischen Literaturrecherche und einer qualitativen Vergleichsanalyse rekonstruiert diese Studie historische Gefahrenkaskaden entlang des Brennerkorridors (A13) sowie der Noto Satoyama Kaido Schnellstraße. Durch die Synthese bestehender Dokumentationen wurden "Partial Impact Chains" entwickelt, um kausale Zusammenhänge zwischen Gefahrenabfolgen und deren Konsequenzen aufzuzeigen. Die Ergebnisse verdeutlichen, dass selbst literaturbasierte, vereinfachte "Partial Impact Chains" als effektive Instrumente zur Visualisierung komplexer Gefahreninterdependenzen und zur Ermöglichung überregionaler Vergleiche dienen. Um die Diskrepanz zwischen Gefahrenprofilen und den räumlichen Maßstäben der beiden Korridore zu überwinden, wurde für diese Studie die Evaluierung von Hangsicherungsmaßnahmen als konsistente Vergleichsbasis definiert. Die Vergleichsanalyse zeigt, dass sowohl der Einsatz von Schutznetzen am Brennerkorridor als auch der Fokus auf Böschungssicherungen und Entwässerungssysteme am Noto-Korridor maßgeblich zur Minderung von Kaskadeneffekten beigetragen haben. Diese Maßnahmen erweisen sich jedoch als unzureichend, um Systemausfälle und massive Beeinträchtigungen an kritischen Gebirgspässen bei multikausalen Gefahrenkaskaden vollständig zu verhindern. Die Analyse identifiziert zudem eine erhebliche Datenlücke sowie eine Asymmetrie der Dokumentationsverfahren zwischen den beiden Untersuchungsgebieten. Dies stellt ein Hindernis für die sektorenübergreifende und transregionale Zusammenarbeit dar, die zur effektiven Bewältigung potenzieller multikausaler Gefahren erforderlich ist. Dennoch kommt die Studie zu dem Schluss, dass „Impact Chains" ein hohes Potenzial als "gemeinsame Sprache" bieten, um den Wissensaustausch zwischen geografisch distanzierten Regionen zu erleichtern. Die vorliegende Arbeit leistet damit einen wesentlichen Beitrag zu künftigen gemeinsamen Bemühungen zur Minderung von Mehrfachgefährdungen. Sie zeigt auf, dass auch eine teilweise Anwendung komplexer Frameworks bereits handlungsrelevantes Wissen generieren kann.

1 Introduction

Mountain regions often struggle to provide easy travel between destinations because of steep terrain, yet these same areas face higher levels of natural hazard exposure than flatter regions. To maintain mobility, societies develop transit corridors that concentrate transport infrastructure and ensure crucial connectivity through the mountains. These corridors support regional and international flows of people, goods, and services, meaning that even localised disruptions can have far-reaching socio-economic impacts. At the same time, climate change and socio-economic development are altering hazard patterns and the criticality of the infrastructure networks, making the resilience of these corridors an increasingly prominent concern in disaster risk and transport policy debates. In recent years, it has become increasingly clear that mountain transit corridors are not only exposed to individual hazard events but also to situations in which multiple hazards interact spatially and temporally. Such interactions are, for instance, storms triggering landslides and floods, or earthquakes weakening slopes that subsequently fail during heavy rainfall. These multi-hazard situations can prolong disruptions, strain emergency response capacities, and challenge traditional, hazard-specific approaches to infrastructure planning and protection.

1.1 Background

Mountain transit corridors are increasingly recognised as critical infrastructure due to their exposure to natural hazards and their role in regional and transnational connectivity. One of those threatening factors in this geographical situation is multi-hazards, which are categorised in three different ways: cascading, compounding, and concurrent events (Pescaroli and Alexander 2018; Gill and Malamud 2016). These terms will be defined in the coming Chapter 3 “State of the Art”, but what matters here is that the likelihood of such multi-hazard events is increasing over time, particularly in relation to climate change. Changing precipitation patterns and rising hazard intensity and frequency are expected to lead to more climate-induced multi-hazard situations (IPCC 2022). Also, understanding the hazard interaction is key to identifying potential risks in case of multi-hazard occurrence. Due to their geographical constraints and cross-border connectivity, disruptions along mountain transit corridors may have significant effects on neighbouring countries. At the European level, transport policy aims to reduce greenhouse gas emissions and external costs while improving accessibility through the development of the Trans-European Transport Network (TEN-T), including core north–south corridors (European Commission 2011). Within this framework, the Brenner Corridor forms a key section of the Scandinavian–Mediterranean corridor, concentrating long-distance road and rail flows in a hazard-prone Alpine bottleneck (European Commission 2011; Cavallaro et al. 2024). In this context, this thesis exclusively focuses on the A13 Brenner Motorway for examination. The reason is that, among the cascading hazards identified in the Noto Peninsula, Japan, the secondary study area selected for comparative analysis, damage has been confirmed specifically on the motorway, which makes the comparison more meaningful.

Additionally, in the case of the Brenner Corridor, resilience strategies have traditionally placed strong emphasis on large-scale structural solutions, most notably the construction of the Brenner Base Tunnel as a long-term, trans-European infrastructure project (Cavallaro and Maino 2014). At the same time, well-established operational measures exist, particularly for managing recurrent hazards such as winter weather conditions, through advanced monitoring systems, predefined procedures, and coordinated emergency protocols (Autostrada del Brennero S.p.A. 2021). However, while these measures are effective in addressing specific and largely foreseeable hazards, their capacity to cope with complex multi-hazard scenarios remains open to discussion. Structural investments and hazard-specific operational procedures may not fully account for cascading or compound events, in which multiple hazards interact across short timeframes, sectors, or national boundaries. This raises the question of whether current resilience strategies sufficiently integrate adaptive and cross-sectoral operational measures for managing extreme and interacting hazard events.

Many mountain corridors function as critical bottlenecks or lifelines because transport flows are channelled through a limited number of routes constrained by topography. This includes the two corridors analysed in this thesis: the Brenner Corridor and the Noto Satoyama Kaido. The importance of these corridors becomes evident when one of these routes is disrupted; detour options are often limited, impractical, or entirely absent, which can isolate certain communities or reroute substantial volumes of international traffic. This dependency on a small number of vulnerable links increases the strategic importance of resilience planning for such corridors, not only at the local but also at regional and transnational scales. The bottleneck and lifeline functions of mountain transit corridors also raise specific governance challenges. Responsibilities for construction, maintenance, and emergency management are often distributed across multiple agencies and authorities, while impacts of disruptions may extend beyond administrative boundaries and affect even distant regions. Consequently, designing resilience strategies for these corridors requires coordination across sectors, scales, and national borders, and demands approaches that can address complex, interacting risks rather than isolated hazard events.

The Brenner Corridor, linking Austria and Italy across the central Alps, is a prominent example of a mountain transit route that combines high exposure to natural hazards with critical European connectivity. Its road and rail infrastructure concentrates a substantial share of north–south traffic across the Alps, and its narrow valleys and steep slopes make it susceptible to landslides, avalanches, floods, and other hazard processes. As a result, disruptions along this corridor can propagate far beyond the immediate area, affecting logistics chains, commuter flows, and cross-border mobility. On the other hand, the Noto Satoyama Kaido on Japan's Noto Peninsula represents a comparable case of a mountain–coastal corridor functioning as a regional lifeline. Running through topographically complex mountainous terrain and further exposed to hazards due to its proximity to a hazard-prone coastline, it plays a crucial role in linking local communities to larger urban centres that concentrate most essential services. Recent events, prominently the 2024 Noto earthquake, have underscored how damage to this corridor can severely constrain emergency access and prolong isolation in hazard-affected areas, thereby exacerbating the humanitarian and socio-economic consequences of such events.

Although the Brenner Corridor and the Noto Satoyama Kaido differ in geographical context, scale, and governance arrangements, they share key characteristics that make them suitable for comparative analysis. Both concentrate critical transport flows within mountainous landscapes exposed to multiple natural hazards, rely on a limited number of routes, and face the risk that disruptions can quickly escalate into wider socio-economic and humanitarian challenges. At the same time, they exemplify different governance scales, one as a trans-European bottleneck, the other as a regional lifeline, creating an opportunity to explore how scale and institutional context shape resilience strategies under multi-hazard conditions. This point is elaborated in greater detail in Chapter 4, "Study Area". To this end, the comparison focuses on how different cascading event chains developed in each context—for instance, the earthquake-rainfall-landslide sequence in Noto versus the heavy rainfall-landslide-protection failure sequence in Brenner. By examining what kinds of impacts were documented and how slope protection measures influenced these outcomes, the research identifies empirical patterns in both corridors. As critical mountain routes highly exposed to cascading hazards, these documented sequential impacts—from initial triggers to road disruptions—provide a concrete basis for examining the role of slope protection in ensuring infrastructure resilience.

The complexity of managing such corridors is further compounded by the evolving nature of the hazards themselves. Multi-Hazard is receiving increasing attention, given the intensity and the anticipated increased frequency of occurrence due to climate change (IPCC 2022). This subsection introduces multi-hazard as a research topic, while more concrete definitions and a detailed literature review are provided in Chapter 3, "State of the Art".

The concept of multi-hazard risk has gained prominence in disaster risk research and international policy, reflecting recognition that different hazards can interact and amplify impacts in various ways, including non-linear ones. Conceptual frameworks describe various forms of interactions, such as concurrent, cascading, and compound events, and emphasise that such processes can undermine the effectiveness of risk reduction measures designed with single hazards in mind. At the same time, systemic risk debates highlight how disruptions can propagate through interconnected infrastructure networks, further expanding the spatial and temporal footprint of local hazard events. Despite the assertion that such conceptual advances, coupled with collaborative research across sectors and regions, are necessary to address the multi-hazards that threaten society in conjunction with climate change, attempts to apply a framework developed in one location to a distant region are scarcely seen (Scolobig et al. 2014). Similar conceptual research includes Albulescu et al. (2026)'s recent comparative study examining hazard responses and governance across two study sites facing the same hazard, and the PARATUS project, which applies a single framework to multiple study sites (Coccuccioni et al. 2023). Many assessments still prioritise single hazards or treat multi-hazard risk at a highly abstract level without fully capturing infrastructure-specific vulnerabilities, interdependencies, and governance constraints. Although hazard interactions and cascading risks are well-recognised conceptually, and increasingly explored through emerging research initiatives and collaborative projects, their systematic integration into infrastructure planning and operational risk governance remains limited. In the context of mountain transit corridors, these limitations are particularly pronounced. There remains a limited understanding of how interacting hazards affect corridors that function as bottlenecks, where transport flows are spatially concentrated, and alternative routes are scarce. Previous studies on the Brenner Corridor and other Alpine transport routes have highlighted susceptibility of these routes to individual hazards such as landslides or floods, but only a few have systematically examined how concurrent, cascading, or compound scenarios may disrupt corridor functionality and challenge existing resilience and governance strategies. This gap is especially relevant in mountainous regions, where hazard interactions can rapidly escalate impacts beyond sectoral or national boundaries.

1.2 Problem Statement

Against this background, recent cross-country comparisons of shared hydrometeorological events, such as the 2021 floods in Romania (Alba County) and the Netherlands (Limburg Province), have demonstrated the value of Impact Chains and tailored metrics for dissecting hazard impacts and adaptation responses, yielding potential lessons across contexts (Albulescu et al. 2026). Yet, applications to cascading landslide sequences in mountain transit corridors, where slope protection measures involve sequential hazard interactions, remain unexplored. The overarching aim of this thesis is to develop and compare qualitative Impact Chains for documented cascading events along the Brenner Corridor (Austria-Italy) and Noto Satoyama Kaido (Japan), as representative mountain bottlenecks/lifelines. This explores patterns of hazard interactions (e.g., heavy rainfall triggering landslides followed by floods) and the role of slope protection in these sequences, using literature-based reconstructions. More specifically, the thesis addresses four interrelated research questions: (1) How can the Impact Chain framework be adapted to a specific infrastructure corridor through a literature-derived approach, and to what extent does this partial adaptation remain effective without stakeholder workshops? (2) What are the documented differences in slope protection measures between the Brenner Corridor and the Noto Satoyama Kaido? (3) What geographical, technical, or governance factors influence these observed differences? (4) To what extent do these slope protection measures effectively mitigate or prevent cascading damage from landslides along the corridors? Detailed objectives, sub-questions, and hypotheses are outlined in Chapter 2.

To address these, the thesis adopts a qualitative, literature-based methodology synthesising scientific publications, official reports, grey literature, and news sources. It constructs case-specific Impact Chains visualising hazard sequences and slope protection measures, then performs comparative analysis to identify similarities, differences, and transferable insights. This bridges multi-hazard conceptual frameworks with practical documentation of mountain corridor disruptions, without probabilistic modelling or simulation. The findings will document how cascading events unfold in each corridor, highlighting slope protection's positioning within sequences and cross-case variations. Where common lessons emerge (e.g., regarding the availability and detail of event documentation), they offer methodological insights into the transferability of Impact Chains; otherwise, they suggest refinements for future research directions. In doing so, this study contributes to the visualisation of multi-hazard sequences and their consequences for transport infrastructure, providing a comparative basis for evaluating how qualitative evidence of infrastructure performance can be integrated into conceptual hazard-sequence frameworks for similar settings.

Conceptually, it operationalises Impact Chain thinking for landslide cascades via qualitative reconstructions; practically, it provides a blueprint for comparing protection measures across corridors, potentially adaptable to other hazard-prone routes.

1.3 Key Definition

In this section, the key concepts used throughout this thesis are defined to ensure a clear and consistent terminology, while a more detailed discussion of these concepts and their theoretical background is provided in Chapter 3, "State of the Art". The aim of this section is to clarify the definitions of terms that are frequently confused and used interchangeably at an early stage, thereby avoiding their misuse within this thesis. The following key concepts are defined based on UNDRR Terminology(United Nations Office for Disaster Risk Reduction (UNDRR) 2017a) and on De Angeli et al. (2022); when the terms are not available there.

Hazard: "A process, phenomenon, or human activity with the potential to cause loss of life, injury, property damage, social-economic disruption, or environmental degradation" (United Nations Office for Disaster Risk Reduction (UNDRR) 2017b). *Hazardous events* represent concrete manifestations of such hazards at particular places and times, whereas this term denotes the underlying type or potential (United Nations Office for Disaster Risk Reduction (UNDRR) 2017c). In this thesis, it encompasses landslides and related processes in the two study sites: the Brenner Corridor and the Noto Satoyama Kaido.

Multi-Hazard: Multiple major hazards within a given context, including simultaneous, cascading, cumulative, or interrelated events (United Nations Office for Disaster Risk Reduction (UNDRR) 2017b). In this thesis, it focuses on cascading events along mountain corridors in the study areas.

Disaster: Serious disruption of community or societal function due to hazardous events interacting with exposure, vulnerability, and capacity, resulting in human, material, economic, and environmental losses (United Nations Office for Disaster Risk Reduction (UNDRR) 2023). This thesis primarily examines hazard sequences, consequences and slope protection measures in the study sites. While other elements such as vulnerability, exposure, and risk are inherent to the study sites, they are treated as static background information rather than variables for analysis. Consequently, these factors are not formally assessed or quantified within the scope of this research.

Risk: "The combination of the probability of an event and its negative consequences" (United Nations International Strategy for Disaster Reduction 2009). Additionally, the following elements: hazard, exposure, vulnerability, and capacity constitute and determine risk, and can be expressed by a risk equation (see below) that enables risk estimation. Applying this same concept, De Angeli et al. (2022) emphasises that in multi-hazard situations, the multi-hazard itself is merely a component of multi-hazard risk, and therefore multi-hazard and multi-hazard risk must not be used interchangeably.

$$Risk = \frac{hazard \times exposure \times vulnerability}{capacity}$$

In this study, while all these components are recognised as integral to risk, the analysis primarily focuses on the qualitative assessment of hazard interactions and the resulting damage.

Vulnerability: "The condition 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" (United Nations Office for Disaster Risk Reduction (UNDRR) 2017d). In this thesis, vulnerability will not be elaborated on, quantified, or assessed, but the general concepts will be referenced as needed, particularly in the governance discussions in the Perspectives chapter, to contextualise the role of slope protection measures in mitigating cascading risks.

Disaster Risk Governance: "The arrangements to guide, coordinate and oversee disaster risk reduction and related areas of policy." Here, disaster risk reduction is defined as the objective in the political context that is supposed to prevent and reduce existing/ potential disaster risk, which contributes to strengthening resilience(UN 2016, pp. 15–16).

Resilience: "The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management" (UN 2016, p. 22).

Exposure: The positioning of people, buildings, infrastructure, production facilities, and other physical human assets in areas susceptible to hazards. It can be characterised by various attributes of the elements at risk, including their construction materials, usage patterns, monetary worth (e.g., for structures), or population counts (De Angeli et al. 2022, p. 2).

Damage: It refers to adverse consequences, specifically, those effects that cause harm to physical assets, human populations, socio-economic structures, and ecological systems (De Angeli et al. 2022, p. 2).

Impact: The complete range of outcomes from a hazardous event or disaster, encompassing both detrimental effects (such as financial losses) and beneficial ones (like economic benefits), spans human, economic, and environmental dimensions. In the present study, this concept is narrowed to encompass solely direct, measurable physical harm to assets; indirect effects or broader categories (e.g., social or environmental) are excluded from consideration (De Angeli et al. 2022, p. 2).

1.4 Thesis Outline

The remainder of this thesis is structured as follows. Chapter 2 presents the research objectives, questions, and hypotheses in detail, clarifying the analytical focus and assumptions guiding the work. Chapter 3 reviews the state of the art on multi-hazard risk, critical infrastructure resilience, and previous studies on Alpine and Japanese transit corridors, and concludes by identifying the main research gaps that the thesis seeks to address. Chapter 4 introduces the two case study areas, describing the geography, infrastructure characteristics, and hazard contexts of the Brenner Corridor and the Noto Satoyama Kaido, and explains the rationale for their comparative selection. Chapter 5 outlines the methodology, focusing on the adaptation of the Impact Chain framework to capture hazard-consequence sequences through event inventories and chronologies. Chapter 6 presents the results, while Chapter 7 discusses their implications for disaster risk governance and infrastructure protection. Finally, Chapter 8 summarises the main insights and limitations, and Chapter 9 reflects on governance and policy implications as well as directions for future research.

2 Research Framework

This chapter delineates the research framework. It begins by articulating the primary research objective, which builds directly on the background and key concepts introduced in the previous chapter. Subsequently, it outlines the research questions and hypotheses derived from this objective, which will be systematically addressed in the “Results” and “Discussion” chapters. The hypotheses are formulated so that they can be answered with a simple yes or no. These elements are intended to clarify the scope of the study and how the planned analysis relates to the overall aims.

2.1 Research Objectives

The thesis pursues the following main objective: to verify whether the Impact Chain framework, established primarily in the European context through projects like PARATUS, can be effectively applied to a geographically and climatically distant region through a partial adaptation. This adaptation entails a literature-derived development that focuses on hazards and consequences, a streamlined approach compared to the extensive stakeholder workshops typically recommended alongside desk research (Albulescu and Armaş 2024; Coccuccioni et al. 2023). Specifically, the framework is applied to the Japanese case study (the Noto Satoyama Kaido), and its validity is assessed through a comparative analysis with historical cascading hazards along the Brenner Corridor motorway, a PARATUS study site where the Impact Chain was originally applied and analysed. This approach tests the framework's transferability beyond Europe to regions prone to multi-hazards under divergent conditions, such as seismic activity combined with heavy rainfall in Japan versus Alpine precipitation-induced events in the Brenner area. Central to this verification is an examination of the framework's utility for capturing hazard chaining and resultant impacts. It evaluates whether literature-derived partial Impact Chains suffice for meaningful insights into cascading sequences and the role of slope protection measures. To ensure comparability, the selection of cascading events is conditioned on the involvement of landslides. These protection measures serve as the primary comparative axis, providing a focused lens for this analysis across two disparate corridors with distinct geohazard profiles.

2.2 Research Questions and Hypotheses

The following research questions guide the study.

RQ1 To what extent is the simplified Impact Chain framework transferable to geographically distant regions?

RQ1a Is the framework effective when developed solely from a literature review without stakeholder workshops?

RQ1b Is the framework effective when limited to hazard-consequence factors?

This set of questions assess the framework's methodological robustness by evaluating its capacity to prioritise hazard interrelationships and structure cascading sequences based exclusively on literature-derived data, without conventional stakeholder engagement.

RQ2 How do the slope protection measures differ between the Brenner Corridor and the Noto Satoyama Kaido?
This explores the structural characteristics and primary functions of the protection systems employed in each corridor, as identified in technical reports.

RQ3 Based on their difference, which kind of factors influence or support this divergence?
This explores potential contextual drivers and regional rationales that underpin the selection of specific protection measures, drawing on a synthesis of grey literature and case studies.

RQ4 Do slope protection measures help to prevent or reduce further damage from cascading effects involving landslides along these corridors?
This evaluates the documented effectiveness and limitations of protection measures in interrupting hazard sequences, specifically examining whether they prevented or merely delayed infrastructure failure during observed cascading events.

Correspondingly, the following hypotheses are formulated to be tested through the subsequent analysis:

H1 The simplified Impact Chain is transferable from the Brenner Corridor to the Noto Satoyama Kaido.

H1a A desk-based development of the Impact Chain is sufficient to reconstruct the chronological sequence of a hazard cascade.

H1b A partial adaptation of the framework serves as a valid analytical tool for prioritising hazard interrelationships.

H2 Post-event documentation confirms that the Brenner Corridor relies on protection nets, whereas the Noto Satoyama Kaido prioritises embankments.

H3 The divergence in protection measures is driven by the distinct regional hazard patterns.

H4 The reviewed literature confirms that implemented slope protection measures effectively mitigate further cascading damage along mountain corridors.

To this end, the following section outlines the scope and delimitations of this study, ensuring alignment with the research questions within the multi-hazard cascading framework.

2.3 Scope and Delimitations

This study is scoped to what is achievable within the six-month master's thesis period, adhering to the research questions outlined in this chapter within the multi-hazard research framework.
- Temporal scope: Recent cascading events amid observed climate change trends, such as increased extreme rainfall intensity (past three years, 2023–2026) (IPCC 2022). This captures contemporary slope protection applications, accounts for climate impacts, and avoids unrecognised discrepancies from comparing distant historical events.
- Methodological delimitations: Sole reliance on literature review (peer-reviewed, grey literature, reports) for Impact Chain construction and content comparison analysis. Excludes primary data collection, stakeholder workshops, and quantitative modelling of vulnerability, exposure, and risk. This partial adaptation (hazards and outcomes only) tests framework transferability under realistic constraints.
- Comparative axes: Noto Satoyama Kaido (embankments, earthquake-rainfall contexts) and Brenner Corridor (natural slopes, precipitation events) as primary slope protection lenses. Selected for shared mountainous motorway exposure to landslide-triggered cascades, despite geographical differences.
- Exclusions: Non-road infrastructure, non-cascading hazards (though relevant slope policy literature is referenced), and coastal cases like National Route 249 (misaligned with mountainous motorway axis).
These delimitations enable focused qualitative synthesis, with trade-offs recognised in the methodology limitations.

3 State of the Art

This chapter reviews the state of the art, in particular, relevant to multi-hazard analysis within the framework of historical cascading events on mountain motorways. It first introduces key definitions and concepts, which are not introduced in Chapter 1, for understanding concurrent, cascading and compound events, with a particular focus on cascading hazard events on the Brenner motorway and the Noto Satoyama Kaido motorway, highlighting their sequences, impacts and the role of risk management features. Finally, the identified research gaps are discussed regarding the effectiveness of slope protection and maintenance measures in preventing or reducing damage from landslides within cascading events along these corridors. Together, these strands provide the conceptual and empirical basis for comparing how road maintenance measures may help to prevent or reduce damage from landslides within cascading events along these corridors.

3.1 Multi-Hazard Concepts for Mountain Corridors

Two study sites that are addressed in this thesis, the Brenner Corridor and the Noto Satoyama Kaido, are categorised as mountain transport corridors. The specific geographical characteristics and the socially significant roles fulfilled by each motorway will be discussed in Chapter 4, Study Area but generally speaking, mountain transport corridors concentrate critical flows of people and goods within narrow valleys, tunnels and passes, often with very limited redundancy. In such settings, multiple natural hazards, such as landslides, avalanches, floods, rockfalls, and in some regions, even wildfires or earthquakes, can act on the same linear infrastructure, either separately or in combination. As a result, even moderate events can trigger disproportionate disruption when they affect key bottlenecks, and the cumulative or interacting effects of several hazards may differ substantially from what single-hazard approaches would suggest. This is particularly evident along the Brenner Corridor, where a trans-European north-south axis intersects with a hazard-prone Alpine environment, raising complex questions about cross-border responsibilities for risk management, emergency response and compensation when disruptions occur (Fikar et al. 2016). To analyse such corridors in a consistent way, this thesis adopts a multi-hazard perspective, which requires clear working definitions of multi-hazard and multi-hazard risk as a basis for the subsequent conceptual and empirical chapters.

3.1.1 Multi-Hazard and Multi-Hazard Risk

This subsection first clarifies how the terms multi-hazard and multi-hazard risk are used in this thesis. The overall argument of the thesis is grounded in a multi-hazard perspective, so it is essential to establish a shared understanding of these concepts. This is particularly important for the analytical framework of this thesis, because the susceptibility of mountain transport corridors depends not only on individual hazards but on how they may interact over time and space, which is not captured by conventional single-hazard assessments. In other words, treating hazards independently would risk underestimating corridor disruption and systemic impacts. At the same time, there is no single, uncontested definition of multi-hazard issued by one authoritative institution. Instead, the concept has evolved from simple overlays of several hazards towards approaches that explicitly consider hazard interactions, cascading effects and dynamic vulnerability as the topic has gained prominence in research and policy. In this subsection, the working definitions adopted for this thesis are derived primarily from recent syntheses such as De Angeli et al. (2022) and related reviews, which compare and consolidate widely cited contributions in the multi-hazard literature.

In international policy documents, multi-hazard is typically framed in broad terms. For instance, UNDRR defines multi-hazard as "(i) the selection of multiple major hazards that a country faces and (ii) specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, taking into account potential interrelated effects. In the Sendai Framework for Disaster Risk Reduction 2015–2030, these hazards include biological, environmental, geological, hydrometeorological and technological processes and phenomena, underlining that multi-hazard assessments should consider a wide range of hazard types rather than a single dominant threat" (United Nations Office for Disaster Risk Reduction (UNDRR) 2017b). At the same time, research has highlighted that multi-hazards should go beyond a simple "multi-layer single hazard" or "all-hazards-at-a-place" perspective, in which independent hazard layers are merely overlaid (Gill and Malamud 2016; Liu et al. 2016). Gill and Malamud (2016), for instance, emphasise that multi-hazard approaches need to account for interactions between hazards and provide typologies of different interaction mechanisms. Building on this evolution, De Angeli et al. (2022) conceptualise multi-hazard as a series of approaches in which more than one hazard in a given area is analysed together with their interrelations, and argue that multi-hazard risk assessments must also consider multi-vulnerability by addressing interdependencies among vulnerable elements. Despite differences in wording, these definitions increasingly converge on the idea that multi-hazard involves multiple hazards, their spatial and temporal co-occurrence, and their interactions, rather than merely co-existing single hazards. This thesis adopts this interaction-focused perspective, given that hazard chains and compounding processes are often the most damaging for mountain transport corridors and their critical functions. In this thesis, a distinction is made between the concepts of multi-hazard and multi-hazard risk. Multi-hazard is understood as an approach in which more than one hazard and their potential interrelations are analysed within a given area, whereas multi-hazard risk refers to assessments that explicitly consider the impacts of multiple hazards, and, where relevant, interdependencies among exposed and vulnerable elements (De Angeli et al. 2022). Rather than developing new probabilistic models, this thesis explores multi-hazard risk qualitatively by synthesising existing literature and case-based evidence, using impact chain visualisations, narrative event descriptions, and event chronology tables for two mountain transport corridors to evaluate how similar disruption patterns and hazard-sequence interactions emerge under different geographical conditions. In line with recent work on multi-hazard and multi-risk, the term multi-risk is not employed in a broad sense to cover all possible impact domains. Still, instead, the analysis focuses primarily on the impacts on transport functions and corridor continuity, while other critical systems are noted insofar as they interact with, or depend on, these transport links.

Drawing on the definitions outlined above, this thesis adopts a working definition of multi-hazard tailored to mountain transport corridors. The analysis focuses on natural hazards that are particularly relevant for the two study areas, namely landslides (including rockfalls and debris flows), avalanches and floods, with wildfires and earthquakes considered where documented events indicate their relevance. These hazards are examined in relation to linear transport infrastructure such as roads, railways and tunnels along the corridors, where disruption of a small number of links can have disproportionate consequences. In terms of temporal relationships, this thesis primarily focuses on cascading events, while also considering the influence of compound conditions and short-term extremes where they act as triggers or intensifying factors for these sequences. This approach shifts the attention from isolated single hazards to the dynamic interactions that characterise corridor disruptions. While the UNDRR provides a comprehensive conceptual framework for disaster risk, this thesis adopts a more focused qualitative approach to examine the mechanisms of corridor disruption (United Nations Office for Disaster Risk Reduction (UNDRR) 2023). In this context, the analysis prioritises the continuity of critical transport functions, specifically, the ability of key road links to remain operational. Rather than assessing risk components independently (such as vulnerability or exposure metrics), the subsequent impact chain diagrams trace the dynamic sequences between hazards, their physical consequences, and the functional response of infrastructure. This allows for a detailed comparison of how specific hazard processes lead to infrastructure failure and how protection measures influence these sequences along the Brenner Corridor and the Noto Satoyama Kaido.

3.1.2 Hazard and Process Groups, Hazard Interactions

As we saw in the previous section, multi-hazards are a set of hazardous events that may interact and make the overall damage much worse. Here are the key characteristics of multi-hazards: they interact in ways unlike those of single hazards, which people traditionally examine in isolation or by simply superimposing

Gill and Malamud (2016). These interactions cause further damage to the given region, its ecosystem, and eventually lead to catastrophic financial, biological, and humanitarian losses. In order to reconstruct the historical events for Brenner and Noto, it will be helpful to explore the established conceptual foundations, categorisations and terminologies relevant to interactions among multiple hazards. This section explores the main factors behind hazard interactions, namely, the categorisation of hazard and process groups, as well as the fundamental dynamics of their interactions.

Building on the classification by Gill and Malamud (2016), this thesis categorises the observed processes into three primary groups to better align with the corridor-specific analysis: natural hazards, anthropogenic hazards, and technological hazards. While they all represent phenomena with the potential for adverse impacts, they differ fundamentally in their origins: natural hazards arise from Earth system processes, anthropogenic processes stem from intentional human activities that alter the environment, and technological hazards result from unintended failures in human-made systems. In the context of this study, natural hazards, such as earthquakes, floods, or landslides, form the baseline for the analysis in both the Brenner Corridor and Noto. Anthropogenic processes, such as road construction or infrastructure loading, are particularly relevant in these settings where human intervention can weaken slopes. Technological hazards, exemplified by power outages or traffic accidents during storms, often interact with these natural events to exacerbate disruptions along transit corridors. While recognising the potential interactions among all three groups, this thesis primarily focuses on the sequences initiated by natural hazards, particularly landslides and earthquakes, as they represent the most documented and critical triggers in the selected 2023–2024 events. Anthropogenic and technological factors are discussed only insofar as they appear in the historical documentation of these specific cases.

Once these groups are identified, it is crucial to examine the interaction relationships between them. According to Gill and Malamud (2016), these dynamics define how one hazard influences another through three primary mechanisms:

- **Triggering:** A primary hazard directly initiates a secondary one (e.g., an earthquake triggering a landslide).
- **Increased probability:** A hazard enhances the likelihood of another event without directly triggering it (e.g., heavy rain saturating soil before an earthquake).
- **Catalysis or impedance:** An environmental condition or hazard accelerates or inhibits the intensity of subsequent events.

These interaction dynamics provide the necessary framework to analyse how damages were amplified during the multi-hazard events in Brenner and Noto.

3.1.3 Compound, Cascading, Concurrent and Extreme Events

Compound events refer to combinations of multiple extremes and/or background conditions that jointly lead to amplified impacts, including cases where individually moderate events become critical when combined. Cascading events describe chains in which an initial physical hazard triggers subsequent failures in human and infrastructural subsystems, resulting in multi-sector disruptions that can no longer be understood as a single event (Pescaroli and Alexander 2018; Alexander and Pescaroli 2019; De Angeli et al. 2022). Extreme events are defined as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (Seneviratne et al. 2012, p. 116). In mountain transport corridors, many realistic multi-hazard events involve compound, cascading, and extreme dynamics, for instance, when intense rainfall and/or snowmelt trigger landslides that then disrupt tunnel operations and wider regional mobility. Here, "intense rainfall" represents extreme events, "intense rainfall or snowmelt which triggers landslides, disrupting tunnel operations and wider regional mobility" overall represents cascading events, and if intense rainfall and snowmelt happen coincidentally at the same time, it is a compound effect. All of the above have adverse impacts on human society and the relevant ecosystems, of course; they all must be investigated equally, but in this thesis, cascading effects will be examined. The reason is to simplify the research process and ensure relevance between Brenner and Noto. There was a set of cascading events that occurred both on Brenner and Noto in 2024. In order to compare, we selected the case for each region involving heavy rain and landslides within the cascading chains. Also, we paid attention to whether these events experienced any type of protection measure disruptions, so that we could discuss what protection measures are effective and what need some improvements in the discussion and perspectives chapters, to provide recommendations for future research orientations.

3.2 Positioning the Comparative Approach within Multi-Hazard Frameworks

While multi-hazard frameworks such as Impact Chains have gained academic traction (Coccuccioni et al. 2023), their practical implementation still faces systemic barriers. As identified by Scolobig et al. (2014), these obstacles are rooted in disjointed conceptual definitions and disparate databases across different scientific sectors. In the context of this thesis, such institutional fragmentation becomes even more complex when comparing two distinct national frameworks, Austria and Japan, where scales, units, and risk cultures differ significantly. Furthermore, differences in the unique scales and units used to quantify risks and damage, such as the Richter scale and the Japan Meteorological Agency scale for representing earthquake impact magnitude, also contribute to this barrier. This makes sharing results and dialogue between risk communities difficult and complex. Such concerns are likely to become particularly apparent when seeking communication between geographically distant regions. As stated in the Introduction, the IPCC has suggested a link between multi-hazards and climate change (IPCC 2022). For instance, condensed rain saturates the ground, rendering it susceptible to landslides, and indeed, abnormal precipitation can trigger landslides. It is argued that as climate change progresses, the frequency of extreme events increases, heightening the likelihood that their impacts will trigger subsequent hazards. Considering that no region is immune to this situation, the approach to multi-hazards should involve cooperation that transcends national and regional boundaries. Indeed, projects such as PARATUS are international initiatives funded by the EU (Coccuccioni et al. 2023). It is reasonable to assume that cooperation should first be established between neighbouring countries and gradually extended to distant nations, especially when they are facing similar circumstances. Therefore, how to overcome the aforementioned concerns in the context of increasing international cooperation is a topic worthy of consideration.

Here, the Impact Chain comes into play. Petutschnig et al. (2023) states that it was originally developed as a standardised structure within GIZ's Vulnerability Sourcebook to support comparisons between different locations and policy decisions. Conceptually, the approach to IC in this thesis can be seen as an extension of that. However, this thesis does not aim for a climate risk and vulnerability assessment like Petutschnig et al. (2023)'s work; rather, it draws inspiration from the multi-hazard analysis of the PARATUS project (Coccuccioni et al. 2023). As a new challenge, it examines what lessons can be drawn by cutting out elements, such as exposure, vulnerability, and risk and focusing solely on hazards, their consequences, and the intervening role of slope protection measures. Also, while Wenzel et al. (2024) establish the broad cascading risks for the Brenner region within the PARATUS framework, this thesis shifts the focus toward evaluating the transferability of such conceptual chains by comparing two geographically and operationally distinct regions. By developing partial Impact Chains for both corridors, the analysis utilises historical documentation to qualitatively examine how slope protection and maintenance practices functioned within these cascading sequences. This approach aims not only to test the transferability of the Impact Chain framework across disparate hazard profiles but also to clarify the systemic role of maintenance in mitigating cascade escalation.

Thus far, we have examined the fundamental significance of comparing disasters in distant regions, drawing upon prior research. Regarding the Brenner Corridor specifically, Wenzel et al. (2024) provide a crucial foundation by developing Impact Chains to analyse multi-hazard interactions, such as floods and landslides, and their cascading effects on cross-border mobility. From here, we shall introduce prior studies that have addressed comparable cascading events in different countries. Albulescu et al. (2026) have recently published a paper examining the same hazards, the 2021 floods in Europe, in the two different countries, the Netherlands and Romania. This is what is known as a cross-country comparison, and in their research, they employed Impact Chains and metrics to examine the same flood-meteorological event.

In line with Baxter et al. (2019), transferability is understood here as the likelihood that similar outcomes can be achieved in a specific new context, while applicability refers to the feasibility of implementing the framework under local constraints. Within the multi-hazard context, European DRR initiatives already emphasise the need to transpose effective measures across social, cultural, and geographical contexts, for instance, through tools such as the ESPREssO Action Database (Baills et al. 2020).

3.3 Relevant Research of Brenner

A notable recent cascading event along the Brenner Corridor occurred during heavy rainfall from 30 to 31 October 2023 in Gries am Brenner, as documented in a couple of grey literature sources (Freiwillige Feuerwehr Gries am Brenner 2023; Haberler et al. 2024). At the A13 near the former customs office (km 33.75), a major debris flow ruptured a protection net, burying both carriageways and engulfing vehicles, which is examined in detail in Chapter 6. Adjacent to A13, the RoLa parking lot's rockfall protection nets effectively prevented falling of materials, highlighting functional slope protection in secondary infrastructure (Freiwillige Feuerwehr Gries am Brenner 2023).

Concurrently, during the same heavy rainfall night of 30–31 October 2023, multiple localised events affected surrounding areas: debris flows closed Obernberger Landesstraße and Vinaders; around 4:20, a hillslope debris flow in Obernbergtal (Au district) damaged a residential building and buried Obernbergstraße at km 3.5; rockfalls damaged Planken and Au structures; and Nösslach experienced flooding requiring vehicle recovery (Freiwillige Feuerwehr Gries am Brenner 2023; Haberler et al. 2024). These multi-hazard responses highlight the Brenner region's susceptibility to rainfall-triggered debris flows, with A13 disruptions exemplifying corridor-scale impacts on critical north-south connectivity across Europe. Although these events introduce compounding aspects within the multi-hazard framework, this thesis focuses exclusively on cascading sequences along A13 for efficiency in slope protection comparison.

For instance, the research conducted by Laimer (2017), including case studies along the Brenner Pass, focuses on anthropogenically induced landslides affecting railway lines but also examines slope instabilities related to forest roads and highways within the same alpine setting. Although his discussion of motorways is largely limited to "very small landslides and erosion problems . . . related to a somewhat insufficient highway drainage system" (Laimer 2017, p. 99), the mechanisms he identifies, such as inadequate drainage, fill slope construction, and instability of earthworks, are directly relevant to linear transport infrastructure in narrow mountain valleys, including the Brenner motorway corridor. According to his findings, more than 70% of landslides that occurred near Austrian railroads between 2005 and 2015 were caused by human activities, highlighting that hazard exposure in such corridors is shaped not only by natural processes but also by technical interventions and the configuration of infrastructure (Laimer 2017). In this valley-constrained setting, infrastructure elements are closely aligned and often spatially co-located, resulting in limited redundancy and strong interdependence between different transport modes, so that disruptions at critical nodes can propagate rapidly across the corridor and lead to broader functional disruptions to regional connectivity.

3.4 Relevant Research of Noto

For the Noto Satoyama Kaido, the 2024 Noto Peninsula Earthquake (Mw 7.6) provided critical evidence regarding the performance of road embankments under extreme seismic and secondary cascading hazards. As documented by the Ministry of Land, Infrastructure, Transport and Tourism (Ministry of Land, Infrastructure, Transport and Tourism 2024a) and further analysed by Chiba (2024), the damage patterns observed along the motorway highlight how past structural interventions influenced the physical consequences of the disaster.

According to the MLIT report (Ministry of Land, Infrastructure, Transport and Tourism 2024a), four primary tendencies were identified in the performance of road embankments:

1. Damage was concentrated in high embankments built over valley-filling stream deposits.
2. Sections restored following the 2007 Noto Peninsula Earthquake, which incorporated improved drainage measures, experienced only minor damage.
3. Conversely, adjacent unreinforced sections with similar environmental factors suffered significant subsidence and severe collapses.
4. Segments opened after 2013, where higher compaction standards were applied, sustained limited disruption overall.

These findings suggest that the physical configuration and prior structural reinforcements are decisive factors in determining whether a hazard initiates a cascading failure of infrastructure. While this thesis primarily focuses on the Noto Satoyama Kaido for its comparative potential, broader regional impacts further illustrate the complexity of such events. For instance, on National Route 249, large-scale slope collapses underscored the limitations of structural measures alone. Furthermore, even where infrastructure remained structurally sound, such as in certain tunnels, functionality was often impaired by slope collapses at portals, a clear example of how secondary hazard processes propagate disruption across the network (Ministry of Land, Infrastructure, Transport and Tourism 2024a).

Chiba (2024) concludes that systematising these characteristics is crucial for identifying future risks of embankment and slope failure. While this thesis does not perform a formal risk assessment, organising these damage characteristics provides a necessary foundation for understanding the physical mechanisms of cascade escalation in mountain transport corridors.

Based on the review of theoretical frameworks and region-specific studies provided in the previous sections, Table 1 synthesises the key literature to clarify the current state of the art. This comparison serves as a basis for identifying the remaining research gaps addressed in this thesis.

Table 1: Selected prior studies on hazard cascades and their implications for transport corridor continuity

Author (Year)	**Focus (Hazard/Area)**	**Key Findings / Methodology**	**Relevance / Research Gap**
Gill and Malamud (2016); De Angeli et al. (2022)	Multi-hazard concepts and interaction typologies	Systematised hazard interactions and the distinction between multi-hazard and multi-risk.	Established the conceptual framework for analysing cascading processes in this thesis.
Laimer (2017)	Austrian mountain corridors (incl. Brenner)	Over 70% of landslides (2005–2015) were anthropogenically induced. Issues in drainage/embankments.	Directly relevant to infrastructure-specific consequences along the Brenner motorway.
Wenzel et al. (2024)	Brenner Corridor (Austria-Italy)	Developed Impact Chains for cross-border mobility under compounding/cascading events.	The primary point of departure for this thesis, applying the PARATUS project's framework.
Petutschnig et al. (2023)	Climate risk and vulnerability assessment	Utilized Impact Chains to support standardized comparisons between locations.	This thesis extends the approach by focusing on the physical hazard cascade and consequences.
Ministry of Land, Infrastructure, Transport and Tourism (2024a) / Chiba (2024)	2024 Noto Peninsula Earthquake	Sections with 2007 drainage measures suffered minor damage. Compaction standards mitigated disruption.	Empirical evidence for the effectiveness of specific slope protection reinforcements.
Albulescu et al. (2026)	2021 European Floods (NL and Romania)	Employed cross-country comparison using Impact Chains and metrics for the same event.	Aligns with this thesis's approach of comparing distant regions and framework transferability.

3.5 Identified Research Gaps

While multi-hazard concepts and cascading hazard frameworks are well established, few studies systematically compare the effectiveness of slope protection measures, such as protection nets and embankments, across distant regions with differing geographical contexts. Specifically, the robustness of these measures to interrupt cascade sequences or limit secondary infrastructure damage remains under-explored in comparative qualitative research.

As seen in the previous sections, pioneering research such as Albulescu et al. (2026) and Coccuccioni et al. (2023) has demonstrated the Impact Chain's capability as a flexible conceptual framework to represent complex interactions between hazards, risks, and vulnerabilities. However, most existing applications focus on comprehensive risk assessments that require extensive data on exposure and vulnerability. This thesis identifies a research gap in the simplified application of this framework: by intentionally narrowing the focus to hazard sequences and the functional response of slope protection measures, it is possible to more clearly isolate and compare the physical mechanisms of cascade escalation.

Therefore, this study addresses this gap by applying a modified, partial Impact Chain approach to the Brenner and Noto corridors. This allows for a direct comparison of how structural interventions function across different regions, providing empirical insights into their role in mitigating landslide-driven cascades along critical mountain motorways.

4 Study Area

Understanding the study area is essential for contextualising the research and defining the boundary conditions of the partial Impact Chains developed later in this thesis. In this chapter, the Brenner Corridor and the Noto Satoyama Kaido are described with a focus on geography, their significance in transit, regional connectivity, and hazard environment, which serve as key inputs for the partial Impact Chain development and comparison analysis in "Results" and "Discussion" chapters. It establishes a foundation for analysing how infrastructure systems respond to multi-hazard challenges across different scales and governance contexts. Furthermore, the specific cascading hazard occurrence cases used for the comparative analysis between Brenner and Noto will be summarised, along with the associated research conducted to date.

4.1 Brenner Corridor: Austria - Italy

4.1.1 Geography

The Brenner Pass (elevation 1,370m, the lowest point on the main Alpine ridge) straddles Austria and Italy within the Central Eastern Alps. It serves as a vital Alpine crossing route linking Northern and Southern Europe (Fikar et al. 2016; Wenzel et al. 2024). More precisely, it is situated in the northern part of the Vipta Valley, cutting through the steep terrain leading to the Purgberg-Treibach mountain (elevation 3,097m). The area surrounding the pass is divided between the railway station and customs zone of the village of Brenner, and the narrow settlement of Gossensass at the foot of the steep slopes. Characterised by steep valley sides, rugged terrain, and a narrow valley floor, even after the motorway opened, the constricted valley floor continues to restrict the placement of transport infrastructure and increases the risk of slope failures and other hazards (Tirol Atlas 2013). Figure 1, adapted from Wenzel et al. (2024), depicts the Brenner Corridor from Kustein to Bolzano. The red line represents the Brenner Highway, while the red circle indicates the location of the A13 Gries am Brenner, where the cascading event under consideration in this thesis occurred. The map in the lower right shows its position at the centre of Europe. It is also evident from the hillshade that mountains surround the corridor.

4.1.2 Significance in Transit and Regional Connectivity

The Brenner Corridor, situated at the heart of Europe and serving as a vital hub connecting north-south transport routes, is consequently one of the most heavily utilised transit connections in Europe, whether by rail or motorway (Fikar et al. 2016, p. 123). First, it should be confirmed that the Brenner Pass is the principal mountain pass within Austria. According to the 2019 Survey of Alpine Crossings in Austria, overall, all ma-

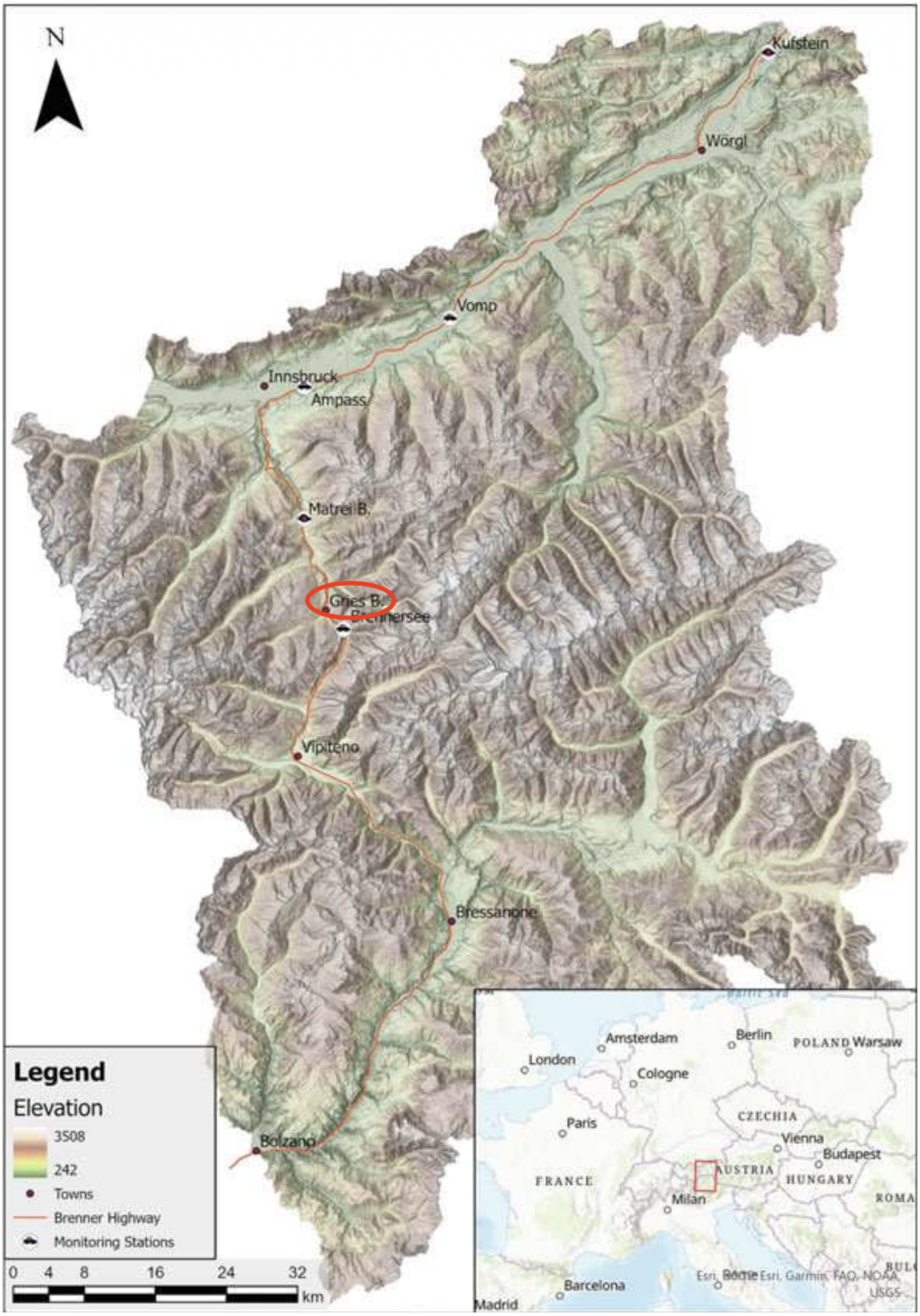

Figure 1: Location of the Brenner Corridor from Kufstein to Bolzano (red line: highway). Red circle marks A13 Gries am Brenner, site of the studied cascading event. Inset: European position; background: shaded DEM (adapted from Wenzel et al. (2024)).

jor Alpine crossings in Austria show an upward trend compared to the 1999 survey (road +73%, rail +30%). Among these, the Brenner Pass accounts for approximately 40% of Alpine freight transport in Austria. In 2019, a total of approximately 54.5 million tonnes were transported via the Brenner Pass, with nearly 90% of this being transit traffic (Wegscheider et al. 2022, p. 7). Additionally, the Brenner Pass maintains its position as the most important Alpine crossing internationally. Despite topographical constraints, this pass handles enormous north-south freight volumes at saturated transport capacity, playing a vital role within the international transport network. Specifically, this corridor is included within the Scandinavian-Mediterranean Core Network Corridor, and is recognised as the main bottleneck within it. This corridor, the longest among the EU's Core Network Corridors, stretches from Finland's border with Russia through Helsinki, Stockholm, and Malmö to reach Germany's ports at Hamburg and Rostock. It then follows heavy traffic routes westward via Hannover and eastward through Berlin and Leipzig, merging at Nuremberg before heading south to Munich, Verona (via the Brenner Corridor), Bologna, Rome, and Naples, with side branches to ports like Genova, Livorno, Bari, and Taranto, ending in Palermo and linking to Malta by sea (European Commission 2024; Cavallaro et al. 2024). Figure 2 visually illustrates how the Brenner Corridor, due to its topographical constraints, is a region where Europe-wide traffic is concentrated. The Brenner Base Tunnel, a major long-term tunnel construction project, is currently underway. Its purpose is to eliminate the bottleneck within the Scandinavian-Mediterranean Core Network Corridor and to realise a faster, more efficient network (Cavallaro et al. 2024).

4.1.3 Hazard Exposure

The region is highly exposed to multiple natural hazards, most notably landslides, rockfalls, avalanches, and forest fires, with documented events periodically affecting both road and rail operations (Ostermann and Sanders 2017; Laimer 2017; Wenzel et al. 2024). Seasonal climatic conditions, including heavy snowfall in winter and intense precipitation in summer, further increase exposure to hazard processes, and intense rainfall has repeatedly triggered landslides and debris flows along the corridor (Fikar et al. 2016).

4.2 Noto Satoyama Kaido, Noto Peninsula, Japan

4.2.1 Geography

The Noto region is situated on the Noto Peninsula, which juts out into the Sea of Japan in the central part of Mainland Japan, covering an area of approximately 2,400 square kilometres. Administratively, it comprises twelve municipalities in Ishikawa Prefecture and one city in Toyama Prefecture. Suzu City, Ishikawa Prefec-

Figure 2: Transport network including the Brenner Corridor. This map depicts the convergence of Europe-wide networks on the Brenner Corridor, underscoring its key role in the Scan-Med Corridor (Wegscheider et al. 2022, p. 62).

ture, situated at the peninsula's tip, the largest peninsula on Japan's Sea of Japan coast, lies approximately 110 km as the crow flies and about 140 km by road from the capital of Ishikawa Prefecture, Kanazawa City. It is approximately 80 km as the crow flies and about 160 km by road from Toyama City, across Toyama Bay. Fig 3 illustrates the geographical context of the Noto Peninsula, with the Noto region, the broad subject of this thesis, shown in red. In addition to the locations indicated on the map, Himi City (Toyama Prefecture) is also inherently included within the definition of the Noto Peninsula (Ministry of Land, Infrastructure, Transport and Tourism 2024e). However, as it is not part of the current review scope and is not traversed by the Noto Satoyama Kaido, it will not be treated as a special case. Here, we list the municipalities traversed by the Noto Satoyama Kaido and therefore subject to review: Kanazawa City, Uchinada Town, Kahoku City, Hōdatsushimizu Town, Hakui City, Shika Town, Nanao City, Anamizu Town, and Wajima City. These municipal names were used as keys during the literature review. Topographically, it comprises the gently rolling, quasi-plateau hills of the peninsula's north and low mountain ranges centred on Mount Hōdatsu, which stands at approximately 640 metres above sea level. The climate is typically rainy for the Sea of Japan coast, with Wajima recording an annual precipitation of approximately 2,100 mm. Peak rainfall occurs during winter, the rainy season, and the typhoon season (Ministry of Land, Infrastructure, Transport and Tourism 2024e). One of the two study sites of this thesis, the Noto Satoyama Kaido, constitutes a unique corridor due to its topographical characteristics. South of the Yanaida Interchange, it follows the coastline, while north of this point, it traverses the mountainous region of the Noto Peninsula. It's characterised by steep coastal slopes, narrow lowlands, and limited connectivity to inland areas. This corridor restricts alternative transport routes while heightening its importance as a primary access and evacuation route. Functionally, the expressway supports not only daily mobility and regional logistics but also plays a critical role in emergency response and post-disaster recovery.

4.2.2 Significance in Transport and Regional Connectivity

As mentioned in the previous section, the Noto Satoyama Kaido is a vital motorway connecting the Noto Peninsula to Mainland Japan. In recent newspaper articles covering its restoration following the 2024 Noto Peninsula Earthquake and following cascading hazards, this corridor was referred to as the "artery", reflecting how residents perceive its importance (The Asahi Shimbun 2024b). It has also been designated by the Ministry of Land, Infrastructure, Transport and Tourism as a Primary Emergency Transport Route. This designation applies to vital routes where passage for emergency vehicles must be secured immediately after a disaster to facilitate evacuation, rescue operations, and the supply of essential goods. These routes include expressways, national highways, and the key roads connecting them (Ministry of Land, Infrastructure, Trans-

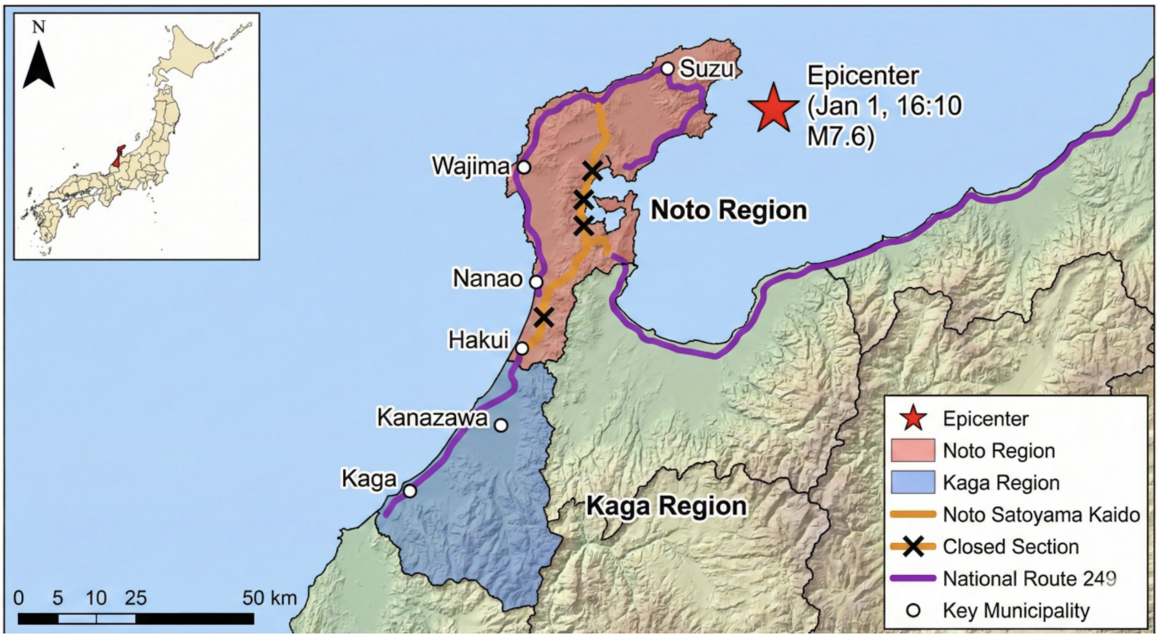

Figure 3: Geographical context of Noto Peninsula (red coloured area) and the Noto Satoyama Kaido (depicted as orange line; black crosses represent closed section during the 2024 Earthquake and aftermath), adapted from Ishikawa et al. (2026). he

port and Tourism 2008). In this thesis, National Route 249 is not included in the study area. This is because it is an entirely coastal road that does not run through mountainous terrain, whereas the Noto Satoyama Kaido snakes through hilly and mountainous sections. As the thesis focuses on slope protection measures on mountain corridors, including Route 249 would not allow for a meaningful comparison with the Brenner corridor.

4.2.3 Hazard Exposure

Historically, the Noto Peninsula has experienced numerous earthquakes and several different hazards associated with or induced by them. As a main regional lifeline, the corridor is highly vulnerable to earthquakes, landslides, and heavy rainfall. This vulnerability was clearly demonstrated by the 2024 Noto Peninsula earthquake, which triggered widespread slope failures and road disruptions across the peninsula, leading to extended closures of sections of the Noto Satoyama Kaido and connecting routes. These closures isolated communities, delayed the transport of relief supplies, and highlighted the challenges of maintaining corridor functionality in a region exposed to frequent, overlapping hazards (Peng et al. 2025). Governance and maintenance are primarily managed by national road authorities and the prefectural government, with decisions on closures and phased reopening directly affecting community isolation and access to essential services during hazard events. Indeed, it has been confirmed that the 2024 compound disaster involving earthquakes, landslides and torrential rain caused several tunnels to collapse, rendering the affected roads impassable (Chiba 2024). This prevented the securing of essential access routes for rescue operations, thereby hindering life-saving efforts. During this period, alongside road repairs, alternative methods such as air routes were attempted. However, the air route failed couple of times during the critical period due to the bad weather (Extreme Disaster Management Headquarters 2024a; Extreme Disaster Management Headquarters 2024b; Extreme Disaster Management Headquarters 2025).

4.3 Similarities and Differences between the two Study Sites

While the Brenner Corridor has trans-European significance, the Noto Satoyama Kaido's value is primarily regional, ensuring access, logistics, and continuity during crises within the peninsula. Nevertheless, both corridors share several structural similarities that make them suitable case studies for examining infrastructure resilience under multi-hazard conditions:

- Both function as geographically constrained transport lifelines with limited redundancy and strong dependence on a single corridor.
- Both are exposed to multiple interacting hazards that can generate concurrent, cascading, or compound impacts on transport infrastructure.
- In both cases, the functionality of the corridor is critical for sustaining mobility, logistics, and socio-economic continuity during and after hazard events.

At the same time, the cases differ with respect to spatial scale (trans-European vs regional), dominant hazard profiles (Alpine vs coastal–seismic), and governance arrangements (cross-border EU corridor vs nationally governed regional lifeline), providing a structured basis for the comparative framework developed later in the thesis.

5 Methodology

This chapter outlines the methodological framework used to investigate historical cascading hazard sequences, their interactions, and the documented consequences on the Brenner motorway and the Noto Satoyama Kaido motorway. The primary objective is to identify cross-regional lessons regarding the effectiveness of slope protection measures within these multi-hazard contexts.

The methodology follows a sequential, qualitative design consisting of:

1. **A semi-systematic literature review** to gather documented evidence of hazard events and protection strategies.

2. **The reconstruction and visualisation of cascading sequences** through simplified Impact Chains (ICs) to map hazard-consequence interrelationships.

3. **A comparative content analysis** between the Brenner and Noto cases, evaluating the divergence of slope protection effectiveness.

To ensure the research questions and hypotheses are addressed with methodological rigour, this study employs a qualitative synthesis of literature-derived evidence. This approach allows for the systematic identification of cascading event chains and the assessment of road impacts based on technical reports and academic studies. Crucially, the hypotheses are framed to be testable through this synthesis, allowing for clear validation (e.g., in a supported/unsupported form) of whether protection measures effectively mitigated the hazard cascades or consequences in each corridor.

The following sections detail the development of this conceptual framework and the specific analytical steps taken to execute this comparative analysis.

5.1 Literature Review Approach

The literature review aimed to examine documented cascading hazard sequences, their interactions and impacts on both the Brenner motorway and the Noto Satoyama Kaido motorway within the multi-hazard framework. Given that the two study sites are far apart, a semi-systematic review approach was adopted for the literature review. According to Snyder (2019), a semi-systematic review is suitable for providing an overview of a research area and tracing how a topic has developed over time. It is also presumed to be particularly effective for comparative research across widely separated regions, where historical studies are scattered, and a fully comprehensive search is challenging. Snyder (2019) also points out that a semi-systematic review can be combined with qualitative analysis, whereas a systematic review can primarily only be combined with quantitative analysis. This approach also aligns well with the aims of this thesis, as studies on cascading events along the distant Brenner and Noto are dispersed across multiple sources.

Sources were collected from u:search, Google Scholar, Science Direct, and other publisher platforms when necessary, using combinations of keywords such as "slope protection", "cascading hazards", "impact chain", "slope protection measures", and "Brenner Autobahn" and related terms. By linking these keywords with the Boolean operator "AND", focused results were obtained through 14 different search strings.

From these searches, a total of 43,252 records were identified across all databases. After removing duplicates and conducting a rigorous screening process of titles and abstracts based on the inclusion and exclusion criteria (Table 2), 18 relevant sources were systematically yielded from 5 of these search strings. The majority of the excluded literature concerned case studies from Noto, focusing specifically on hazards such as submarine landslides or pure earthquake engineering, which lacked the multi-hazard or infrastructure focus necessary for this comparative analysis.

To ensure a comprehensive qualitative synthesis, particularly regarding theoretical foundations and recent real-world incidents, these systematically identified sources were supplemented by 57 additional sources. These include 22 fundamental theoretical papers and Alpine-specific studies identified through prior research trajectories and backward snowballing (e.g., Gill and Malamud (2016)), as well as 35 official reports (e.g., Extreme Disaster Management Headquarters (2024a)) and selected news articles retrieved through targeted manual searches for event-specific data. In total, 75 sources were utilised for the analysis.

All search strategies, including the detailed results of the 14 systematic search IDs, snowballing (SN01), and prior knowledge (PK01) are detailed in the search ID table (Appendix A) and the literature management table (Appendix B) provided in the Appendices, following the guidelines by Karolinska Institutet University Library (2021).

5.2 Hazard Interaction Visualisation

Hazard interactions were visualised through impact chains, primarily following the conceptual approach proposed in the PARATUS project. Impact chains are used as analytical tools to trace how climate or natural hazards, exposure and vulnerability combine to generate impacts on specific systems (Coccuccioni et al. 2023; Albulescu and Armaş 2024). However, in this thesis, impact chains are adapted to focus only on hazards and their consequences documented for the Brenner motorway and the Noto Satoyama Kaido, explicitly incorporating slope protection elements as nodes and links. Therefore, particular attention was given to sequences where landslides affected road infrastructure and where slope protection measures influenced

Table 2: Inclusion/Exclusion Criteria

Category	Include	Exclude	Notes
Language	English, German, Japanese	All others	
Timeframe	Primarily last 10yrs; literature up to 2006 if scarce	Published before 2010 (normally excluded); exceptions are 1. older key works 2. literature relevant to the hazard on the Noto Peninsula on 25.03.2007	—
Topic/ Scope	Multi-hazard conceptual frameworks, hazard interactions, cascading effects, impacts, impact chains, slope failure, cascading events on the Brenner motorway (on 13.10.2024)/ Noto Peninsula (on 01.01.2024 or if relevant to the slope protection measures, on 25.03.2007)	Single events without link to hazards or infrastructure; purely social impact studies without infrastructure component; cascading hazards not on the Brenner motorway/ the Noto Peninsula; reports only on earthquake and submarine landslides	—
Document type	Peer-review articles, conference proceedings, high-quality government or intergovernmental reports, selected news articles*	Low-detail news items; sources lacking methodological transparency	*News articles can only be used when: 1. To provide recent, local, event-specific information 2. To illustrate social context, public perception, or responses to hazard events 3. When academic or official reports are lacking or outdated for particular sites, events, or community impacts.

the progression or impacts of cascading events, while risks, vulnerabilities, and exposures are deliberately omitted to avoid unnecessary complexity. The following elaborates on this unique adaptation of the impact chain framework. The impact chain approach proposed by the PARATUS project typically serves as a comprehensive visualisation tool that illustrates the interrelationships among key elements: hazard, exposure, vulnerability, impact, and risk, often presented in diagrammatic form. According to the PARATUS framework, while participatory workshops are often emphasised to capture socio-economic narratives, impact chains can also be validly developed through a desk-based analysis of scientific literature and evidence (Coccuccioni et al. 2023). Due to time and resource constraints, the latter approach was adopted in this thesis. Some versions of this framework even incorporate additional factors, such as global environmental change drivers, to contextualise evolving risk patterns over time. However, this thesis deliberately limits the scope to hazards and their direct consequences, as documented in the literature for the Brenner motorway and the Noto Satoyama Kaido, while explicitly positioning slope protection measures as central nodes and links within the chains.

This partial adaptation is necessary because the study relies exclusively on a qualitative reconstruction from existing literature sources. Incorporating exposure (e.g., traffic volumes, alternative routes) and vulnerability (e.g., material strength, geological conditions) would demand quantitative data such as GIS-based spatial analysis or detailed asset inventories, which are challenging to obtain comprehensively within the six-month timeframe of a master's thesis. As noted in Chapter 1, risk itself is not simply a product of hazard and consequence alone; it arises from their interaction with exposure and vulnerability, adjusted for capacities, often expressed through established equations like *Risk = Hazard × Exposure × Vulnerability / Capacity* (De Angeli et al. 2022). Without reliable quantitative inputs for these elements, including risk, would introduce unsupported assumptions and undermine the analysis's credibility.

By focusing solely on hazards, consequences, and slope protection, this approach maintains methodological rigour while enabling a clear comparative examination of cascade sequences across the two corridors. The benefits include enhanced transparency in tracing how slope protection intervenes in documented events (e.g., interrupting debris flows or attenuating secondary impacts) and feasibility for literature-only synthesis, directly supporting the research questions on measuring differences and effectiveness. While this partial chain omits a fuller risk picture, addressed as a limitation in Section 5.4, it prioritises depth in the core comparative axis over breadth, allowing meaningful insights into protection performance under cascading conditions.

Therefore, it is logically sound to focus on cascading chains involving instances where landslides impacted mountain corridors and where slope protection measures influenced the progression or effects of cascade phenomena, deliberately excluding risk, vulnerability, and exposure.

The reconstruction proceeded in four sequential steps. First, a preliminary "Event Description" was drafted for each case study to provide a qualitative overview of the disaster context based on initial literature screening. Second, a detailed "Event Inventory" was compiled to consolidate scattered information from multiple sources into a consistent structure, categorised into: (1) Hazard and Physical Processes, (2) Consequences, and (3) Emergency Response and Recovery. Third, these details were synthesised into a standardised "Event Chronology Table" (Tables 4 and 5). To ensure cross-case comparability between the disparate contexts of Brenner and Noto, a harmonised analytical framework was developed. As detailed in Table 3, this framework consists of four consistent fields, Time/Phase, Event Description, Slope Protection Role, and Road Impact & Response, allowing for a systematic alignment of scattered data into a comparable temporal progression. This step focused on filtering out non-essential details while specifically recording the timing of triggers, subsequent slope failures, and any reported protective or emergency measures. Finally, these chronologies were translated into partial Impact Chains.

In these diagrams, nodes represent individual hazard states or documented consequences (including slope protection elements), while arrows represent causal links documented in or strongly inferred from the literature. The primary purpose of these chains is not to quantitatively model physical processes but to integrate existing knowledge into a transparent, system-focused representation. Furthermore, these partial impact chains serve as the foundation for the comparative analysis between Brenner and Noto. These narratives describe, in chronological order, how the documented hazard sequences unfolded and where slope protection measures influenced the progression or attenuation of impacts. Consequently, both the chains and the narratives are best understood as qualitative, evidence-based reconstructions of historical events rather than independent scenario-modelling exercises.

Table 3: Harmonised fields used in the Event Chronology Tables (Tables 4 and 5) for chronology compilation

Field	Description
Time/Phase	Specifies the exact timing of the trigger or the specific recovery phase (e.g., Transition, Partial/Full Recovery).
Event Description	Describes the physical hazard process, including the triggering event (seismic loading or rainfall) and the resulting slope movements.
Slope Protection Role	Analyses how structural or operational protection measures responded to the hazard (e.g., resilience, failure, or need for upgrades).
Road Impact & Response	Summarises the systemic consequences for the road network and the corresponding emergency or restoration actions taken.

5.2.1 Hazard Selection Criteria

Brenner

For the Brenner corridor, this thesis focuses on a single, well-documented landslide case affecting the Brenner Autobahn (A13) near the former customs area at Gries am Brenner, as reported by GeoSphere Austria (Haberler et al. 2024). In this event, intense rainfall in the southern part of the Innsbruck-Land district led to flooding, debris flows, and a large landslide that blocked both carriageways of the A13 during the night of 31 October, with additional instability requiring further protective and remediation measures at the slope. This specific case is selected because it directly involves a highway slope in a mountain corridor setting that is comparable to the Noto Satoyama Kaidō, and because the documentation provides sufficient detail on triggering conditions, slope response, and subsequent safety measures to allow a meaningful comparison with the Noto case.

This case was selected because (i) it occurred directly on the Brenner Motorway (A13), (ii) it is documented by reliable institutional sources such as GeoSphere Austria, and (iii) it represents a recent cascading event in which intense rainfall triggered slope failures, making it temporally comparable to the Noto case under current discussions about increasingly condensed extreme precipitation in a changing climate. In addition, the magnitude and complexity of the event are well suited to the scope of a master's thesis, allowing a focused yet meaningful one-to-one comparison with the Noto Satoyama Kaidō corridor.

Noto

The 2024 Noto Peninsula earthquake (Mw 7.6) generated an extensive multi-hazard sequence, including more than 1,000 landslides across Ishikawa Prefecture, with several large-scale embankment collapses documented on the Noto Satoyama Kaidō itself; the overall scale and spatial spread exceed what can be exhaustively covered in this thesis. According to precipitation observations by the Japan Meteorological Agency at Shika City, a daily total of 29 mm of precipitation was recorded on 3 January 2024, which is interpreted here as a substantial rainfall event (Japan Meteorological Agency 2025b); consequently, landslides reported on and after the 4 January bulletin are regarded as having been triggered by a combination of earthquake shaking and rainfall, whereas earlier landslides are interpreted as primarily earthquake-induced. Precipitation data for Anamizu Town, which is located closer to the mountainous section of the Noto Satoyama Kaidō, largely contain missing values, making a detailed assessment of local hydrometeorological conditions difficult at present (Japan Meteorological Agency 2025b); future studies using higher-resolution and more complete precipitation datasets are expected to better constrain the timing and intensity of rainfall in this area.

To maintain a clear focus and ensure comparability with the Brenner corridor case, this study adopts explicit criteria for selecting events and evidence. First, with respect to spatial relationship, the analysis is restricted to the mountain corridor of the Noto Satoyama Kaidō and its surroundings; phenomena occurring outside the Noto Peninsula or at greater distances from the corridor are not considered further, so that the discussion remains centred on slopes that interact directly with the road infrastructure. Second, regarding hazard types, the thesis concentrates on the earthquake itself and on subsequent rainfall-related landslides, as these processes are directly responsible for slope instabilities affecting the corridor, and their timing can be reasonably reconstructed from official bulletins and meteorological observations. Third, in terms of consequences, emphasis is placed on slope instabilities and their implications for accessibility, emergency response, and local communities, rather than on a full inventory of all economic losses, in order to stay close to the core theme of slope processes and protection measures.

This delimitation allows a structured comparison between Noto and Brenner that is grounded in reproducible sources, such as reports by professional societies and documentation by Japanese authorities including MLIT and the Cabinet Office, while keeping the volume of data manageable for a master's thesis. The spatial focus on the corridor-scale environment also reflects how slope protection and hazard management are typically planned and implemented in practice, providing a realistic frame for interpreting both pre-existing measures and observed failures. If more detailed spatial information on individual collapses becomes available in future work, the corridor boundaries and distance thresholds used here can be refined accordingly, but such refinements would not alter the basic logic of separating predominantly earthquake-induced failures from those influenced by the subsequent rainfall event.

5.2.2 Review Process for Identifying Hazard Sequences

Although both cases followed a fundamentally similar systematic process for identifying and reconstructing hazard sequences from literature sources, several key differences in data availability, documentation styles, and contextual factors necessitate dedicated subsections for each. This modular approach not only highlights methodological adaptations to case-specific challenges but also enhances the overall reproducibility of the partial impact chain development, allowing future researchers to trace and replicate the sequence identification steps independently for each corridor. The primary differences include:

- Variations in referenced materials: For Brenner, reliance on Geosphere Austria's gravitational mass movement reports (e.g., Haberler et al. (2024)) contrasts with Noto's use of comprehensive Cabinet Office damage assessments and MLIT engineering surveys on post-2024 cascading events along the Noto Satoyama Kaido (e.g., Ministry of Land, Infrastructure, Transport and Tourism (2024f)).
- Differences in hazard scales: Brenner events involve localised heavy rainfall-induced landslides causing traffic disruptions confined to the Alpine vital route, whereas Noto's involved the Mw 7.6 earthquake, followed by cascaded hazards and consequences such as delayed heavy rains amplifying widespread landslides across the peninsula (sequential cascades, over several days).

This separation not only accommodates case-specific nuances but also facilitates direct cross-case comparison of sequence identification challenges, bridging European and Japanese documentation styles toward unified partial impact chain insights.

Brenner

The primary source for the Brenner case is the detailed Geosphere Austria report on gravitational mass movements in Austria for 2023 (Haberler et al. (2024)), which provides authoritative timelines and descriptions of the Gries am Brenner debris flow event. From this starting point, snowballing techniques were systematically applied to identify further sources, primarily high-quality news articles from German-language media like ORF and Der Standard, which offered eyewitness accounts and immediate post-event visuals. However, these initial materials left notable gaps, especially on precise hazard timelines, further details of the cascading hazards (such as the sequence from initial slope instability to road blockage), and the performance of slope protection measures like protective nets during the event. To complement this missing information comprehensively, an additional targeted literature review was conducted, incorporating peer-reviewed Alpine hazard studies to fill in the operational and structural response aspects critical to the impact chain.

Noto

For the Noto case, the primary source is the damage report series issued by the Cabinet Office, which meticulously documents the 2024 Noto Peninsula cascading events and impacts on infrastructure, including the Noto Satoyama Kaido. Snowballing techniques were then employed to expand the source pool, drawing primarily from complementary official documents such as MLIT report on road damages, JMA precipitation data, linking post-earthquake rains to secondary landslides, and selected news articles from Japanese media like NHK for supplementary timelines and residents' perception. The Cabinet Office reports are detailed and abundant, covering everything from fundamental information on each and every hazard that occurred to regional isolation effects, allowing a robust reconstruction of cascades. Specifically, the necessary information was gathered through a structured four-step process: First, targeted search keywords (e.g., "Noto Satoyama Kaido", "slope failure") were defined based on research questions. Second, these were systematically queried across the PDF reports using the search function. Third, the extracted timelines and sequence were cross-verified against MLIT/JMA reports and data to confirm causal links, such as earthquake-induced cracking followed by rain-triggered amplification. Fourth, snowballing identified any overlooked details that can help visualise the partial impact chain.

5.2.3 Drawing Process for Impact Chain

As a drawing tool, draw.io (https://app.diagrams.net/) was used. The visualisation process focused on mapping the sequential dependencies between hazards and their consequences based on the empirical evidence discussed in Chapter 6.

5.3 Comparative Content Analysis: Brenner vs. Noto

To contextualise the findings from the reconstructed impact chains of the Brenner corridor, a qualitative comparative framework was developed using the 2024 Noto Peninsula earthquake sequence along the Noto Satoyama Kaido as the reference case. This cross-regional comparison tests the transferability of the partial impact chain approach from a European Alpine setting (Brenner, a PARATUS study site) to a seismically active Japanese mountainous corridor, despite differences in hazard profiles and scale. The two sites were selected for their shared characteristics as narrow mountain motorways exposed to landslide-dominated cascades, with limited redundancy and high criticality for transnational (Brenner)/regional (Noto) connectivity. Both feature documented recent events (Brenner 2023 heavy rain-debris flow; Noto 2024 earthquake-rainfall-slope failures) where slope protection measures played a documented role, enabling direct assessment of intervention points in sequences. Differences, Alpine precipitation focus vs. seismic-rainfall cascading and protection nets vs. reinforced embankments, allow exploration of context-driven comparative analysis.

The comparison is structured along two main dimensions:

- **Hazard sequences**: Trigger types (e.g., rainfall intensity vs. seismic acceleration), cascade length/progression (number of links), and propagation patterns (spatial extent along corridor).
- **Slope protection effectiveness**: Measure types (design), positioning in chains (pre-trigger/pre-failure/post-impact), and documented outcomes (damage reduction).

Following Mayring (2014)'s structuring of qualitative content analysis, categories were deductively defined from theory, incorporating clear recording units and quantitative elements such as text shares per theme. To identify whether a specific document treats a particular topic as its primary focus, a three-step decision logic was applied: (i) explicit mention in the title, headings, or opening section (operationalisation of the recording unit); (ii) the text devoted to that theme occupying at least approximately 30% of total volume (integrating Mayring (2014)'s quantitative step of analysing category frequencies and volumes); and (iii) evidence of analytical depth indicated by causal explanations or quantitative details (following Mayring (2014)'s emphasis on systematic category definition and the establishment of clear evaluation criteria). Based on these criteria, the intensity of information in each document was systematically categorised into a four-tier scale (Primary Focus, Secondary Focus, Minimal Mention, and No Mention) to visualise the documentation density. By establishing our own evaluation criteria based on the ideas outlined in Mayring (2014)'s work, we aim to summarise and compare the focus of each key document and the descriptions relating to slope protection measures.

5.4 Limitations Relating to Methodology

The methodological approach of this thesis is subject to several limitations.

While the literature review draws on publications in English, German and Japanese, the use of multilingual sources inherently carries the possibility of interpretive variation. Also, as a non-native speaker of English and German, it cannot be denied that there may be a bias in the literature search. Differences in terminology, institutional vocabulary and hazard classification systems between languages may affect how certain concepts are represented. These risks were mitigated through cross-referencing of multiple documents.

Although the Impact Chain framework is typically used for comprehensive risk assessments, this thesis deliberately adapted it to focus on hazards and their consequences. This targeted scoping was chosen to ensure analytical depth in tracing specific hazard-sequence interactions and the responses of slope protection measures within the available research period. By focusing on qualitative reconstructions rather than a full-scale vulnerability assessment, the analysis prioritises the detailed examination of how physical cascades unfold in different geographic contexts. Additionally, the developed Impact Chains represent simplified conceptual models and do not replace physical or statistical modelling. The reconstruction of hazard sequences is inherently qualitative and relies on interpretive judgement based on documented historical evidence.

Differences between artificial embankments in Noto and predominantly natural slopes in the Brenner Corridor may limit the direct comparability of protection measures. In addition, the geographically distant locations (Japan vs. Austria-Italy) introduce contextual variations in climate, geology, regulatory frameworks, and socio-economic conditions, potentially complicating cross-case generalisations. These challenges were mitigated by focusing the comparative analysis on shared characteristics: both as critical mountain corridor motorways with slope protection measures, comparison of recent cascading events involving landslides (within the past three years under climate change influences), and ensuring analytical focus on transferable insights into multi-hazard impacts. Future studies could incorporate quantitative modelling or local fieldwork to validate these qualitative comparisons.

5.5 Usage of AI

To ensure the rigorous analysis of multilingual primary sources and to bridge the linguistic gap between Japanese (native), English, and German (non-native), this study utilised Machine Translation (MT) for initial drafting and Large Language Models (LLMs) as supplementary tools for translation and stylistic refinement. The primary objective of using AI was to maintain the transparency and accuracy of the author's original arguments while ensuring academic clarity in English. To mitigate the risk of hallucinations or unauthorised alterations to the research findings, a specific prompting strategy was employed. The AI was strictly instructed to act as a linguistic collaborator rather than a content generator. A representative example of the prompts used is as follows:

"*Please translate/refine the following text, adhering strictly to the author's original arguments and nuances without introducing any external information or unverified facts. If there are critical suggestions for clarity, please list them separately as bullet points.*"

6 Results of the Hazard Sequence Visualisation and Comparative Content Analysis

As outlined in Chapter 5 (Methodology), the Impact Chain framework, typically designed for comprehensive multi-hazard analysis incorporating hazards, consequences, vulnerability, exposure, and risk (Coccuccioni et al. 2023), was adapted here to focus solely on hazards and consequences. Two partial Impact Chain visualisations were thus developed using event-specific grey literature (primarily official reports and emergency logs). To ensure a systematic comparison, each case study is documented using an identical dual-layered approach: an event inventory and an event chronology table. The event inventory serves as the primary qualitative database, capturing detailed process interactions and responses of slope protection measures, which help in understanding the unique role of slope protection in each event. The event chronology table then provides these details in a standardised temporal sequence, offering the necessary abstraction to develop the subsequent Impact Chains. By presenting both the detailed collection of evidence (Inventory) and its temporal extraction (Table) side-by-side, this chapter provides a transparent process for developing the Impact Chains, thereby supporting the subsequent comparative analysis between Brenner and Noto. Building on these visualisations, hazard sequences for each event and documented slope protection performance were systematically extracted from relevant sources, then subjected to comparative analysis. As described in Chapter 5, this examined whether slope protection measures functioned effectively, via qualitative content analysis coding and counting selected keywords/phrases across the literature. Sections 6.1 and 6.2 present these results for each study area. First, the narrative descriptions for each event (Section 6.1.1 and 6.2.1) are provided to offer a bird's-eye view of each event; this ensures the reader understands the essential context before engaging with more technical and detailed information. Then, the event inventories (Section 6.1.2 and 6.2.2) are used to elucidate the interrelationships between hazards and impacts by categorising all documented details. These are followed by the event chronology tables (Table 4 and 5) that standardise the temporal sequences. Finally, the developed Impact Chain diagrams (Fig. 4 and 5) are presented. It should be reiterated that all this content was derived from the literature, and no stakeholder workshops, as recommended by the PARATUS project, were conducted. The reason for this, as outlined in the Methodology chapter, is to examine whether it is even possible to construct an impact chain based solely on a literature review without holding stakeholder workshops, and, if so, whether there is a significant difference in its significance compared to cases where stakeholder workshops were conducted. This addresses the research question 1 (RQ1), which will be answered based on the results presented throughout this chapter. Furthermore, a synthesis of findings for all RQs and hypotheses will be specifically provided in Section

6.3.3. Based on these two visualisations, we then present the results of a content analysis examining the extent to which slope protection measures were effective in each region and how they were documented.

6.1 The Cascading Hazards in the Brenner Autobahn

6.1.1 Event Description

On the night of October 31, 2023, a prolonged heavy rainfall triggered a debris flow event, which eventually disrupted the A13 Brenner Autobahn in both directions at km 33.75 (over $\sim$80 m), close to the former customs checkpoint at Gries am Brenner, which buried a northbound vehicle (occupants unharmed), leading to a complete closure of the road for several days (ORF Tirol 2023). Thereafter, until geological assessments were completed and the road was fully reopened, a single-lane counterflow operation was in place for several weeks (5min.at 2023). This event exemplifies cascading multi-hazards in alpine corridors, where intense precipitation triggered slope failure despite protective measures.

6.1.2 Event Inventory

The following subsections provide a comprehensive inventory of facts regarding the Brenner debris-flow cascade, categorised by hazard mechanisms, slope responses, consequences, and recovery measures. While Table 4 summarises the temporal progression and specific timings of the event to provide a chronological foundation, this qualitative outline emphasises the process interactions and protection measure responses necessary for constructing the subsequent Impact Chain.

1. Hazard and Physical Process

- **Trigger Mechanism: Intense Rainfall**
  Heavy and sustained downpours from late Monday into early Tuesday saturated the steep west-facing slopes above the A13 motorway at km 33.75. Data from Land Tirol (2023) show, precipitation reached a maximum of 118 mm/day—120–200% of the long-term average in the Brenner region, aligning with regional extremes across Tyrol and climate, amplified patterns that initiated significant slope instability (Haberler et al. 2024). According to GeoSphere Austria (2023), a heavy rain warning had already been issued the day before.

- **Primary Hazard: Debris Flow Mobilisation**
  At approximately $\sim$02:40 AM, a debris-laden flow involving loose rock masses and uprooted trees overtopped and breached existing slope protection measures (protection nets). The landslide incor-

porated significant woody debris, which increased the destructive force of the flow as it descended toward the motorway lanes (Haberler et al. 2024).

- **Slope Instability** Post-event geological assessments identified approximately $4,000\,m^3$ of unstable material remaining on the slope. Coupled with unfavourable weather forecasts, this residual mass posed a continuous threat of secondary slides, dictating the duration of the emergency phase (Haberler et al. 2024).

2. Consequences

- **Failure of Slope Protection Measures**

  Existing protection nets were breached by the momentum of the flow. While the nets partially intercepted the debris and likely prevented more severe damage to vehicles, the volume exceeded their design capacity, resulting in the total blockage of the corridor (Haberler et al. 2024; ORF Tirol 2023).

- **Immediate Impacts: Motorway Blockage**

  A full closure in both directions halted critical TEN-T north-south freight (54.5 Mt/Year; Cavallaro et al. (2024)). Although a northbound vehicle was struck and engulfed by the debris, both occupants were rescued unharmed. This lack of fatalities suggests that even in structural failure, the protection measures provided a critical temporal and physical buffer (ORF Tirol 2023; Haberler et al. 2024).

- **Impacts on Regional Connectivity** The closure of the A13 necessitated an immediate traffic diversion via the B182 (Brennerbundesstraße). Given the inherent capacity constraints of the local road network compared to the motorway, ASFiNAG anticipated significant traffic disruptions, particularly affecting the morning rush hour (meinbezirk.at 2023).

3. Emergency Response and Recovery

- **Emergency Stabilisation Measures** The voluntary fire brigade (Freiwillige Feuerwehr Gries am Brenner) conducted initial clean-up using heavy machinery. ASFiNAG subsequently coordinated the removal of the loose material and stabilised the slope to prevent further cascades (Freiwillige Feuerwehr Gries am Brenner 2023; 5min.at 2023).

6.1.3 Event Chronology Table

As mentioned above, Table 4 aims to clearly depict the timeline and sequence of events. For clarity, certain terms related to phases are predefined here, fundamentally common to both the Brenner and Noto cases.

Phase: Divided into three categories based on road openness for later comparative analysis.

1. Transition: Phase where emergency response work, such as emergency road opening, is underway.
2. Partial Recovery: State where traffic functions have recovered (e.g., single-lane functionality restored) but due to imperfections, inconveniences remain.
3. Recovery: State where not only traffic functions have recovered, but restoration has reached pre-hazard levels.

Additionally, to ensure the transparency and reliability of the reconstructed timeline, specific sources are noted individually within each table cell. This reflects the process of cross-referencing multiple grey literature and news articles to build a comprehensive chronology.

Besides, three points are clarified before presenting the table.

- **Information Volume and Event Scale**: The difference in the volume of information between the two tables reflects the distinct spatial and temporal scales of the events. While the Brenner case focuses on a localised, rapid debris-flow cascade, the Noto case covers a wider geographic area and a more prolonged sequence of seismic and pluvial interactions, necessitating a more extensive documentation of events.
- **Classification of Elements**: The columns are categorised to align with the subsequent Impact Chain development and comparative analysis: 'Event Description' primarily captures the hazards (and operations where appropriate), 'Slope Protection Role' focuses on the structural responses (process), and 'Road Impact and Response' documents the direct consequences (impact). This ensures a consistent transition from raw data to the visualisation process.
- **Temporal Resolution**: The temporal resolution of the tables varies depending on the intensity of the event phase. High-resolution (daily) entries are used for the acute hazard phase, where rapid changes occurred, whereas lower resolution (weekly or monthly) is applied to the recovery phase to capture long-term restoration processes and cumulative efforts.

6.1.4 Partial Impact Chain Visualisation

Based on the event inventory and chronological data presented in the previous sections, a partial Impact Chain was constructed to visualise the causal relationship between the documented hazard and consequences (see Figure 4). The visualisation illustrates how the primary trigger—heavy rainfall—propagated through the physical failure of slope protection systems to result in a cascade of impacts. Specifically, it

Table 4: Chronology of the Brenner A13 Debris-Flow Event and Response Strategy

Time/Phase	Event Description	Slope Protection Role	Road Impact & Response
30–31 Oct 2023	Prolonged intense rain saturated west-facing slopes above A13 (km 33.75) (Haberler et al. 2024).	Existing protection nets in place.	No immediate impact; slope saturation initiated.
02:40, 31 Oct	Debris flow (loose rock and wood) descended from a steep gully (Haberler et al. 2024).	Nets breached by mass momentum (Haberler et al. 2024; ORF Tirol 2023).	Full closure; northbound car engulfed (occupants unharmed, no fatalities)(Haberler et al. 2024; ORF Tirol 2023).
Immediate Post-failure	Initial emergency response by FF Gries am Brenner and ASFiNAG (Freiwillige Feuerwehr Gries am Brenner 2023).	Nets may have provided a critical buffer despite structural failure.	Diversion via B182; significant traffic disruptions anticipated (ORF Tirol 2023; meinbezirk.at 2023).
Days after (Transition/Partial Recovery)	Heavy machinery deployed for clearance; 4,000 m^3 unstable mass identified (Haberler et al. 2024).	Remaining measures deemed insufficient due to slope instability; further sliding risk.	One lane per direction reopened; prolonged partial closure initiated (5min.at 2023).
Several Weeks (Recovery)	Targeted maintenance and removal of residual 4,000 m^3 material (Freiwillige Feuerwehr Gries am Brenner 2023; 5min.at 2023).	Stabilisation and repair of the protection system.	Full restoration and reopening following finalised works.

maps the sequence from the rupture of a protection net to the long-term closure of the A13. This diagram serves as a conceptual framework for understanding the cascade of consequences following the structural failure, bridging the gap between raw event data and the subsequent socio-economic impacts. Additionally, it highlights how residual slope instability, identified post-event, necessitated prolonged operational restrictions to ensure safety.

6.2 The Cascading Hazards in the Noto Satoyama Kaido Motorway

6.2.1 Event Description

As described in Chapter 4, the Noto Satoyama Kaido was subject to extensive retrofitting following the 2007 earthquake (Mw 6.9). These measures, including geotextile-reinforced soil and drainage improvements, were specifically designed to mitigate embankment failures in the region's stream-filled catchment terrains (Morimoto et al. 2017; Tsukada 2024). The 1 January 2024 earthquake, however, represented a cascading event where the seismic intensity significantly surpassed these pre-existing design limits. The Mw 7.6 main-

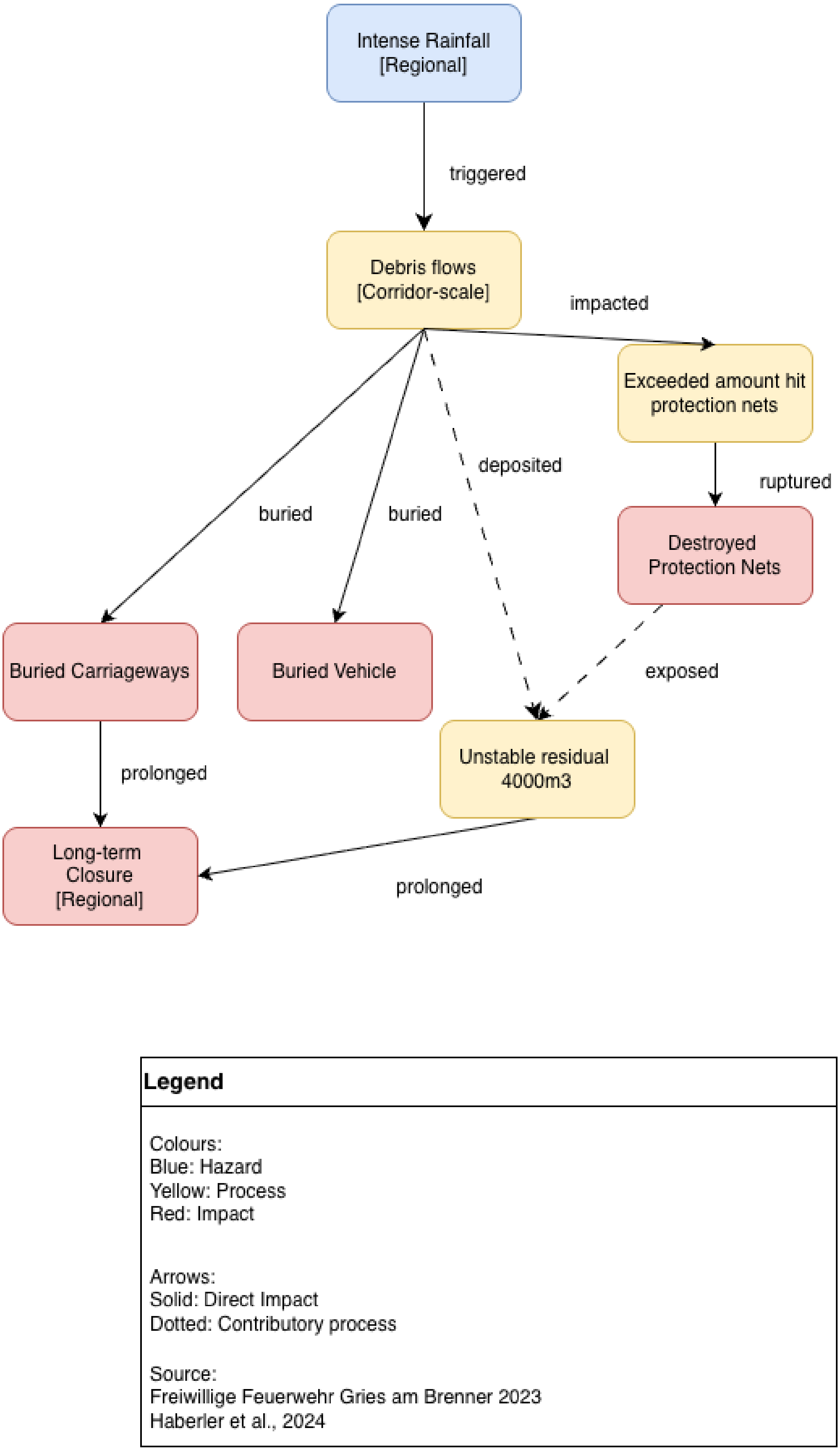

Figure 4: Partial Impact Chain for the A13 Gries am Brenner debris-flow cascade (30–31 Oct 2023, km 33.75) (Haberler et al. 2024; Freiwillige Feuerwehr Gries am Brenner 2023).

shock triggered a new sequence of large-scale collapses across mountainous sections, particularly in high-fill embankments. To maintain consistency with the Brenner case study, the following sections adopt the same structural framework: identifying the sequence of hazards, the structural response of slope protection measures, and the subsequent consequences. Given the magnitude of Mw 7.6, the earthquake's impact was geographically extensive, resulting in diverse damage across the country. However, as justified in the methodology (Chapter 5), this analysis focuses specifically on the Noto Satoyama Kaido. This corridor is designated as a Primary Emergency Transport Route by MLIT and plays a vital role in connecting the peninsula tip to the wider region. By visualising the hazard sequence, including responses of slope protection measures, the aim is to compare and contrast two distinct corridors and to highlight the interrelationships among hazards, slope protection measures, and consequences. Accordingly, Table 5 provides a chronological summary of the relevant hazard sequences, from the initial seismic trigger to the resulting regional isolation, based on evidence derived from recent technical surveys and literature sources (Chiba 2024; Ministry of Land, Infrastructure, Transport and Tourism 2024f; Extreme Disaster Management Headquarters 2024a).

6.2.2 Event Inventory

The following subsections offer a comprehensive inventory of documented facts for the Noto Satoyama Kaido corridor earthquake-landslide cascade, organised by hazard mechanisms, slope (embankment) responses, consequences, and recovery measures. Table 5 offers a chronological summary of key timings and progression, laying the groundwork for analysis, while this outline highlights process interactions and slope protection responses essential to the subsequent Impact Chain. The whole structure mirrors that of the Brenner case study, to ensure the application of the same framework, so that one can compare the two hazard cascades that occurred in distinct places yet under comparable conditions.

1. Hazard and Physical Process

- **Trigger Mechanism: Mw 7.6 Mainshock**

  On 1 January 2024, the Noto Peninsula Earthquake (JMA intensity 7) generated extreme seismic loading. According to Ministry of Land, Infrastructure, Transport and Tourism (2024a), the intensity of the ground motion exceeded the seismic design standards established during the post-2007 restoration works.

- **Primary Hazard: Embankment Instability and Collapse**

  The intense shaking triggered continuous and large-scale collapses of high embankments. These failures were concentrated in stream-filling sections, where topographical factors and groundwater pathways combined with the high seismic intensity to cause a sudden loss of shear strength in the fill material, leading to massive structural breaches across the motorway (Ministry of Land, Infrastructure, Transport and Tourism 2024a; Chiba 2024; Tsukada 2024).

2. Consequences

- **Slope Protection Response: Damage Patterns by Embankment Condition after the Earthquake**
  As reported by Ministry of Land, Infrastructure, Transport and Tourism (2024a), the embankment damage along this corridor fell into three primary patterns.
  - Non-retrofitted sections with similar pre-existing risk factors: severe damage (e.g., major subsidence)
  - Sections retrofitted after the 2007 Earthquake: In many of those sections where combined measures such as geotextile-reinforced soil, enhanced drainage, and retained embankments were implemented, the damage was limited to minor ones.
  - Sections reconstructed with improved soil: notable collapses and/or subsidence in some cases.
- **Immediate Impacts: Road Network Disruption**
  Closures of the Noto Satoyama Kaido corridor (e.g., Fig. 3 black crosses on the map) significantly hindered relief operations.
- **Isolated Communities**
  Due to road closures on a maximum of 42 routes, including the Noto Satoyama Kaido at 87 locations, isolated villages occurred one after another.

3. Emergency Response and Recovery

- **Emergency Road Opening**
  The immediate response focused on road opening to secure routes primarily for emergency vehicles. [1] While the Self-Defence Forces (SDF), in cooperation with the private sector, initiated clearing on several prefectural roads to bypass major blockages on the Noto Satoyama Kaido corridor, the corridor itself remained constrained by numerous embankment failures (Extreme Disaster Management Headquarters 2025, p. 78).

[1] Road opening refers specifically to the process of clearing a route primarily for emergency vehicles, by carrying out minimal debris clearance and making simple adjustments to uneven surfaces. This measure is carried out particularly during the large-scale disaster recovery phase in Japan to ensure effective rescue operations (Ministry of Land, Infrastructure, Transport and Tourism 2024d).

- **Phased Restoration Strategy**

  Recovery of the corridor followed a phased approach: prioritising the resolution of community isolation through temporary emergency access, followed by the restoration of single-lane traffic, and eventually full two-way functionality (Ueda 2024). During the single-lane traffic phase, while the northbound lane (bound to the peninsula tip) was fully opened, the southbound lane (bound to the wider community) required the use of general roads, causing congestion in the evening (The Asahi Shimbun 2024a).

- **Delegation of Recovery Authority** Given the extensive damage along the corridor, with 27 sections having collapsed, and instability was also confirmed in the embankments that had not yet collapsed. Consequently, the government has agreed to undertake restoration work on the Noto-Satoyama Kaido, which is typically managed by Ishikawa Prefecture, which owns the corridor, legally speaking (Yamakoshi 2024, p. 257).

- **Secondary Hazard Mitigation: Adjusted Rainfall Warning Thresholds**

  In response to the earthquake's intensity, the Japan Meteorological Agency (JMA) has lowered the threshold for issuing a heavy rain advisory to 70-80 % of the usual level. Immediately after the earthquake, rain was forecast for several days, and heavy rain actually fell, leading to a heavy rain advisory. The maximum daily total precipitation in the region along the Noto Satoyama Kaido (Shika, Nanao, and Mii[2]) was 29 mm. (Japan Meteorological Agency 2025b).

- **Long-term Recovery and Measures** In July, nearly the full route resumes two-way traffic, excluding heavily damaged sections, around the Noto Ohashi bridge vicinity. Full restoration is completed by 10 September, including the Noto Ohashi vicinity (The Asahi Shimbun 2024a). However, all of this merely completes the emergency repairs; improvements to the slope protection measures are required based on the lessons learnt from this hazard sequence (Ministry of Land, Infrastructure, Transport and Tourism 2024a; Chiba 2024). Additionally, traffic conditions returned to pre-earthquake levels by the end of 2025, with full restoration—including further slope protection improvements—anticipated around spring 2027 (Ministry of Land, Infrastructure, Transport and Tourism 2024b).

[2] As mentioned in 5.2.1 Hazard Selection Criteria for Noto case in the Methodology Chapter, strictly speaking, data from Anamizu Town would better match the corridor's path, but since Anamizu's precipitation data were missing, data from the adjacent Mii area were used instead.

6.2.3 Event Chronology Table

Table 5 represents the timeline of the cascade, having the same structure as the table for the Brenner case. The phases indicated in Table 5, Transition, Partial Recovery, and Recovery, follow the same definitions as those established for the Brenner case (see Section 6.1.3), ensuring a consistent basis for the subsequent comparative analysis. To maintain the same approach as the Brenner case, specific sources are added within each table cell as well, ensuring transparency of the cross-referenced timeline.

6.2.4 Partial Impact Chain

Using the event inventory and chronological data outlined earlier, a partial Impact Chain illustrates the links between documented hazards and their consequences for the Noto case (see Figure 5). The visualisation depicts how the primary trigger—the January 1 earthquake—acted on slopes and embankments, leading to embankment failures. As described in the event inventory (Section 6.2.2), slope protection measures along the corridor fell into three main categories, each resulting in slightly different embankment failure outcomes. However, the earthquake's intensity exceeded the assumptions during the 2007 retrofits, ultimately causing all three types to collapse; this led to multiple road breaks where embankments had supported the structure, rendering sections impassable and resulting in full closure. Consequently, a maximum of 33 villages became isolated. Additionally, heavy rain—equivalent to a rain advisory—fell two days after the earthquake, triggering further instability and embankment failures that exacerbated the isolation.

6.3 Comparative Analysis

Based on the individual results presented in Sections 6.1 and 6.2, this section conducts a comparative analysis to identify the commonalities and differences between the Brenner and Noto cases. Given the numerous contextual differences between the cases, the primary objectives are to extract shared elements and explore potential lessons learnt from them. This analysis then directly addresses Research Questions 1–4. To clarify the analytical framework, Table 6 outlines how each question and its hypothesis are evaluated against the collected evidence.

6.3.1 Similarities and Differences in Hazards Cascades

While both the Brenner and Noto cases represent typical hazard cascades triggered by environmental forces, they exhibit fundamental differences in their triggering mechanisms and sequential progression. In the Brenner case, the cascade followed a relatively linear path: intense rainfall led to localised debris flows,

Table 5: Chronology of the Noto Satoyama Kaido Earthquake-induced Cascade and Recovery Process

Time/Phase	Event Description	Slope Protection Role	Road Impact & Response
1 Jan 2024, 16:10	M_w 7.6 Earthquake (JMA Intensity 7); multi-point embankment failures	Load exceeded 2007 design; retrofitted sections showed relatively higher resilience	Full closure of the entire corridor, due to numerous embankment failures.
2 Jan 2024	Emergency Road Opening on bypass routes (Extreme Disaster Management Headquarters 2025, p. 78).	Damage more extensive than 2007; priority shifted to non-motorway repairs for more effective rescue operations	Noto Satoyama Kaido remained damaged at 67 locations (Ministry of Land, Infrastructure, Transport and Tourism 2024f); rescue operations were hindered.
3–5 Jan 2024	Post-earthquake rainfall (max. 29 mm/day); Heavy rain advisory issued (Japan Meteorological Agency 2025a, p. 29). Simultaneous closures of the Noto Satoyama Kaido and National Route 249.	Lack of reinforced protection led to additional landslides under secondary rainfall across Ishikawa Prefecture, including Noto Peninsula (Extreme Disaster Management Headquarters 2024b, p. 17).	Maximum isolation of communities: 33 villages/towns recorded. Affected population max. 3,345 people (Ministry of Land, Infrastructure, Transport and Tourism 2024f).
Late Jan 2024 (19–23 Jan) (Transition)	Emergency access secured through the corridor.	Additional embankment instability confirmed; due to the extensive damage, the National gov. took over the restoration (Yamakoshi 2024, p. 257)	Substantial resolution of community isolation; relief logistics improved (Ministry of Land, Infrastructure, Transport and Tourism 2024c).
15 Mar 2024 (Partial Recovery)	Completion of emergency opening (The Asahi Shimbun 2024b).	Single-lane functionality restored (Northbound only)	Partial reopening (Northbound only); Southbound congestion via general roads (The Asahi Shimbun 2024a).
July–Sept 2024 (Recovery)	Resumption of two-way traffic on nearly full route; 10 Sept: Full restoration including Noto Ohashi vicinity (heavily damaged area) (The Asahi Shimbun 2024a).	Completion of emergency repairs; long-term slope protection upgrades required based on event lessons (Ministry of Land, Infrastructure, Transport and Tourism 2024a; Chiba 2024).	Projected return to pre-quake traffic by late 2025; permanent embankment improvements anticipated by spring 2027 (Ministry of Land, Infrastructure, Transport and Tourism 2024b).

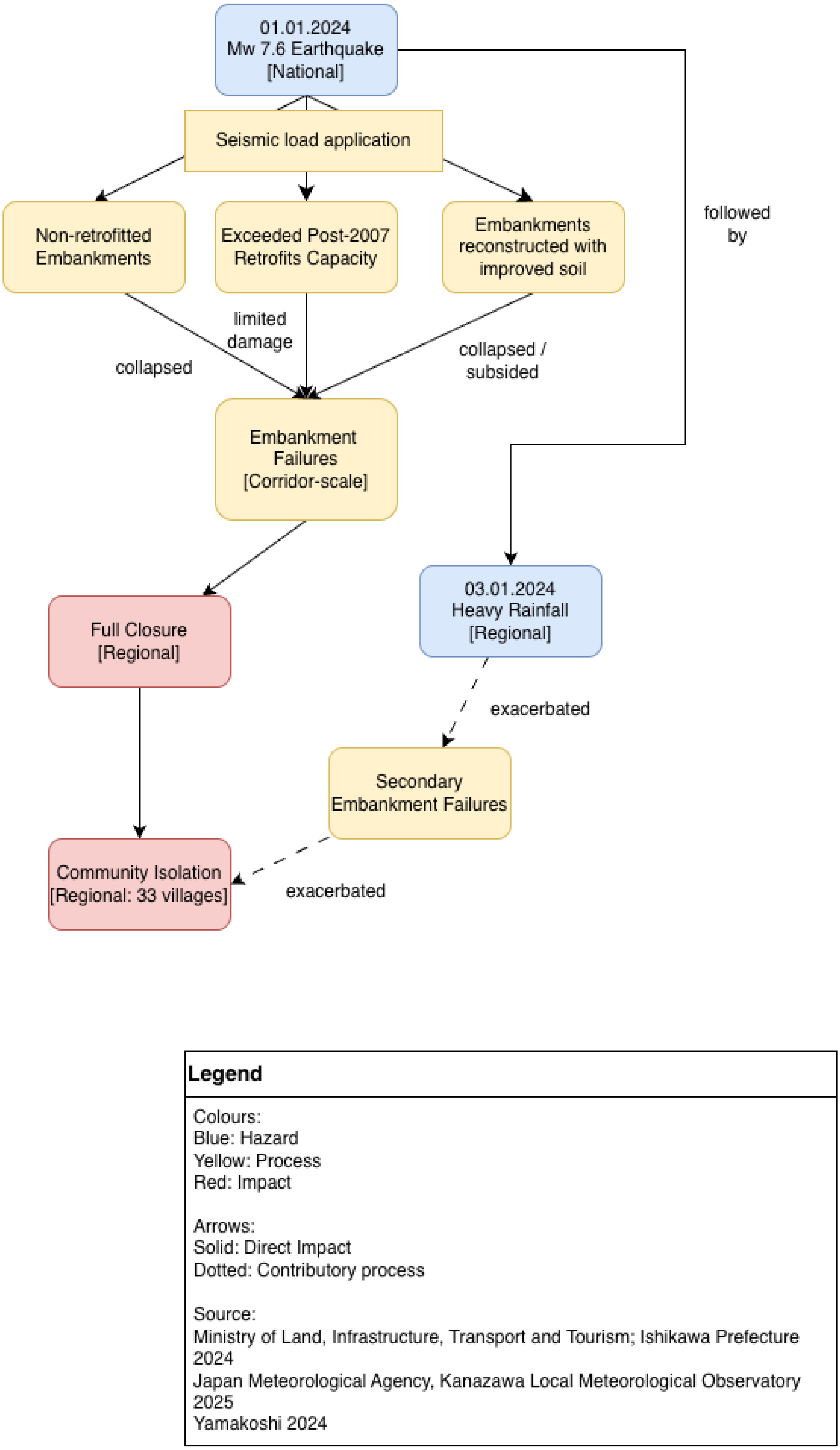

Figure 5: Partial Impact Chain for the Noto Satoyama Kaido motorway cascade (01–03 Jan 2024, km 90) (Ministry of Land, Infrastructure, Transport and Tourism 2024f; Japan Meteorological Agency 2025a; Yamakoshi 2024).

Table 6: Mapping of Research Questions/Hypotheses to Relevant Analysis and Discussion

ID	Research Question	Hypotheses	Relevant Analysis
RQ1	Transferability of simplified ICs: 1a. Effectiveness of desk-based development? 1b. Effectiveness of partial factor adaptation?	H1a. Desk-based development is sufficient for chronological reconstruction. H1b. Partial adaptation is a valid tool for prioritising interrelationships.	Sections 6.1 and 6.2 (IC development); Findings 1 (6.3.3); methodological reflections in 7.1.1.
RQ2	Difference of slope protection measures between corridors?	Brenner relies on protection nets, while Noto prioritises embankments.	Comparison of 'Slope Protection Role' in Table 4 and 5. ; Synthesis of slope protection measures in Section 6.3.2; Finding 2 (6.3.3).
RQ3	Contextual factors influencing the divergence?	Driven by distinct regional historical hazard patterns.	Identified as a data gap in Finding 3 (Section 6.3.3); further addressed through inferential analysis in Section 7.4.
RQ4	Do slope protection prevent or limit cascading effects from landslides on these corridors?	Literature on each case indicates slope protections contribute to mitigating further cascading effects from landslides in these corridors.	Finding 4 (Section 6.3.3), based on the integrated results from 6.3.1 and 6.3.2.

which directly impacted the road infrastructure. In contrast, the Noto case presents a more complex multi-hazard interaction. Due to the distinct geographical and geological contexts of these two distant regions, the divergences outnumber the similarities. The following table (Table 7) summarises these key characteristics before diving into a detailed comparative analysis.

First, intensity and frequency are essential factors in understanding the magnitude of these cascades. In the Brenner case, the event was preceded by an extraordinary meteorological anomaly; a heavy rain warning was issued for a record-breaking maximum precipitation of 118 mm/day. Although a specific return period was not identified in the available literature, the rainfall reached 120–200% of the long-term average precipitation for the region, confirming its extreme nature (Land Tirol 2023). Similarly, the Noto event was triggered by a Mw 7.6 earthquake, a major seismic event. Although its moment magnitude was smaller than that of the catastrophic Mw 9.0 Great East Japan Earthquake of 2011, it reached the maximum level of 7 on the JMA seismic intensity scale, representing the highest possible level of ground shaking. Regarding frequency, while a similar cascade sequence occurred 17 years ago in 2007, the intensity of the 2024 event surpassed its predecessor. Although some media reports suggested a return period of several thousand years (The Sankei Shimbun 2024), peer-reviewed geological data remains limited. Therefore, this study treats the event as a rare, large-scale earthquake within a broad range of 10^3 to 10^4 years. This extreme rarity and high intensity

Table 7: Summary of Key Characteristics and Divergences in the Observed Cascades

Attribute	**Brenner Corridor**	**Noto Satoyama Kaido**
Hazard Intensity	High-intensity prolonged rainfall of max. 118 mm/day: A heavy rain warning issued	Mw 7.6/JMA intensity 7 (Earthquake) + Heavy rainfall max. 29 mm/day
Damage Magnitude	Concentrated volume (more than 4000m^3)	Distributed damage sections (67 damages in total on the Noto Satoyama Kaido motorway and its embankments); total mass unquantified
Historical Frequency	120–200% of long-term average precipitation in the Brenner region (Land Tirol 2023)	Recurring cascade; similar cascade (earthquake-induced embankment failures) occurred in 2007.
Slope Characteristics	natural slope with vegetation and protection nets	Artificial embankments with local improvements based on 2007 lessons
Primary Trigger	Heavy Rainfall (Meteorological)	Earthquake (Seismic)
Warning Lead Time	24 hours	5–10 seconds
Warning Operational Adjustments	Standard meteorological thresholds	Thresholds lowered to 70-80% of their usual levels due to soil saturation from seismic impact
Spatial Scale	Localised (Site-specific focus)	Regional (Peninsula-wide disruption)
Cascade Structure	Linear (4 links; Fig. 4)	Loop structure confirmed (6+ links; Fig. 5)
Secondary Trigger	None (Single event sequence)	Subsequent Rainfall (2 days later)
Human Impact	No casualties (Single vehicle damaged)	Significant fatalities and injuries (Regional escalation)
Recovery Nature	Single-lane operation due to debris removal & geological assessment	Starting with road opening, then single-lane operation, and plan to complete structural foundation reconstruction

are the primary commonalities between the two cases.

A critical divergence also lies in the geomorphological setting of the affected corridors. The Brenner cascade occurred on natural slopes protected by vegetation and steel nets. In contrast, the Noto Satoyama Kaido is constructed on artificial embankments. Naturally, protection measures differ between mountain slopes and man-made structures. Interestingly, although embankments are engineered structures, the Noto case revealed a high diversity in failure modes. Some sections reinforced after 2007 remained intact, while others, despite being reinforced with improved soil, suffered large-scale collapse or subsidence. Furthermore, sections that were not damaged in 2007 and thus remained unreinforced became the sites of major failures in 2024. This suggests that even with human intervention, managing the stability of engineered slopes under extreme seismic loading remains a significant challenge.

Finally, the structural progression of the cascades differs significantly. While the Brenner case followed a relatively linear trajectory, the Noto case exhibited a cyclic or loop structure. In Noto, the initial seismic shock triggered the first wave of embankment failures, which was then exacerbated two days later by heavy rainfall, leading to a secondary wave of failures. Consequently, despite these structural differences, a fundamental sequence remains common to both: Heavy rainfall $\rightarrow$ slope/embankment failure $\rightarrow$ closure or partial closure of a critical arterial corridor $\rightarrow$ secondary impacts such as traffic congestion and community isolation. The following sections will further examine these aspects by focusing on (1) the role of early warnings and initial response, (2) cascade propagation and spatial scale, and (3) the persistence of the recovery phase.

- **The Role of Early Warnings and Initial Response**

  First, it is essential to outline the operational environment prior to the initial hazard. A key difference lies in the predictability and lead time: while the heavy rain warning had been issued by Geosphere Austria a day before the Brenner event, the Earthquake Early Warning (EEW) for the Noto case allowed only seconds of notice, forcing an immediate transition into a state of emergency without room for prior operational adjustments (GeoSphere Austria 2023; Japan Meteorological Agency 2025c). Specifically, the Geosphere Austria heavy rain warning was issued approximately 24 hours prior to the peak debris flow on October 31, 2023. In contrast, the JMA Earthquake Early Warning provided 5-10 seconds of notice for the Mw 7.6 event on January 1, 2024. This disparity in foresight—hours versus seconds—highlights how meteorological predictability enables proactive monitoring, unlike seismic immediacy. However, if we shift our perspective and compare them again, we can see that they do have some things in common. In both cases, the issuance of a heavy rain warning preceded the onset of the most destructive phase of the event. Although the available data from grey literature is insufficient to quantify whether these warnings directly mitigated the impacts (a point to be further explored in the Discussion), it is factually evident that both warnings were followed by significant cascading effects. This commonality underscores that even with pre-event warnings, these corridors' exposure represents a critical bottleneck in the multi-hazard cascade.

- **Cascade Progression and Spatial Scale**

Regarding the progression from the primary hazard to the impact, the Brenner case exhibited a relatively linear cascade: intense rainfall saturated the soil, triggering a debris flow that gained momentum, uprooted vegetation, and eventually breached slope protection nets to obstruct the corridor. In the earlier visualisation, this comprised 4 links: rainfall → soil saturation → debris flow → protection net breach → road blockage (Fig. 4). In contrast, the Noto cascade followed a more complex trajectory. The initial seismic shock acted as the primary trigger for embankment deformations, which exhibited 6+ links: earthquake → initial embankment failures → heavy rainfall → additional landslides and embankment failures → blockages exacerbated → traffic flow halt (Fig. 5), with the failures amplified by secondary rainfall on January 3. This added complexity in Noto prolonged propagation over days versus Brenner's hours. This secondary trigger, for which a separate warning was issued, based on the adjusted thresholds given the saturated soil due to the earthquake, interacted with the already weakened stability of the slopes, leading to prolonged cascading effects. A structural comparison of the Impact Chains (Fig. 4 vs. Fig. 5) further highlights the divergence in the cascade complexity. In the Brenner case, the chain represents a "point-source" failure where the causal links are unidirectional and time-compressed. The rapid transition from rainfall to blockage indicates a high-intensity but transient event. In contrast, the Noto Impact Chain exhibits a "distributed-source" failure. The initial earthquake induced latent instability across the embankment structures, which was then activated by the subsequent rainfall. In other words, the primary hazard (earthquake) expanded the potential for failure that the secondary hazard (rainfall) eventually realised. This branching structure in the Noto Impact Chain signifies that the road blockage was not a result of a single mechanical failure, but an accumulation of sequential impacts that overwhelmed the corridor's physical resilience over a multi-day period. Regarding the spatial scale, the Noto case demonstrated a much wider geographical escalation compared to the localised Brenner event. According to the Cabinet Office reports, before the heavy rain, a total of 13 landslides had been confirmed (3 in Niigata Prefecture[3], 4 in Toyama Prefecture[4] and 6 in Ishikawa Prefecture); however, following the rain on 3 January, the total rose significantly to 48 (11 in Niigata Prefecture, 9 in Toyama Prefecture and 28 in Ishikawa Prefecture), which means the subsequent rainfall triggered additional landslides across a broad region (Extreme Disaster Management Headquarters 2024b). This widespread distribution of an increase in additional hazards, occurring simultaneously across three prefectures, highlights that the seismic impact preconditioned the soil stability on a regional scale. In this context, the functional failure of the Noto Satoyama Kaido motorway was not an isolated event but part of a synchronised regional state of

[3] a neighbouring prefecture of Ishikawa Prefecture
[4] another neighbouring prefecture of Ishikawa Prefecture

emergency that hindered large-scale emergency logistics across the Hokuriku region and relief efforts of the Noto Peninsula.

- **Persistence and Recovery Phase**

  The persistence of the cascading effects also differed due to the nature of the physical damage. In the Brenner case, the recovery process was relatively straightforward, focusing on debris removal and the restoration of slope protection nets to re-establish corridor functionality. In contrast, the Noto case required a far more prolonged recovery phase. Because the initial seismic shock had compromised the structural stability of the embankments, the recovery was not a simple matter of clearance but required a multi-stage reconstruction of the road's foundation. This fundamental difference in the depth of the damage dictates the long-term persistence of the cascade in the Noto region compared to the more transient disruption in the Brenner corridor. Specifically, the heavy rainfall triggered slope failures that obstructed critical transportation arteries (as described in Chapter 4), leading to the isolation of surrounding communities and/or regional socio-economic disruption. In both cases, the lack of network redundancy significantly amplified the severity of the cascade. As discussed in Chapter 4, the Brenner corridor's closure necessitated a detour via the B182, which struggled to accommodate the diverted traffic (see Table 4 Immediate Post-failure). Similarly, in the Noto case, the Noto Satoyama Kaido remained closed or only partially operational for months. Even after the completion of emergency road opening (see Table 5 15 March), vehicles were diverted to local general roads during the prolonged recovery phase. Consequently, both regions experienced severe traffic congestion during rush hours, representing a critical decline in road network functionality that persisted long after the initial hazard. The contrast in these recovery timelines illustrates the difference between a "transient cascade" in the Brenner case and a "prolonged cascade" in the Noto case. In Brenner, the transition from emergency response to recovery was relatively rapid once the physical debris was cleared. However, in the Noto case, the cascade was stretched over months because the ongoing aftershocks and secondary rainfall kept the restoration activities themselves under constant hazard exposure. Therefore, the persistence of the Noto cascade should be defined not merely as a delay in construction, but as a period of uninterrupted hazard succession that fundamentally challenged the resilience of the regional transportation network.

6.3.2 Documentation related to Slope Protection Measures

Since the foundation of this study's methodology lies in a literature review, this section revisits the references consulted to examine their coverage and the insights derived from them. Table 8 summarises the relationship between sources and coverage of the content, specifically focusing on mentions of slope protection, to reflect on the research findings. However, as noted in Chapter 5: Limitations relating to methodology, it must be acknowledged that the author is a native Japanese speaker and a non-native speaker of German and English, who utilised AI as a supplementary tool for translation and nuanced interpretation as mentioned in Chapter 5, enabling a rigorous analysis of technical primary sources in non-native languages while acknowledging inherent limitations in the investigation scope.

First, a common principle maintained during the literature review for both Brenner and Noto was the prioritisation of official reports. Given the nature of disaster topics, initial Google search results are often dominated by media coverage (e.g., digital news). Although media reporting is useful for immediate situational awareness, this study prioritises official technical reports and hydrological/geomorphological assessments issued by government agencies and research institutes. This selection ensures that the comparative analysis is based on validated quantitative data, such as precipitation intensity and structural damage classifications, rather than qualitative media narratives. By including specific names of relevant organisations, such as "Geosphere Austria" or "Cabinet Office" in search queries, we endeavoured to collect documents that ensure reliability and obtain specific numerical data from primary sources. Specifically, for the Brenner case, the Land Tirol (2023) contributed to comparing the official view with the Noto case, noting that precipitation on October 31, 2023, reached 120–200% of the long-term average (see "Historical comparison" in Table 8). For the Noto case, by focusing on disaster information reports from the Cabinet Office and various reports from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), particularly the Ministry of Land, Infrastructure, Transport and Tourism (2024a), we succeeded in gathering data on specific embankment failure trends along the Noto Satoyama Kaido and referencing areas improved based on the 2007 earthquake. This level of detail, typically absent in general news coverage, facilitated the extraction of core characteristics necessary for comparing two extremely distant cases. An unexpected finding during this process was that, in the absence of a centralised technical report from the motorway operator (ASFiNAG), the operation logs from the Voluntary Fire Brigade of Gries am Brenner (*FF Gries am Brenner*) served as a critical primary source. These records provide specific descriptions of movements immediately after the debris flow, rescue activities involving heavy machinery following the mobilisation, and road-clearing operations. Because these records include on-site photography and real-time intervention logs, they were highly useful for increasing the resolution of the situation on that day and understanding the overview. In other words, they proved to be an invaluable source, providing high-resolution on-site data that compensated for the absence of centralised technical reports from the motorway operator (ASFiNAG).

The following table (Table 8) synthesises the primary sources most frequently consulted for each case study, categorised by their respective study areas. To capture the significance of slope protection measures within the content analysis framework, the evaluation criteria are organised as follows: ’Primary Hazard’ and ’Hazard Process’ document the initiation and progression of the event. ’Impact & Interaction’ focuses specifically on the physical contact between the hazard and slope protection measures, reflecting the failure modes of the infrastructure. ’Historical Comparison’ functions as the documentation of the validation of these measures based on past failure. Finally, ’Consequences & Recovery’ serves as a proxy for the broader socio-economic outcomes resulting from these interactions; e.g., service interruption and residual damage impact. This categorisation ensures that the content analysis encompasses the full scope of slope protection influences: from the primary hazard intensity impacting the protection measures, to the recovery timeline, which reflects the broader consequences resulting from the performance or failure of these slope protection systems. By scrutinising these diverse documentation focuses, the study identifies how information regarding physical measures is integrated into broader hazard cascade documentation narratives in each region. To maintain the analytical focus on structural and policy-based aspects of slope protection and avoid a shift towards media-centric analysis, news outlets are consolidated under a single ‘News Articles’ category, rather than listing individual news sites. This consolidation was a strategic choice to highlight the shared functional role of media in recording ’Emergency Logistics’ and ’Recovery Timelines’, aspects that are frequently abstracted in high-level official/technical reports.

Before proceeding to the specific content analysis of each source, it is essential to outline the structural differences in how information is documented in both cases. The documentation for the Brenner case is characterised by a tri-layered structure, comprising technical, administrative, and operational reports that collectively compensate for the absence of centralised motorway operator data. In contrast, the Noto case is characterised by a fragmented yet high-volume landscape of governmental and grey literature. Navigating these diverse reports required rigorous cross-referencing to distinguish between overlapping titles and isolate the specific temporal/spatial data needed to differentiate seismic-induced hazards from subsequent rainfall-induced ones.

The significance of the symbols utilised in the table is defined as follows:

- ◎ **(Primary Focus):** Indicates that the topic is a central pillar of the source. The assignment of this symbol requires fulfilling at least two of the following predefined criteria: (1) explicit mention in the title or introductory paragraph, (2) the topic occupying approximately 30% or more of the total textual volume dedicated to the event, or (3) the presence of in-depth technical analysis of numerical data or hazard sequences.

- ○ **(Secondary Focus):** Denotes that the topic is treated as supplementary information. This is assigned when the topic meets only one or none of the primary focus thresholds, yet remains supported by at least one piece of primary quantitative evidence, such as a map, table, or specific data.
- △ **(Minimal Mention):** Signifies a superficial or brief reference to the topic without substantive data or in-depth technical examination.
- **— (No Mention):** Indicates the total absence of the topic within the consulted material.

While the assignment of these symbols involves a degree of qualitative assessment by the author, reproducibility is maintained through the rigorous application of the aforementioned criteria. This systematic categorisation allows for a clear visualisation of the information density and the disparity in documentation focus between the two geographically and contextually distinct cases. Applying these criteria to the selected literature yields the following results for each case study.

Regarding the Geosphere Austria technical report (Haberler et al. (2024)), the categorisation was determined by the specific focus on the progression of the event. 'Hazard Process' and 'Impact & Interaction' were both classified as Primary Focus (◎) as they fulfill at least two criteria: they occupy approximately 50% of the total textual volume and provide in-depth descriptions of the physical interaction, such as the breaching of the protection net (*Schutznetz durchschlugen*) and the subsequent burial of both carriageways. In contrast, while the report mentions the ongoing instability and recovery prospects, 'Primary Hazard' and 'Consequences & Recovery' were assigned a Secondary Focus (○) due to their relatively constrained textual volume on this specific page, despite providing essential quantitative data such as the 4,000 m^3 of residual unstable material.

In the Geosphere Austria Record of Severe Weather Events (*Unwetterchronik*) (GeoSphere Austria (2023)), the analysis focuses exclusively on the documentation related to the A13 motorway and its adjacent slopes. Under this specific scope, 'Consequences & Recovery' was identified as a Primary Focus (◎). This is because the information regarding the post-impact operational status—specifically the multi-week single-lane restriction (*wochenlang nur einspurig*)—occupies more than 50% of the textual volume dedicated to the A13 case. While the record briefly mentions the triggering rainfall and the burial of the carriageway, these elements are categorised as Secondary Focus (○) due to the lack of detailed technical interaction analysis regarding the slope protection measures themselves.

Regarding the Hydrology Report from the State Government of Tyrol (Land Tirol (2023)), the evaluation focuses on the specific section dedicated to precipitation analysis. 'Primary Hazard' is categorised as a Primary Focus (◎) because it fulfils two essential criteria: (1) it provides high-resolution quantitative data, such as the 118 mm daily maximum at the Brenner station, and (2) it includes spatial interpolation maps that visualise the intensity distribution across the region. Additionally, 'Historical Context' is assigned as a Secondary Focus (○). While the data is validated against long-term averages (1991–2020), this topic neither constitutes the primary objective of the document nor occupies 30% of the relevant descriptive volume within the section, serving instead as supplementary evidence to contextualise the current hazard intensity.

In the official intervention log of the Voluntary Fire Brigade of Gries am Brenner (Freiwillige Feuerwehr Gries am Brenner (2023)), the documentation emphasis is placed on the operational dynamics of the event. 'Hazard Process' is categorised as a Primary Focus (◎) because the report provides precise temporal and spatial data, such as the exact time of the debris flow (02:44) and its extent across both carriageways. Similarly, 'Consequences & Recovery' is assigned a score of ◎, as more than 60% of the A13-related description is dedicated to the emergency logistics, including the mobilisation of heavy machinery (*Radlader*) and the subsequent handover of the site to the motorway operator (ASFINAG). While the record mentions the triggering rainfall and the impact on a passenger vehicle, these are treated as Secondary Focus (○) due to the lack of broader meteorological analysis or structural engineering details.

Regarding the 'News Articles' category (ORF Tirol (2023), 5min.at (2023), and meinbezirk.at (2023)) highlights the functional role of media in documenting the socio-economic aftermath. 'Consequences & Recovery' is categorised as a Primary Focus (◎) as these sources provide detailed, real-time updates on operational restrictions, including the diversion of passenger cars to the B182, the suspension of heavy goods vehicles (HGVs) on the Italian side, and the phased reopening of lanes monitored by the ASFINAG. In contrast, 'Primary Hazard' and 'Hazard Process' remain as Secondary Focus (○); while they contribute specific quantitative data like the 80 m extent of the debris flow at km 33.850, their primary narrative remains centred on traffic logistics rather than technical hazard analysis. Finally, 'Impact & Interaction' is assigned a Minimal Mention (△), as narrative descriptions are confirmed but details are lacking.

For the MLIT technical report regarding road structure damage (Ministry of Land, Infrastructure, Transport and Tourism (2024a)), the categorisation of ◎ for 'Impact & Interaction' is justified by the extensive documentation of structural failures primarily across the Noto Satoyama Kaido motorway. Rather than focusing on the temporal progression of the event ('Hazard Process'), approximately half of the report is dedicated to forensic engineering analysis. This details how seismic forces and subsequent landslides physically interact with embankments; other structures, such as bridges and tunnels, were excluded as they fall outside the research scope. Furthermore, while the document outlines technical considerations for reconstruction, 'Consequences & Recovery' is also assigned a Primary Focus (◎) because it fulfils (2) and (3) of the criteria, namely more than 30% of content provides engineering guidelines on reconstruction.

Regarding the MLIT report on emergency restoration works (Ministry of Land, Infrastructure, Transport and Tourism (2024d)), it should be noted that this analysis covers a series of documents (No. 1 to No. 4), all of which were confirmed to follow a consistent structure before being evaluated. The categorisation of ◎ for both 'Impact & Interaction' and 'Consequences & Recovery' is justified by the document's exclusive focus on the operational response. Across all the records, nearly 100% of the content is dedicated to visualising the spatial distribution of road damage and the subsequent restoration timeline. For 'Impact & Interaction', the report provides high-resolution photographic evidence of structural failures, such as large-scale longitudinal cracks and embankment failures on the Noto-Satoyama Kaido. Simultaneously, 'Consequences & Recovery' is also evaluated as a Primary Focus (◎) due to the detailed documentation of recovery logistics, including specific completion dates, the names of the private sector contractors involved, and sequential progress photos. Notably, scientific analysis of the seismic event ('Primary Hazard') and its physical progression ('Hazard Process') are absent, reflecting the document's functional role as a record of emergency engineering management.

The analysis of the damage reports issued by the Extreme Disaster Management Headquarters (Extreme Disaster Management Headquarters (2024a), Extreme Disaster Management Headquarters (2024b), and Extreme Disaster Management Headquarters (2025)) adopts a multi-temporal approach to capture the evolving nature of the cascading hazard sequence. Among the 60 reports published, the 1st, 6th, and 60th editions were selected to establish a baseline for the initial seismic impact, identify secondary landslides triggered by rainfall around January 3rd, and verify the final consolidated damage report, respectively. Throughout this series, 'Consequences & Recovery' is designated as a Primary Focus (◎), as the reports primarily document a wide range of the socio-economic consequences of the hazards, including the number of landslides observed, casualty counts, and the restoration of essential services. While 'Primary Hazard' and 'Hazard Process' are assigned a Secondary Focus (○), their inclusion is critical for this research; specifically, the 6th report provides essential evidence to determine the sequence of hazards and assist in constructing the impact chain, thereby differentiating between earthquake-induced landslides and those exacerbated by subsequent rainfall. This is because the 1st report, recorded as of 5:30 a.m. on January 2nd, only shows the damage caused by the earthquake itself. In contrast, the 6th report was issued after the heavy rain advisory on January 3rd, capturing the additional landslides triggered by this meteorological event; thus, the discrepancy between these two reports allows for a clear distinction of earthquake-induced landslides and rainfall-induced ones. Finally, the 60th report was utilised to verify the ultimate damage toll and the long-term restoration measures not yet present in the earlier bulletins.

The analytical report by Chiba (2024) provides a geo-morphological perspective on the road damage, shifting the focus from mere observation to causal analysis. 'Impact & Interaction' is categorised as a Primary Focus (◎) because the entire study is dedicated to correlating seismic intensity with micro-topography, slope gradients (averaging 32.6° for slope failures), and road geometry, such as embankment height. Specifically, by identifying the specific vulnerability of valley topography and older sections of the road network, the report offers a high density of information regarding how the natural terrain and man-made structures interacted during the seismic event. In contrast, 'Historical Context' and 'Primary Hazard' are assigned a Secondary Focus (○); while the author references the service years of the roads and specific seismic values (e.g., intensity 6.0), these data points serve as supporting evidence for the primary interaction analysis rather than being the central theme of the documentation. Finally, 'Consequences & Recovery' is assigned a Minimal Mention (△); while the authors suggest that their findings may contribute to future disaster prevention strategies, the document lacks any specific operational recovery plans, timelines, or socio-economic impact data. This distinction highlights the report's analytical role in technical forensic analysis rather than disaster management logistics.

The news articles from the Asahi Shimbun (The Asahi Shimbun (2024b) and The Asahi Shimbun (2024b)) regarding the Noto case primarily focus on the logistics of reconstruction. 'Consequences & Recovery' is designated as a Primary Focus (◎), as the reports provide greater details, including restoration timelines, spatial mapping of recovery zones, and qualitative insights from interviews with road planning officials. In contrast, 'Impact & Interaction' is assigned a Minimal Mention (△); while narrative descriptions of the extensive road damage are present, they lack the technical or quantitative data necessary for structural analysis. Furthermore, it must be noted that this evaluation is specific to the sources selected by the author. While a vast number of other media reports exist, many of which focus heavily on the intensity of the seismic trigger to capture readers' attention, the 'Primary Hazard' and 'Hazard Process' categories are marked as △ or omitted here to reflect the specific content of the referenced articles.

In summary, this comparative content analysis of ten primary sources reveals a clear difference in documentation focus between the Brenner and Noto cases. For the Brenner case, information is fairly fragmented; technical data, ranging from hydro-meteorological records to physical event descriptions, emergency operational logs, and traffic logistics, are dispersed across different organisations. This necessitated a cross-referencing approach to reconstruct the hazard cascade. In contrast, the Noto case is characterised by a high volume of centralised government and analytical reports that integrate structural forensic damage reports with socio-economic recovery timelines. However, these documents are distributed across various agencies, resulting in a complex landscape of overlapping information. The multi-temporal sampling of the Cabinet Office reports was essential to distinguish between earthquake-induced landslides and those trig-

Table 8: Comparative Analysis of Information Focus in Primary Documentation

Source Document	Primary Hazard	Hazard Process	Impact & Interaction	Historical Comparison	Consequences & Recovery
Brenner Case					
Geosphere Austria Report 2024	○	◎	◎	—	○
Geosphere Austria Record 2023	○	○	○	—	◎
Hydrology Report (Tirol) 2023	◎	—	—	○	—
Fire Brigade[1] Report 2023	○	◎	○	—	◎
News Articles (tirol.ORF.at) 2023	○	○	△	—	◎
Noto Case					
MLIT (Structural Analysis) 2024	○	○	◎	○	○
MLIT (Road Opening Report) 2024	—	—	◎	—	◎
Cabinet Office Report 2024	○	○	—	—[2]	◎
Chiba (Road Damage) 2024	○	—	◎	○	△
News Articles (Asahi, etc.) 2024[3]	△	—	△	—	◎

Note: ◎: Primary focus; ○: Secondary Focus; △: Minimal mention; —: No Mention.
[1] *Freiwillige Feuerwehr Gries am Brenner*
[2] Nothing regarding the historical comparison was reported
[3] Scores based on specific recovery-oriented reports.

gered by subsequent rainfall. While these reports vary in their primary focus, their collective value lies in documenting the performance and failure modes of slope protection measures under hazard intensities. This systematic mapping of information density provides a solid empirical foundation for discussing how slope protection performance is recorded and evaluated in different contexts.

6.3.3 Key Findings addressing Research Questions and Hypotheses

By synthesising the findings from the previous documentation analysis, the following responses to the research questions emerge from the literature evidence. These shall be further explored in the Discussion Chapter.

RQ 1: To what extent is the simplified Impact Chain framework transferable to geographically distant regions? (Sub Q1: Effectiveness of desk-based/Sub Q2: Effectiveness of partial factors)

Hypothesis 1: The simplified Impact Chain is transferable from the Brenner Corridor to the Noto Satoyama Kaido. (H1a: A partial adaptation of the framework serves as a valid analytical tool for prioritising hazard interrelationships. H1b: A desk-based development of the Impact Chain is sufficient to reconstruct the chronological sequence of a hazard cascade.)

Findings 1: The hypothesis was validated. The development of the Impact Chain solely from literature proved effective for visualising the temporal sequence of hazards. For instance, in the Noto case, it allowed for the differentiation between seismic and rainfall-induced landslides, which would otherwise be blurred in non-sequential reporting. However, absence of vulnerability, risk and exposure should be noted, which will be further explored in Chapter 7.

RQ 2: Difference of the slope protection measures between the Brenner Corridor and the Noto Satoyama Kaido?

Hypothesis 2: Post-event documentation confirms that the Brenner Corridor relies on protection nets, whereas the Noto Satoyama Kaido prioritises embankments.

Findings 2: The hypothesis was confirmed. A clear divergence in physical measures was identified: the Brenner case relies heavily on protection nets to intercept debris, whereas the Noto Satoyama Kaido prioritises embankment stabilisation and soil-based structures to withstand seismic forces.

RQ 3: Based on the difference, which kind of factors influence or support this divergence?

Hypothesis 3: The divergence in protection measures is driven by the distinct regional hazard patterns.

Findings 3: The findings did not provide direct evidence to support this hypothesis. While the literature confirmed that distinctly different structures are used for slope protection in the Brenner and Noto cases (as shown in Findings 2), the referenced reports contained no clear documented rationales regarding the strategic or historical factors behind these design choices (such as the specific rationale for adopting these measures). However, since several inferences can be made based on the results of this analysis, these will be further explored in the Discussion chapter.

RQ 4: Do slope protection measures help to prevent or limit cascading effects from landslides on these corridors?

Hypothesis 4: The reviewed literature confirms that implemented slope protection measures effectively mitigate further cascading damage along mountain corridors.

Findings 4: The hypothesis was partially supported, revealing both the contribution and the inherent limitations of the measures. Literature evidence confirms that slope protection measures provided a degree of initial resilience; however, they were ultimately insufficient to prevent infrastructure failure and service interruption in both cases. Specifically, in the Brenner case, Haberler et al. (2024) indicates that the protection nets intercepted a portion of the mass, but were eventually breached, leading to the burial of the A13. In the Noto case, while reinforcements based on the 2007 earthquake lessons reportedly mitigated damage in specific sections, they could not prevent widespread embankment failures (Chiba 2024; Ministry of Land, Infrastructure, Transport and Tourism 2024a). Consequently, in both cases, the measures failed to break the hazard cascade, resulting in significant regional socio-economic impacts due to road blockages.

7 Discussion

7.1 Methodological Reflections and Limitations

This analysis utilised established research methodologies that were strategically adapted due to significant resource and data constraints. The following sections examine the advantages and disadvantages revealed by these adaptations, comparing the modified approach with the original, standardised methodologies.

7.1.1 Strengths and Constraints of Literature-Based Partial Impact Chains

While the Results chapter previously introduced the adapted Impact Chains (ICs) to answer the Research Question 1, this section expands upon those findings to provide a deeper methodological reflection. Developing Impact Chains solely from literature presented both significant utility and inherent limitations.

The standardised IC methodology, as demonstrated by Coccuccioni et al. (2023) within the PARATUS project, typically involves an exhaustive participatory process. Given the project's nature, funded by the EU's Horizon Europe to develop a disaster preparedness platform, it relies heavily on co-designing narratives primarily through stakeholder workshops to capture broad socio-economic impacts. As noted in the Methodology Chapter, however, ICs can be developed either through such participatory approaches or through desk-based analysis of scientific literature and evidence. Although the partial IC constructed in this study, omitting core components such as vulnerability, exposure, and risk, initially raised concerns about its analytical depth, the application to the Noto case proved otherwise; the IC served as a vital tool for deconstructing the complex hazard cascade (Earthquake $\rightarrow$ Primary Landslides $\rightarrow$ Rainfall $\rightarrow$Secondary Landslides). It enabled a systematic temporal mapping of events that might have remained blurred in standard narrative reporting. Nevertheless, the reliance on documentation (primary administrative records) limited the spatial resolution of the findings. For instance, while the Noto documentation revealed a significant increase in casualties and structural damage during the secondary rainfall-induced landslides, the data remained aggregated at the prefectural level (Ishikawa Prefecture). To achieve a more granular understanding, such as municipality-level impacts, a participatory approach involving field surveys and/or direct engagement with local authorities would be necessary.

Furthermore, while this study successfully reconstructed the hazard sequences and consequences, the deliberate exclusion of vulnerability, exposure, and risk factors, as defined in the Introduction, poses a challenge for comprehensive policy recommendations. As expressed by the risk equation (see Section 1.3), risk is a function of the interaction between hazard, exposure, and vulnerability, moderated by capacity (De Angeli et al. 2022, p. 3). While the present hazard analysis explains what happened (the physical manifestation), a full assessment of other core elements is required to explain why the impacts were so damaging to specific communities. Without these elements, which characterise the susceptibility and positioning of assets (United Nations Office for Disaster Risk Reduction (UNDRR) 2017d; De Angeli et al. 2022), it remains difficult to propose targeted structural or non-structural interventions. Future research should therefore leverage the network identified during the data-gathering phase to move beyond the current desk-based scope. By inviting local stakeholders to workshops and integrating their on-the-ground insights, researchers can complete the Impact Chain and provide fruitful proposals to key decision-makers and practitioners. This methodological reflection directly addresses RQ 1, validating Hypothesis 1: while an Impact Chain constructed solely from literature is a powerful analytical tool for visualising complex hazard sequences, its utility for comprehensive risk management remains partial without the integration of vulnerability and exposure factors.

7.1.2 Reflections on the Modified Semi-Systematic Literature Review

While Snyder (2019) defines the semi-systematic review as a tool for tracing the historical development of broad topics, this study expanded that definition to track the specific progression of cascading events at two distinct locations. This adaptation was necessary to address the information asymmetry in the documentation of these events between the Brenner and Noto cases. Although both sites relied primarily on public reports (e.g., the Amt der Tiroler Landesregierung and GeoSphere Austria for Brenner; the Cabinet Office and MLIT for Noto), the structure and focus of these documents differed markedly. One side provided highly technical, event-specific monitoring data, while the other offered comprehensive but fragmented administrative hazard/disaster records. Therefore, instead of a uniform search string, the search strategy was tailored to the specific documentation style of each regional authority to ensure a balanced comparison.

In addition to these structural differences, a significant challenge was the language and accessibility barrier, with primary documentation for Brenner in German and Noto in Japanese. Although standardised reviews often prioritise consistency in language and source type, this study actively incorporated multilingual grey literature, including administrative reports, news archives, and Cabinet Office bulletins. This adopted approach was indispensable for the Impact Chain (IC) construction, as it allowed for the reconstruction of precise chronological order, such as the timing of specific warnings and localised slope failures, that peer-reviewed academic articles often lack in the immediate aftermath of events.

These qualitative complexities also dictated the scale of the literature review. Although systematic reviews typically handle hundreds of sources to ensure statistical breadth, this study intentionally focused on a curated set of key document groups. The Noto documentation was characterised by “fragmentation” (i.e., information that was abundant in volume but scattered in distribution), while the Brenner data was "piecemeal" (limited specific documentation). To bridge this gap and bring both cases onto the common analytical ground of the Impact Chain, the focus was shifted from quantitative volume to a qualitative case-study approach. Prioritising the depth of specific event sequences over the quantity of sources was essential to capture the complex cascading mechanisms unique to each corridor.

7.1.3 Reflections on the Modified Contents Analysis

While the content analysis in this study was inspired by Mayring (2014) deductive category application, the process was deliberately simplified to suit the nature of the available data. Specifically, a full-scale manual coding process (line-by-line tagging) was not performed. This decision was made because the documents were already highly structured official reports; therefore, a traditional coding approach was deemed less effective than a systematic scoring method for assessing how slope protection measures were prioritised across different regional contexts.

In place of formal coding, a multi-tiered evaluation system was developed as a robust alternative. This system utilised three specific criteria; (1) explicit mention in key sections, (2) textual volume (the approx. 30% threshold), and (3) analytical depth, to categorize the prominence of slope protection related topics into four levels: Primary Focus (◎), Secondary Focus (○), Minimal Mention (△), and No Mention (—). This approach allowed for a strategic reading of the documents, moving beyond a simple mention of measures to a qualitative and semi-quantitative assessment of their significance. The "30% text share" rule, in particular, provided an objective threshold to distinguish between a "central pillar" of a report and mere supplementary information. By establishing these clear thresholds for each symbol, the study ensured a transparent and reproducible comparison between the Japanese and Austrian cases, providing a clear rationale for how different authorities prioritise structural mitigation in their hazard narratives.

7.2 The Fragility of Corridors: Trans-Alpine Corridor and Peninsula Arteries

While the previously discussed content analysis highlights the disparity in documentation, the underlying reality of both cases is the inherent fragility of the corridors themselves. On the one hand, news reports regarding the Brenner event cited ASFiNAG's concern over the immediate disruption to morning commuters; on the other hand, the situation underscores a deeper systemic vulnerability within trans-Alpine logistics. The Brenner Pass serves as a critical TEN-T corridor, handling 54.5 Mt of freight annually and according to a survey by Wegscheider et al. (2022), transit traffic (international freight) accounts for 85% of its total volume, representing its position as one of the most important transalpine routes in the world (Wegscheider et al.

2022, p. 7). This suggests that even a temporary, localised closure of the A13 has an immediate economic ripple effect across borders. Therefore, any operational reliance on the B182, a route with significantly lower capacity, for a period of several weeks implies a substantial, albeit unquantified, strain on long-haul logistics. The fact that an event of this scale resulted in such extensive documentation is a testament to the vital role this specific corridor plays; in alpine regions, the lack of redundant, high-capacity diversion routes transforms even minor hazards into large-scale logistical bottlenecks.

A similar, yet more existential, fragility was observed in the Noto case. The simultaneous incapacitation of both the Noto-Satoyama Kaido and National Route 249, the so-called peninsula's primary "artery", resulted in the physical severance of entire communities. This necessitated the "Kushigata-Keikai" (comb-like road clearing) strategy, where emergency teams attempted to reach isolated coastal areas via multiple inland routes (The Asahi Shimbun 2024b).

This isolation also highlights a fundamental limitation of traditional warning systems. In the Brenner case, the timely issuance of heavy rain warnings the day before might have allowed for proactive adjustments among operators, potentially contributing to avoiding casualties with only one vehicle affected, despite the debris flow (Haberler et al. 2024). Conversely, in Noto, although the JMA took the proactive step of lowering advisory thresholds due to post-earthquake instability, the subsequent rainfall-induced landslides caused significant additional damage (Extreme Disaster Management Headquarters 2024b, p. 17). This disparity suggests that the effectiveness of a warning is fundamentally dependent on the recipient's freedom of mobility, even when the relevant agencies issue highly sensitive systems by lowering warning thresholds. Even for individuals without physical disabilities, mobility is denied if the evacuation routes, namely the corridors themselves, are physically blocked or destroyed. This underscores the dual nature of the Noto Satoyama Kaido corridor as both a lifeline and a hazard target, which was one of the primary targets of the hazard cascade. In such a state of enforced isolation, warnings have less of their functional utility as the physical infrastructure for escape is unavailable, highlighting a fundamental challenge in corridor-dependent regions.

Furthermore, the weight of these corridors differs significantly in their human consequences. While the Brenner closure primarily risks wide-scale economic disruption, the Noto closure directly threatened human survival. By January 5th, 33 communities remained isolated, and rescue efforts were further hampered by weather conditions that grounded helicopters for at least two days during the critical first ten days (Extreme Disaster Management Headquarters 2024b). During these periods, severed road networks meant that areas outside the city centre were accessible only by air; consequently, when flight was impossible, both rescue operations and the delivery of essential supplies were entirely suspended. In the harsh January cold, victims in these isolated clusters struggled to survive without heating, mobile signal, medical supplies, or basic sanitation. As the “72-hour golden window”, the period during which survival rates remain highest, passed with around 300 rescue requests unaddressed, the paralysis of the road network became a matter of life and death (Ishikawa Prefectural Government 2024; Ministry of Land, Infrastructure, Transport and Tourism 2002). Despite these differing scales of impact, comparing the two cases remains highly significant. Both demonstrate that in modern, corridor-dependent societies, the failure of a single critical link creates a systemic bottleneck that exceeds the management capacity of traditional single-hazard protocols, regardless of whether the primary consequence is economic or existential.

7.3 Information Landscapes: Volume, Access, and Structure

Regarding the availability and nature of data, a significant information asymmetry was observed between the two cases. While the minimum necessary grey literature and news articles for a comparative study were collected, the overall volume for the Brenner case was limited. As two and a half years have passed since that specific cascade event, it is highly probable that information has shifted from public memory into administrative archives. Official documents, such as those from public sector entities like GeoSphere Austria, provided highly reliable outputs regarding the event’s conclusions. However, the inputs, the raw, real-time decision-making processes, remained unclear, making a detailed forensic reconstruction nearly impossible. Furthermore, compared to Japanese documentation, German-language materials tended to be more condensed and summarised, which limited the ability to trace a detailed timeline. While these observations may be specific to this single case and cannot be universalised, the scarcity of data suggests a need for improved information sharing. Whether such data is intentionally kept within internal sectors due to cultural administrative norms, distinct from the author’s background, remains speculative. However, as noted in the methodology’s limitations (see Section 5.4), the author’s proficiency in German search queries may have also played a role. This linguistic barrier underscores the profound value of international collaborative research projects like PARATUS; such initiatives should expand beyond Europe to a global scale, where Japan’s extensive disaster expertise could prove invaluable, which is a point further explored in the Perspectives Chapter.

In contrast, the Noto case was characterised by an overwhelming information environment, flooded with blog entries, breaking news, and administrative/academic reports. This abundance of data, especially when it comes to the administrative reports, was largely due to the numerous, similar-looking reports issued by various sub-agencies of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Identifying the most relevant and up-to-date correct information for specific topics imposed a high identification cost in terms of time and effort. This cost was further exacerbated when reports frequently cross-referenced or excerpted each other with subtle differences. However, viewed positively, this volume reflects high transparency and the public availability of operational documents, which opens doors for future research. Conversely, this accessibility assumes a near-native proficiency in Japanese and a high tolerance for meticulous data collection, potentially posing a barrier to international collaboration, the underlying theme of this study, which is further explored in Chapter 9.

Furthermore, the documentation of the 2024 Noto Peninsula earthquake revealed both an extraordinary agility and areas for structural improvement. The Cabinet Office's first disaster report was remarkably released just 13 hours after the initial earthquake on January 1st, 2024 (Extreme Disaster Management Headquarters 2024a). This occurred during the "Sanganichi" (the first three days of the New Year), a period in Japan as culturally sacred for rest as the Christmas holidays are in Austria. Despite this, the commitment to coordinate with relevant ministries and update information every 24 hours reflects an exceptional institutional agility. Nevertheless, from a researcher's perspective, there is room for improvement regarding version control and the visibility of updates. While minimal measures, such as including version numbers in URLs and underlining new text, were implemented, the sheer volume of updates forced researchers to manually scour hundreds of pages to ensure no critical information was missed. The implementation of (possibly AI-driven) automated summarisation or document management systems with automated change logs would significantly benefit not only future researchers but also frontline responders who rely on these reports during active crises.

To contextualise these findings within broader multi-hazard research challenges, the five core pillars proposed by Šakić Trogrlić et al. (2024) provide a useful analytical lens. This challenge of navigating fragmented yet voluminous data underscores a broader systemic issue in multi-hazard governance: the gap between high-level institutional agility and practical inter-disciplinary integration. While the Japanese Cabinet Office demonstrated remarkable speed in data dissemination, the identification cost realised in this study suggests that a more harmonised, cross-sectoral database is required to translate raw information into actionable knowledge. A comparative reflection on the Austrian context reveals a different structural approach. The Disaster Competence Network Austria (DCNA) serves as a pivotal bridge between researchers and practitioners, categorising expertise into specific hazard groups such as mass movements and critical infrastructure (Disaster Competence Network Austria 2026). However, as noted in broader multi-hazard research discourse, even well-established networks often struggle with the silo effect, where expert groups focus on single-hazard categories without a clear framework for the overlapping, interconnected nature of multi-hazard events, such as the rainfall-induced landslides seen in both Brenner and Noto. Building on existing efforts to release data quickly and structure expertise by hazard type, the findings from this study suggest that there is a pressing need for a unified information architecture that exceeds sectoral boundaries, to address these realities, as proposed by Šakić Trogrlić et al. (2024). By integrating diverse data sources through advanced technologies, such as AI-driven change logs or structural GIS mapping, authorities can move beyond the overwhelming information environment toward a more holistic multi-hazard risk assessment framework. This evolution from "single-sector documentation" to "trans-disciplinary information synthesis" is essential; without it, even the most agile government response remains hindered by the structural difficulty of tracing complex multi-hazard narratives in real-time. Although it was difficult to identify an ongoing project within the DCNA network that precisely reflects the "Earthquake-Rainfall-Landslide" sequence observed in the Noto and Brenner cases, the network actively fosters cross-sectoral disaster response through initiatives such as "FloodPrep". This project, which focuses on pluvial flooding in cities like Innsbruck and Graz, integrates hydrodynamic simulation models with real-time operational needs of emergency services and infrastructure operators. While FloodPrep primarily addresses heavy rainfall and urban flooding rather than a multi-hazard cascade in a strict geological sense, it exemplifies a trans-disciplinary approach by bridging the gap between scientific simulation and real-world crisis management. By utilising AI-supported validation and incorporating data from fire brigades and municipal authorities, such initiatives provide a vital template for addressing the unpredictable nature of multi-hazard events (Disaster Competence Network Austria 2025). Even if specific landslide-focused multi-hazard projects were not explicitly identified in the current documentation, the collaborative framework established by DCNA should be recognised internationally as it enhances the collective capacity to respond to complex, interconnected multi-hazard risks.

7.4 Strategic Drivers of Slope Protection

Building on Findings 3, which noted a lack of explicit documented rationales for the divergence in slope protection measures, this section provides an inferential analysis to address RQ 3 by examining the underlying drivers that influence these slope protection choices. The selection of slope protection measures is fundamentally dictated by the underlying geological and topographical constraints. In the Brenner region, the Wipp Valley is characterised by steep, hard-rock faces where deep-seated gravitational slope deformations (DSGSD) and large-scale rock avalanches have historically occurred (Ostermann and Sanders 2017). In such alpine environments, modifying the entire slope is physically and economically unfeasible. Consequently, the engineering approach shifts toward surface defence, typical of the flexible barrier systems (e.g., Schutznetz) widely employed in Alpine regions. These systems are generally designed to intercept and dissipate the energy of falling debris before it reaches the transport corridor.

The choice of netting reflects a strategy of mitigated absorption. As reported by GeoSphere Austria, during the October 2023 event, the installed nets initially contained a significant volume of material before eventually reaching their structural limit and being breached (Haberler et al. 2024, p. 32). It is plausible to infer that in the Alps, the priority is placed on speed and flexibility, because netting can be rapidly deployed or replaced, allowing international logistics to resume within days. It can be an engineering philosophy that prioritises the smooth economic flow of the corridor, accepting a degree of sacrificial damage to the protection nets themselves in exchange for rapid restoration of the flow.

In contrast, the Noto-Satoyama Kaido represents a fundamentally different engineering challenge, rooted in what can be termed the "dual role of embankments". In the complex, undulating topography of the Noto Peninsula, where many roads rely on engineered slopes to maintain level transit surfaces, which means embankments are not merely roadside protection; they serve as the foundational substructure upon which the road itself is built. Here, the embankment acts as an artificial slope created to bridge topographical gaps and provide a level transit surface.

However, the 2024 Noto cascade revealed that this foundation is also a primary target of the hazard. While a net is designed to protect the community below from the slope above, an embankment is designed to support the road above. Yet, it remains utterly defenceless against seismic forces and the subsequent loss of structural integrity, especially when saturated by post-event rainfall. In this context, surface defence like netting is rendered rather pointless. When the seismic trigger destabilises the very artificial slope that supports the corridor, the damage is not merely an obstruction to be cleared, but a structural failure requiring massive reconstruction. This vulnerability by design became a fatal flaw in the Noto case, where the destruction of the road's foundation led to the prolonged severance of the peninsula's primary artery. However, this reveals a profound developmental dilemma: as seen in the numerous communities left isolated in the early stages of the Noto cascade, these roads, despite their inherent fragility, remain the absolute prerequisite for human habitation and emergency access. In such geographically constrained regions, the decision to construct and maintain these corridors is not merely a matter of engineering choice, but an existential necessity, even when the resulting infrastructure remains precariously exposed to catastrophic failure. Ultimately, the divergence in slope protection strategies, from surface defence in the Brenner to structural foundation in Noto, it is deducted that these drivers are not merely technical, but are deeply rooted in the regional socio-economic priorities and the specific nature of the hazard cascade. This qualitative inference bridges the gap identified in Findings 3, providing a strategic context that traditional administrative reports often omit.

8 Conclusion

The research was conducted in order to apply the Impact Chain framework, which is established in the European context, to a distant region in Asia, Japan. This research demonstrated that the Impact Chain framework itself is a rather flexible framework, which enables visualising the sequences of cascading hazards. The visualisation serves as a lens to compare two different regions with the same/similar type of geo-hazard. However, this approach has its limitations, which will be discussed later in Section 8.4. In this chapter, we first summarise the findings and discussion to determine how the questions posed at the outset of the study in the first section were answered, and how the hypotheses were either confirmed or refuted. Next, we shall revisit the 'common critical role played by mountain passes in distant regions', which was the centrepiece of this study, and summarise this within the framework of multi-hazard research. Furthermore, we shall summarise the contribution this study makes to the current research landscape and how it can be integrated into future research; finally, we shall summarise the limitations of this study, which have been mentioned in several places, and the directions for future research.

8.1 Synthesis of Research Findings

Regarding RQ1 and Hypothesis 1, the findings from the Noto and Brenner cases validate that the Impact Chain framework is a highly adaptable structure, capable of being constructed even under significant data constraints and the absence of stakeholder workshops. As demonstrated in Findings 1, the partial IC proved effective for visualising the chronological sequence of hazards. However, as discussed in Chapter 7, this utility is limited to cascading events reconstruction. For projects aimed at robust policy recommendations, the integration of Vulnerability, Risk, and Exposure, elements excluded from this study, remains indispensable. A complete multi-hazard analysis requires capturing the lived experiences of stakeholders to translate hazard sequences into actionable risk reduction strategies.

In response to RQ2 and RQ3, the literature review confirmed a marked divergence in slope protection measures between the two regions (Findings 2). While the specific administrative rationales were not explicitly documented (Findings 3), this study deduced that these choices are driven by topographical constraints and engineering philosophies. In the Brenner region, the focus is on surface protection (netting) to shield communities below from natural rockfall and potentially even from debris flow. Conversely, the Noto Satoyama Kaido represents a foundational protection approach, where artificial embankments, the road's very substructure, must be defended against failure, whatever hazard happens. This suggests that protection measures are not merely technical choices but are dictated by the landscape itself.

One of the key findings of this study is that the selection of slope protection measures is not merely a matter of technical optimisation, but is deeply rooted in the topographical constraints of the terrain and the engineering philosophy of 'what needs to be protected'. The approach observed in the Brenner Corridor is, so to speak, based on the concept of 'protecting the area below the slope'. The rugged natural slopes of the Alps defy any attempt by humans to exert complete control over the mountains themselves. Consequently, assuming that rockfalls and debris flows will occur, 'flexible barriers' are selected to dissipate and capture their energy just before they reach the transport routes. Here, priority is given to a balance between efficiency and flexibility: even at the cost of the 'sacrifice' of the protective barriers, the aim is to restore the continuity of international logistics behind them within a short timeframe. In contrast, the approach taken on the Noto Satoyama Highway is based on the philosophy of 'protecting the top of the slope'. In this corridor, the slope (embankment) is not merely an obstacle, but a 'structural foundation' supporting the road itself. In Japanese construction methods, which involve filling in valleys and building roads on artificial foundations, a slope collapse immediately results in the loss of the road surface. Consequently, rather than surface protection using netting, a 'rigid' defence is pursued, which involves strengthening underground drainage functions and increasing the rigidity of the ground itself. What this comparison reveals is that the effectiveness of protective measures should not be measured solely by the 'magnitude of the hazard', but depends on the context of 'what spatial role the infrastructure plays within the local community'.

Regarding RQ4 and Hypothesis 4, the effectiveness of these measures showed a mitigated failure pattern. In Brenner, nets functioned until their structural threshold was breached by excessive debris volume. In Noto, reinforced sections demonstrated less damage than unreinforced ones. However, in both cases, the corridors suffered closures lasting weeks to months, failing to prevent large-scale socio-economic disruption. Thus, while structural measures may delay damage, they do not ensure corridor continuity in the face of complex hazard cascades. In this study, the fact that both cases were forced to close to traffic for periods ranging from several weeks to several months might, at first glance, appear to suggest a 'failure' of existing slope protection measures. However, this outcome should not be viewed as a simple engineering defeat. Rather, it should be redefined as an exposure of the 'structural limitations' of structures designed to withstand a single hazard, revealing their powerlessness in the face of 'cascading effects' such as post-earthquake rainfall or record-breaking sediment inflows exceeding design thresholds. Neither the breach of the Brenner barrier nor the collapse of the roads in Noto was due to the inadequacy of existing technology; rather, it was the result of unpredictable 'cascading disaster' scenarios outpacing modern static design standards. The lesson to be learned from this 'failure' is that simply raising physical barriers is not the solution. No matter how robust a structure may be, it will eventually reach its limits within a cascade of events.

Consequently, we could say that building resilience by combining a strategy of 'resistance', involving the reinforcement of physical infrastructure, with 'non-structural measures' such as the rapid sharing of information, evacuation plans and the securing of alternative routes, has become an indispensable requirement in this era of multi-hazard risks.

8.2 The Corridor Fragility in the Multi-Hazard Framework

The sequential hazard events followed by corridor paralysis in both study areas underscore the vital yet fragile role of mountain passes. The Brenner Pass, as a pillar of international logistics, and the Noto Satoyama Kaido, as a lifeline for easily-isolated Peninsula communities, both revealed that modern society remains subservient to geographical constraints. Despite advanced engineering, the single-link failure of a corridor creates a systemic bottleneck. Addressing this requires moving beyond structural engineering toward the Collaborative Approach advocated by the DCNA (Austrian transdisciplinary knowledge transfer platform) and PARATUS (EU-funded international research project). Enhancing information exchange and transdisciplinary coordination is the only way to manage risks that exceed the design limits of physical barriers. A comparison of the social and economic impacts caused by the disruption of the two corridors highlights the difference in the 'quality of vulnerability' inherent in each corridor. The paralysis of the Brenner Corridor resulted in a critical infrastructural bottleneck, causing friction in the cross-border movement of goods and incurring certain 'time costs' for the European economy. The stagnation may represent a significant blow to corporate supply chains, both in terms of time and money. On the other hand, the disruption in Noto was a 'crisis of survival' that threatened the right to life of isolated communities. The situation, in which rescue teams could not reach the area and access to medical care was cut off, proved precisely that the corridor is a 'lifeline'. What is important here is not a comparison of which disaster was more severe, but the fact that both share a common vulnerability: they are 'irreplaceable'. The economic losses incurred over several weeks at the Brenner Pass and the 72-hour survival crisis in Noto both illustrate how, even in a highly developed modern society, we remain excessively dependent on specific, narrow lines (corridors). This 'over-reliance on corridors' is one of the factors that amplifies multi-hazard risks, and I hope that within the framework of international risk management, the concept of 'corridor resilience', aimed at equally safeguarding both economic and humanitarian values, will gain wider recognition.

8.3 Theoretical and Practical Contributions

This research contributes to the DRM field by proving that a hazard-consequence focused IC can serve as a rapid situational assessment tool when time and resources are limited. Practically, this may be useful for initial inter-agency briefings where a quick, structured overview of the disaster narrative is required. However, the study also reaffirms the theoretical necessity of the full Impact Chain. Risk is not a sum of hazards and consequences; it is a function of hazard, exposure, and vulnerability. Without these, we cannot document the latent risks that have not yet manifested but exist as future threats. Therefore, this study concludes that for long-term multi-hazard risk reduction, a partial adoption of the framework is insufficient for risk calculation, though highly effective for event reconstruction.

8.4 Limitations and Future Research

The most prominent limitation of this study is its inherent inability to quantify absolute risk levels due to the deliberate scoping of the study. Future research should explore the threshold of utility: at what point does a simplified IC stop being helpful and start being misleading? Furthermore, adding the 'Capacity' factor to the risk equation, as suggested by De Angeli et al. (2022), would be a fruitful next step.

Finally, this study suggests that international comparative analysis should be more actively pursued. Despite the cultural and geographical distance between Japan and Austria, shared challenges—such as mountain road maintenance and cascading landslides—provide a rich ground for mutual learning. The essence of the collaborative approach lies in bridging these diverse regional experiences to build a universal resilience framework.

8.5 Final Reflections: Beyond Cultural and Administrative Divergence

Finally, I wish to reflect on the personal and academic journey that underpinned this study. Having been raised in Japan, a nation defined by its frequent encounters with large-scale disasters, and now pursuing my studies in Austria, a country with its own distinct alpine hazard landscape, I have personally witnessed what I term 'Cultural and Administrative Divergence' in reactions.

On one hand, the Japanese administrative response is characterised by extraordinary speed and meticulous detail; yet, as this study highlighted, the information is often 'scattered' across various ministries, imposing a high 'identification cost' on those seeking a holistic view. On the other hand, Austrian documentation tends to be highly refined and condensed, yet it faces the persistent challenge of 'sectoral siloing,' where expertise is deeply specialised but sometimes lacks a unified multi-hazard framework.

The most profound insight gained through this research, however, is that these cultural and structural differences should not be viewed merely as barriers to research. Instead, they represent 'diverse arsenals' in our collective fight against the escalating threats of multi-hazards. The process of comparing two geographically distant corridors and re-examining shared physical phenomena, such as cascading landslides, allows us to relativise our own national ’common sense’ and discover novel solutions that might remain hidden within a single-country study.

The ultimate defence against the unpredictable nature of climate-induced multi-hazards lies in our ability to collaborate as a unified human society. This ’collaborative approach,’ which bridges linguistic, cultural, and sectoral divides, is not just a methodological choice; it is an existential necessity. By synthesising global expertise, we move from being fragmented responders to a resilient, trans-disciplinary force.

9 Perspectives

The comparative analysis of the Brenner Corridor and the Noto Satoyama Kaido has revealed that despite geographical and cultural distances, mountain corridors share a universal fragility in the face of cascading hazards. This study has demonstrated that the Impact Chain framework can bridge these distant experiences; however, the true potential of such a collaborative approach remains untapped due to systemic constraints. Looking forward, this chapter explores the transformative possibilities of a multi-hazard research landscape, assuming a hypothetical environment with unlimited resources, unconstrained by budget, time, or human capital, to address the escalating threats of the 21st century.

9.1 Overcoming Institutional and Systemic Barriers through Radical Collaboration

The necessity of a collaborative approach in multi-hazard risk management has been advocated since at least 2016. However, as emphasised by Scolobig et al. (2014), significant institutional barriers remain, such as single-risk-centred regulations and fragmented responsibilities. If one were to imagine a research environment with unlimited resources, unconstrained by budget, time, or human capital, the first objective would be to dissolve these silos through a permanent, trans-disciplinary infrastructure for risk governance. In such an idealised scenario, the model established by the Austrian Disaster Competence Network Association (DCNA) and the EU-funded PARATUS project serves as a foundational blueprint. PARATUS, in particular, represents the cutting edge of multi-hazard research by applying a consistent framework across diverse study sites to bridge the gap between scientific analysis and policy recommendation. While currently constrained by European borders, its collaborative essence, integrating cross-sectoral expertise to manage complex hazard interactions, is precisely what the global disaster risk management (DRM) community requires.

With unlimited resources, this collaborative essence would further transition from static Impact Chain diagrams to dynamic virtual simulations. By integrating high-resolution terrain models with real-time sensory data, such as soil moisture monitoring and satellite-based precipitation figures, a global platform could simulate potential cascading failures in a virtual space before they manifest. This would also allow, for instance, road managers to test 'what-if' scenarios, enabling the pre-emptive deployment of resources to the most risk-exposed segments of any given mountain corridor.

9.2 A Global Multi-Hazard Knowledge Commons: Bridging Diverse Experience

With unlimited resources, the next logical evolution of projects like PARATUS would be an expansion to a truly global scale, specifically bridging advanced yet geographically distant disaster-prone regions, such as Austria, Japan, and beyond. This study has highlighted that while both nations possess deep expertise, they suffer from opposite data challenges: Austria's highly specialised but siloed sectoral data versus Japan's rapid, meticulous, but scattered administrative reporting.

While this study focused specifically on the Brenner Pass and the Noto Satoyama Kaido, a resource-unlimited scenario would envision a Real-Time Global Multi-Hazard Platform designed to proactively structure and exchange emerging insights across borders. The following cases are presented not as an exhaustive list of requirements, but rather as illustrative examples of the latent knowledge that could be unlocked through such a platform. Drawing on my background and the specific findings of this research, these two points highlight how region-specific experiences can be elevated to universal lessons:

1. **Upscaling Structural Lessons from Noto:** The mechanisms by which specific embankment improvements along the Noto Satoyama Kaido withstood seismic-induced pluvial stress, while unreinforced sections failed, may offer invaluable data for other earthquake-prone regions, such as Italy or Turkey. Access to the specific engineering details of these Japanese rigid defences could facilitate the pre-emptive reinforcement of global mountain infrastructure against complex seismic-hydrological cascades and vice versa.

2. **Expanding the Scope to Climate-Induced Melt:** Similarly, Japan's recent experiences with the 2023 Yamagata landslide (The Nikkei 2023) may provide a crucial precedent for the Alps. While the event's greater physical details remain a subject for future investigation, the event's significance lies in its cascading nature, triggered by record snowfall followed by unseasonably high temperatures and intermittent rainfall. This reflects the escalating threats in Austria, where rising temperatures are destabilising glaciers and increasing water infiltration. The knowledge gained from the Yamagata's snowmelt-rain-landslide sequence could be a useful survival manual for Alpine communities facing the consequences of rapid glacier retreat.

To facilitate this, an unlimited resource pool would fund a dedicated professional role of 'Disaster Data Curators.' These would be specialists fluent not only in the technical complexities of disaster mitigation but also in the administrative and linguistic cultures of relevant regions. Their role would be to 'translate' and structure domestic/regional disaster archives, which are often exhaustive but fragmented, into globally standardised Impact Chain formats, ensuring that domestic expertise becomes a global asset. By employing such specialists, this global platform could systematically reconstruct and store data encompassing the full spectrum of disasters, ranging from high-frequency, chronic events to low-frequency, high-impact (LFHI) catastrophes, from any affected region where documentation and lived experiences exist. This transformation would turn localised, often inaccessible administrative reports into a universally shared knowledge base. It would allow researchers and practitioners from any corner of the globe to refer to these diverse precedents as a comparative benchmark for their own multi-hazard risks. It is through this structural harmonisation that regional expertise, regardless of its origin, truly becomes a global public good. It must be noted, however, that in a global collaboration, defining a universal standard often leads to intense political debate over institutional hegemony. To mitigate this, a 'rotating leadership' model could be employed, where the project's lead agency shifts periodically among participating regions to ensure equitable representation and diverse methodological contributions. Alternatively, establishing a permanent, politically neutral research body, modelled after the International Institute for Applied Systems Analysis (IIASA), would be essential. By operating independently from immediate national political interests, such a platform can maintain its focus on scientific integrity and long-term disaster resilience.

9.3 From Forensic Reconstruction to Proactive Policy Mainstreaming

Ultimately, the goal of this collaborative approach is to move from forensic event reconstruction to proactive policy mainstreaming. In a world of unlimited resources, every mountain corridor, including both the Brenner Pass and the Noto Satoyama Kaido, would be managed under a Joint Multi-Risk Commission. This commission would facilitate ongoing scenario-sharing and synchronised policy adaptation, ensuring that structural resistance is always bolstered by non-structural agility. At its core, this global collaborative platform is a project to maximise human survival probabilities in an increasingly unpredictable climate. Therefore, access to these multi-hazard insights must be governed by a principle of universal benefit, due to the nature of the insights, which are potentially life-saving. No citizen should be excluded from the protections of this platform due to geopolitical friction or administrative boundaries; the safety of communities, wherever they are, must transcend political agendas.

The ultimate perspective offered by this study is that difference is not a barrier but an asset. The divergence in engineering philosophies and administrative cultures between Austria and Japan represents a diverse "global arsenal" of solutions. By investing heavily in the linguistic and structural harmonisation of these knowledge bases, the international community can finally shift from fragmented, reactive responses to a unified, resilient force capable of outpacing the cascading complexities of the 21st century.

References

5min.at (2023). *Nach Unwettern: Mure sorgt für Teilsperre der Brenner-Autobahn*. News article on mudslide incident in Gries am Brenner following heavy rain on October 30-31, 2023; updated at 09:15. URL: https://www.5min.at/5202310310910/nach-unwettern-mure-sorgt-fuer-teilsperre-der-brenner-autobahn/ (visited on 03/02/2026).

Albulescu, A.-C., I. Armaş, M. De Ruiter, T. Stolte, and T. Endendijk (2026). "Shared Floods, Shared Lessons: An Impact Chain and Metrics-Based Cross-Country Analysis of the 2021 Floods as a Blueprint for Improved Disaster Risk Management". In: *Earth's Future* 14.1, e2025EF006996. DOI: 10.1029/2025EF006996. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2025EF006996 (visited on 02/16/2026).

Albulescu, A.-C. and I. Armaş (2024). "An impact-chain-based exploration of multi-hazard vulnerability dynamics: The multi-hazard of floods and the COVID-19 pandemic in Romania". In: *Natural Hazards and Earth System Sciences* 24.8, pp. 2895–2922. DOI: 10.5194/nhess-24-2895-2024. URL: https://doi.org/10.5194/nhess-24-2895-2024.

Alexander, D. and G. Pescaroli (2019). "What Are Cascading Disasters?" In: *UCL Open Environment* 1, e003. ISSN: 2632-0886. DOI: 10.14324/111.444/ucloe.000003. URL: https://pmc.ncbi.nlm.nih.gov/articles/PMC10171413/ (visited on 11/02/2025).

Autostrada del Brennero S.p.A. (Jan. 31, 2021). *Winter road service*. Autostrada del Brennero S.p.A. URL: https://www.autobrennero.it/en/road-safety-/winter-road-service/ (visited on 12/25/2025).

Baills, A., G. Grandjean, A. Maspataud, S. Ettinger, J. Abad, N. Dias, K. Albris, J. Hemmers, G. Clegg, and C. Martucci (2020). "The ESPREssO Action Database: Collecting and Assessing Measures for Disaster Risk Reduction and Climate Change Adaptation". In: *International Journal of Disaster Risk Reduction* 48, p. 101599. DOI: 10.1016/j.ijdrr.2020.101599. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212420919307903 (visited on 02/16/2026).

Baxter, S., M. Johnson, D. Chambers, A. Sutton, E. Goyder, and A. Booth (2019). "Towards Greater Understanding of Implementation during Systematic Reviews of Complex Healthcare Interventions: The Framework for Implementation Transferability Applicability Reporting (FITAR)". In: *BMC Medical Research Methodology* 19.1, p. 80. DOI: 10.1186/s12874-019-0723-y. URL: https://bmcmedresmethodol.biomedcentral.com/articles/10.1186/s12874-019-0723-y (visited on 02/16/2026).

Cavallaro, F. and F. Maino (2014). “An Approach To Manage Conflicts In The Construction Of New Transport Infrastructures: The Case Of The Brenner Hs/Hc Railway Line”. In: *WIT Transactions on Ecology and the Environment*. DOI: 10.2495/EID140431. URL: https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the-environment/181/26008 (visited on 01/03/2026).

Cavallaro, F., C. Costa, I. De Biasi, A. Fabio, and S. Nocera (2024). “Sustainable Pathways for Mitigating Externalities in Long-Distance Terrestrial Transport”. In: *Transport Policy* 154, pp. 207–221. ISSN: 0967070X. DOI: 10.1016/j.tranpol.2024.05.026. URL: https://linkinghub.elsevier.com/retrieve/pii/S0967070X24001513 (visited on 01/07/2026).

Chiba, Y. (2024). “Traffic Facilities Damages Caused by the 2024 Noto Peninsula Earthquake, Ishikawa Prefecture, Japan”. In: *Journal of Japan Society for Natural Disaster Science* 43.3, pp. 437–448. DOI: 10.24762/jndsj.43.3_437.

Coccuccioni, S., F. Romagnoli, M. Pittore, B. E. Konukçu, S. Kundak, Ç. Göksu, A. A. Aşıcı, K. Y. Arslanlı, D. Kalkanlı, E. Ö. Pak, L. Savelberg, P. Kalubowila, I. Armas, D. T. Danila, G. Osaci, C. Albulescu, T. Wenzel, P. Marr, F. Atun, M. Bockarjova, and B. Witvliet (July 31, 2023). *Report on participatory workshops in the four application case study sites, including impact chains diagrams for each analysed event*. Deliverable D1.1. Version V3. EURAC Research.

De Angeli, S., B. D. Malamud, L. Rossi, F. E. Taylor, E. Trasforini, and R. Rudari (2022). “A Multi-Hazard Framework for Spatial-Temporal Impact Analysis”. In: *International Journal of Disaster Risk Reduction* 73, p. 102829. ISSN: 2212-4209. DOI: 10.1016/j.ijdrr.2022.102829. URL: https://www.sciencedirect.com/science/article/pii/S2212420922000486 (visited on 11/02/2025).

Disaster Competence Network Austria (2025). *FloodPrep: Real-time Simulation and Decision Support for Heavy Rainfall and Pluvial Flooding*. Project information page; project duration 01.11.2025–31.10.2027, coordinated by University of Innsbruck and funded by FFG KIRAS. URL: https://www.dcna.at/index.php/en/floodprep.html (visited on 03/29/2026).

— (2026). *Expert Groups*. Vienna, Austria. URL: https://www.dcna.at/index.php/en/expert-groups.html (visited on 03/29/2026).

European Commission (2011). *White paper on transport : roadmap to a single European transport area : towards a competitive and resource efficient transport system*. DOI: doi/10.2832/30955.

— (2024). *Scandinavian-Mediterranean Core Network Corridor*. URL: https://transport.ec.europa.eu/other-pages/transport-basic-page/scandinavian-mediterranean-core-network-corridor_en (visited on 02/08/2026).

Extreme Disaster Management Headquarters (2024a). *Damage Situation, etc. Related to the 2024 Noto Peninsula Earthquake: 1st Report*. PDF report. As of 7:00 a.m., January 2, 2024. In Japanese. URL: https://www.bousai.go.jp/updates/r60101notojishin/r60101notojishin/pdf/r60101notojishin_01.pdf (visited on 02/24/2026).

— (2024b). *Damage Situation, etc. Related to the 2024 Noto Peninsula Earthquake: 6th Report*. PDF report. In Japanese. URL: https://www.bousai.go.jp/updates/r60101notojishin/r60101notojishin/pdf/r60101notojishin_06.pdf (visited on 03/20/2026).

— (2025). *Damage Situation, etc. Related to the 2024 Noto Peninsula Earthquake: 60th Report*. Government damage report 60. In Japanese. Cabinet Office, Government of Japan. URL: https://www.bousai.go.jp/updates/r60101notojishin/r60101notojishin/pdf/r60101notojishin_60.pdf (visited on 03/20/2026).

Fikar, C., P. Hirsch, M. Posset, and M. Gronalt (2016). "Impact of Transalpine Rail Network Disruptions: A Study of the Brenner Pass". In: *Journal of Transport Geography* 54, pp. 122–131. ISSN: 09666923. DOI: 10.1016/j.jtrangeo.2016.05.018. URL: http://linkinghub.elsevier.com/retrieve/pii/S0966692316302940 (visited on 09/05/2025).

Freiwillige Feuerwehr Gries am Brenner (2023). *++EINSATZ++ Unwettereinsätze in Gries am Brenner*. Detailed operations log for severe weather events from October 30-31, 2023. URL: https://www.ff-griesambrenner.at/l/einsatz-unwettereinsatze-in-gries-am-brenner/ (visited on 03/02/2026).

GeoSphere Austria (2023). *Severe Weather Chronicle for Austria, October 2023*. In German. Part of the "Unwetterchronik" section of the GeoSphere Austria Climate Portal. GeoSphere Austria Climate Portal. URL: https://klimaportal.geosphere.at/unwetterchronik/?jahr=2023&monat=10 (visited on 03/22/2026).

Gill, J. C. and B. D. Malamud (2016). "Hazard interactions and interaction networks (cascades) within multi-hazard methodologies". In: *Earth System Dynamics* 7.3, pp. 659–679. DOI: 10.5194/esd-7-659-2016. URL: https://esd.copernicus.org/articles/7/659/2016/esd-7-659-2016.html.

Haberler, A., M. Lotter, and A. Koçiu (2024). *Gravitative Massenbewegungen in Österreich: Online-Meldungen 2023*. Berichte der GeoSphere Austria 151. Online- und Druckausgabe, ISSN (Online): 2960-4893. Wien: GeoSphere Austria, Kompetenzeinheit Gravitative Naturgefahren. URL: https://www.geosphere.at.

IPCC (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate*

Change. Accessed: 2025-10-19. Intergovernmental Panel on Climate Change. URL: https://www.ipcc.ch/report/ar6/wg2/resources/spm-headline-statements/.

Ishikawa, A., S. Fujimoto, and T. Mizuno (2026). “Anomalous Surge in the Mobility Scaling Exponent Reveals Unique Collective Behavior during the 2024 Noto Peninsula Earthquake”. In: *Journal of Social Physics*.

Ishikawa Prefectural Government (2024). *6th Disaster Response Headquarters Meeting on January 3, 2024*. https://www.youtube.com/watch?v=MQmuMXD7W_8. Ishikawa Prefecture Official Channel. (Visited on 03/29/2026).

Japan Meteorological Agency (2025a). *Ishikawa Prefecture Meteorological Annual Report, 2024*. Annual report. In Japanese. Kanazawa, Ishikawa, Japan: Japan Meteorological Agency, Kanazawa Local Meteorological Observatory. URL: https://www.jma-net.go.jp/kanazawa/data/nenpo/2024.pdf (visited on 02/24/2026).

— (2025b). *Past Meteorological Data Download*. Accessed via interactive table for past weather data download. URL: https://www.data.jma.go.jp/risk/obsdl/#!table (visited on 02/24/2026).

— (2025c). *Questionnaire Survey Results on the Use and Acquisition of Earthquake Early Warnings and Tsunami Warnings Related to the 2024 Noto Peninsula Earthquake*. Government survey report. In Japanese. Tokyo, Japan: Seismology et al., pp. 1–31. URL: https://www.jma.go.jp/jma/press/2508/08d/betten2_r6noto_rikatsuyou.pdf (visited on 03/22/2026).

Karolinska Institutet University Library (2021). *Presenting your search*. Karolinska Institutet University Library. URL: https://kib.ki.se/en/search-evaluate/presenting-your-search (visited on 12/26/2025).

Laimer, H. J. (2017). “Anthropogenically Induced Landslides – A Challenge for Railway Infrastructure in Mountainous Regions”. In: *Engineering Geology* 222, pp. 92–101. ISSN: 00137952. DOI: 10.1016/j.enggeo.2017.03.015. URL: https://linkinghub.elsevier.com/retrieve/pii/S0013795216307335 (visited on 01/07/2026).

Land Tirol (2023). *Hydrologische Übersicht – Oktober 2023*. German. Tech. rep. Accessed: 2026-03-23. Reports 118 mm daily precipitation at Brenner/Obernberg station on 30 October 2023, linked to Gries am Brenner debris flow event. Land Tirol – Hydro Tirol. URL: https://www.tirol.gv.at/fileadmin/themen/umwelt/wasserkreislauf/downloads/hueb_1023.pdf.

Liu, B., Y. L. Siu, and G. Mitchell (2016). “Hazard Interaction Analysis for Multi-Hazard Risk Assessment: A Systematic Classification Based on Hazard-Forming Environment”. In: *Natural Hazards and Earth System Sciences* 16.2, pp. 629–642. ISSN: 1561-8633. DOI: 10.5194/nhess-16-629-2016. (Visited on 01/20/2026).

Mayring, P. (2014). *Qualitative content analysis: theoretical foundation, basic procedures and software solution*. Klagenfurt: Mayring, Philipp, p. 143. URL: https://nbn-resolving.org/urn:nbn:de:0168-ssoar-395173.

meinbezirk.at (2023). *Nach Murenabgang auf A13 wieder je eine Fahrspur pro Richtung frei*. URL: https://www.meinbezirk.at/stubai-wipptal/c-lokales/nach-murenabgang-auf-a13-wieder-je-eine-fahrspur-pro-richtung-frei_a6352391 (visited on 03/15/2026).

Ministry of Land, Infrastructure, Transport and Tourism (2002). *Chapter 1: Reducing Disaster-related Fatalities*. In Japanese. URL: https://www.kkr.mlit.go.jp/plan/daishinsai/1.html (visited on 03/29/2026).

— (2008). *Emergency Transport Roads*. URL: https://www.mlit.go.jp/road/bosai/measures/index3.html (visited on 02/09/2026).

— (2024a). *Damage Analysis of Road Structures (Bridges, Earth Structures, and Tunnels) in the 2024 Noto Peninsula Earthquake*. Government report. In Japanese. Tokyo, Japan: Council for Social Infrastructure Development, Road Subcommittee, Subcommittee on Road Technology.

— (2024b). *Disaster Recovery of Noto-Oetsu Expressway and Noto Satoyama Kaido*. In Japanese. Official webpage updated through 2025 with progress reports and press releases on road restoration following the 2024 Noto Peninsula Earthquake. URL: https://www.hrr.mlit.go.jp/kanazawa/douro_kengendaikou/ (visited on 03/21/2026).

— (2024c). *Main Initiatives for Recovery and Reconstruction from the 2024 Noto Peninsula Earthquake*. Government policy report. In Japanese. Tokyo, Japan: Ministry of Land, Infrastructure, Transport and Tourism. URL: https://www.mlit.go.jp/policy/shingikai/content/001741240.pdf (visited on 03/21/2026).

— (2024d). *On Emergency Restoration (Road Opening) Works*. https://www.mlit.go.jp/road/road_fr4_000151.html. In Japanese. Road Bureau, Ministry of Land, Infrastructure, Transport and Tourism. URL: https://www.mlit.go.jp/road/road_fr4_000151.html (visited on 03/20/2026).

— (2024e). *Regional Revitalisation: Noto Area Peninsula Promotion Policy*. In Japanese. Ministry of Land, Infrastructure, Transport and Tourism. URL: https://www.mlit.go.jp/kokudoseisaku/chisei/kokudoseisaku_chisei_tk_000118.html (visited on 02/09/2026).

— (2024f). *Road Recovery Status in the Noto Peninsula after the 2024 Noto Peninsula Earthquake*. PDF document. URL: https://www.mlit.go.jp/road/road_fr4_000151.html (visited on 03/20/2026).

Morimoto, R., K. Kawamura, T. Miyashita, T. Yamagishi, H. Takahashi, and M. Tsuda (2017). "Embankment collapse of the Noto Satoyama Kaido (former Noto Toll Road) caused by the Noto Peninsula Earthquake and estimation of the groundwater level". In: *Japanese Geotechnical Journal* 12.2, pp. 177–195. DOI: 10.3208/jgs.12.177.

ORF Tirol (2023). *Unwettereinsätze in Gries am Brenner*. URL: https://tirol.orf.at/stories/3230501/ (visited on 03/02/2026).

Ostermann, M. and D. Sanders (2017). "The Benner Pass Rock Avalanche Cluster Suggests a Close Relation between Long-Term Slope Deformation (DSGSDs and Translational Rock Slides) and Catastrophic Failure". In: *Geomorphology*. Slope Tectonics: Inherited Structures, Morphology of Deformation and Catastrophic Failure 289, pp. 44–59. ISSN: 0169-555X. DOI: 10.1016/j.geomorph.2016.12.018. URL: https://www.sciencedirect.com/science/article/pii/S0169555X16312296 (visited on 12/30/2025).

Peng, X., F. Wang, M. Miyajima, M. Yoshida, S. Zhang, and Z. Fu (2025). "Brief Report of a Field Investigation in Noto Peninsula, Japan, after the 2024 Noto Earthquake". In: *Geoenvironmental Disasters* 12.1, 11, s40677-025-00315–x. ISSN: 2197-8670. DOI: 10.1186/s40677-025-00315-x. URL: https://geoenvironmental-disasters.springeropen.com/articles/10.1186/s40677-025-00315-x (visited on 12/19/2025).

Pescaroli, G. and D. Alexander (2018). "Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework". In: *Risk Analysis* 38.11, pp. 2245–2257. ISSN: 1539-6924. DOI: 10.1111/risa.13128. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/risa.13128 (visited on 12/26/2025).

Petutschnig, L., E. Rome, D. Lückerath, K. Milde, Å. Gerger Swartling, C. Aall, M. Meyer, G. Jordá, J. Gobert, M. Englund, K. André, M. Bour, E. M. N. A. N. Attoh, B. Dale, K. Renner, A. Cauchy, S. Reuschel, F. Rudolf, M. Agulles, C. Melo-Aguilar, M. Zebisch, and S. Kienberger (2023). "Research Advancements for Impact Chain Based Climate Risk and Vulnerability Assessments". In: *Frontiers in Climate* 5, p. 1095631. DOI: 10.3389/fclim.2023.1095631. URL: https://www.frontiersin.org/articles/10.3389/fclim.2023.1095631/full (visited on 02/16/2026).

Šakić Trogrlić, R., K. Reiter, R. L. Ciurean, S. Gottardo, S. Torresan, A. S. Daloz, L. Ma, N. Padrón Fumero, S. Tatman, S. Hochrainer-Stigler, M. C. de Ruiter, J. Schlumberger, R. Harris, S. Garcia-Gonzalez, M. García-Vaquero, T. L. Arévalo, R. Hernandez-Martin, J. Mendoza-Jimenez, D. M. Ferrario, and P. J. Ward (2024). "Challenges in assessing and managing multi-hazard risks: A European stakeholders' perspective". In: *Environmental Science and Policy* 157, p. 103774. DOI: 10.1016/j.envsci.2024.103774.

Scolobig, A., A. Garcia-Aristizabal, N. Komendantova, A. Patt, A. Di Ruocco, P. Gasparini, D. Monfort, C. Vinchon, M. Bengoubou-Valerius, R. Mrzyglocki, and K. Fleming (2014). "From multi-risk assessment to multi-risk governance: Recommendations for future directions". In: *Understanding Risk: The Evolution* *of Disaster Risk Assessment*. Ed. by Global Facility for Disaster Reduction and Recovery (GFDRR). Washington, DC: International Bank for Reconstruction and Development, pp. 163–167.

Seneviratne, S. I., N. Nicholls, D. Easterling, C. M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, X. Zhang, M. Rusticucci, V. Semenov, L. V. Alexander, S. Allen, G. Benito, T. Cavazos, J. Clague, D. Conway, P. M. Della-Marta, M. Gerber, S. Gong, B. N. Goswami, M. Hemer, C. Huggel, B. Van Den Hurk, V. V. Kharin, A. Kitoh, A. M. K. Tank, G. Li, S. Mason, W. McGuire, G. J. Van Oldenborgh, B. Orlowsky, S. Smith, W. Thiaw, A. Velegrakis, P. Yiou, T. Zhang, T. Zhou, and F. W. Zwiers (2012). "Changes in Climate Extremes and Their Impacts on the Natural Physical Environment". In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Ed. by C. B. Field, V. Barros, T. F. Stocker, and Q. Dahe. 1st ed. Cambridge University Press, pp. 109–230. DOI: 10.1017/CBO9781139177245.006. URL: https://www.cambridge.org/core/product/identifier/CBO9781139177245A030/type/book_part (visited on 02/07/2026).

Snyder, H. (2019). "Literature Review as a Research Methodology: An Overview and Guidelines". In: *Journal of Business Research* 104, pp. 333–339. ISSN: 01482963. DOI: 10.1016/j.jbusres.2019.07.039. (Visited on 02/04/2026).

The Asahi Shimbun (2024a). *Noto Satoyama Kaido Returns to Two-Way Traffic*. In Japanese. Original title: "Satoyama Kaido, two-way traffic." The Asahi Shimbun. URL: https://digital.asahi.com/articles/DA3S15986248.html (visited on 03/20/2026).

— (2024b). *Recovery Progress on Noto Satoyama Kaido: Full Access Expected, Aiding Wajima Support*. URL: https://www.asahi.com/articles/ASS7L3RCGS7LPJLB00NM.html?iref=pc_rellink_05 (visited on 02/09/2026).

The Nikkei (2023). "Three Factors Behind the Yamagata Landslide: The Overlooked Role of Snowmelt Water". In: *Nihon Keizai Shimbun*. In Japanese. URL: https://www.nikkei.com/article/DGXZQOUE046JE0U3A100C2000000/ (visited on 03/30/2026).

The Sankei Shimbun (2024). *Noto Peninsula Earthquake: A Major Earthquake Occurring at Multi-Millennial Intervals?* In Japanese. The Sankei Shimbun. URL: https://www.sankei.com/article/20240105-TZ5FLLUZLBNYBNSLPMMMARPHXE/ (visited on 03/23/2026).

Tirol Atlas (2013). *Brenner/ Brennero*. Population data as of 12/31/2013. URL: https://tirolatlas.uibk.ac.at/wsgi/places/show?id=210010&lang=en (visited on 02/08/2026).

Tsukada, Y. (2024). "Considering Large-Scale Embankment Failures Caused by the Noto Peninsula Earthquake". In: *Journal of the Japan Society for Natural Disaster Science* 43.2, pp. 171–174.

Ueda, M. (2024). *Reconnecting Noto's "Main Artery": Four Sleepless Days to Open the Road through Public–Private Cooperation*. In Japanese. The Asahi Shimbun. URL: https://digital.asahi.com/articles/ASS7L3RCGS7LPJLB00NM.html (visited on 03/20/2026).

UN (2016). *Report of the Open-ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction*. New York: United Nations General Assembly. URL: https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf (visited on 02/11/2026).

United Nations International Strategy for Disaster Reduction (2009). *2009 UNISDR terminology on disaster risk reduction*. Geneva: United Nations International Strategy for Disaster Reduction (UNISDR). URL: https://www.preventionweb.net/files/7817_UNISDRTerminologyEnglish.pdf (visited on 02/11/2026).

United Nations Office for Disaster Risk Reduction (UNDRR) (2017a). *The disaster risk reduction (DRR) glossary*. The Sendai Framework Terminology on Disaster Risk Reduction. URL: https://www.undrr.org/drr-glossary/terminology (visited on 02/10/2026).

— (2017b). *The Sendai Framework Terminology on Disaster Risk Reduction: "Hazard"*. Accessed 19 January 2026. URL: https://www.undrr.org/terminology/hazard.

— (2017c). *The Sendai Framework Terminology on Disaster Risk Reduction: Hazardous Event*. Accessed April 27, 2026. URL: https://www.undrr.org/terminology/hazardous-event (visited on 04/27/2026).

— (2017d). *The Sendai Framework Terminology on Disaster Risk Reduction: Vulnerability*. Accessed April 27, 2026. URL: https://www.undrr.org/terminology/vulnerability (visited on 04/27/2026).

— (2023). *Disaster. Definition in the Disaster Risk Reduction Glossary*. UNDRR. URL: https://www.undrr.org/terminology/disaster (visited on 02/11/2026).

Wegscheider, S., L. Hübner-Weiss, and S. Schwillinsky (2022). *Erhebung alpenquerender Güterverkehr 2019 Österreich*. German. Endbericht. Erhebung alpenquerender Güterverkehr 2019 Österreich (CAFTA2019). Wien, Österreich: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. URL: https://www.bmimi.gv.at/dam/jcr:47a1aa22-4cd8-4fbb-9e02-59ad7b74e8b7/CAFTA19_Endbericht_UA.pdf (visited on 02/07/2026).

Wenzel, T., P. Marr, T. Glade, F. Höfler, A. Preißler, M. Adams, S. Cocuccioni, M. Pittore, M. Hürlimann, C. Van Westen, and F. Atun (2024). "Local Natural Hazards, Cascading to Cross-Regional Risks and Impacts Along the Main Transit Route from North and South in the Austrian Alps". In: *Proceedings of the 7th International Conference on Earthquake Engineering and Seismology*. Ed. by M. A. Erberik, A. Askan, and M. K. Kockar. Vol. 401. Cham: Springer Nature Switzerland, pp. 359–369. DOI: 10.1007/978-3-031-57357-6_32. URL: https://link.springer.com/10.1007/978-3-031-57357-6_32 (visited on 09/05/2025).

Yamakoshi, N. (2024). “Road Disaster Prevention Measures in Response to the 2024 Noto Peninsula Earthquake: Considering the Geographical Disadvantages of a Peninsula”. In: *Legislation and Research* 469. In Japanese, pp. 251–271. URL: https://www.sangiin.go.jp/japanese/annai/chousa/rippou_chousa/backnumber/20240920.html (visited on 03/20/2026).

Appendix

This appendix provides the detailed records of the literature identification and selection process described in the Methodology section. The following tables report the search strings, strategies, and outcomes used to ensure the transparency and reproducibility of this study.

- **Appendix A: Search ID table**
  Details the 14 systematic search strings, snowballing (SN01), and prior knowledge (PK01) used across various databases. It records the specific keywords, databases, hits, and the number of sources finally included from each string. Note that some strings yielded zero relevant results after screening, which is reported for methodological transparency.

- **Appendix B: Literature Management Overview**
  Provides a comprehensive list of the 40 core academic sources utilised for the analysis. This includes the 18 sources yielded from the systematic search, as well as 22 sources identified through backward snowballing (SN01) and prior knowledge (PK01).

Appendix A: Search ID table

Search ID	Database/ Platform	Database Category	Document type	Search String/ Strategy	Language Filter	Time Filter	Search date	Hit	Included
G01_GS_initial	Google Scholar	Search Engine	Journal Article	"Noto Satoyama Kaido"	E+J	2015-2025	19.12.25	23	1
G02_GS_tnet	Google Scholar	Search Engine	Journal Article	"Trans European Networks-Transport" AND "Brenner"	E+G	2010-2025	03.01.26	92	1
G03_GS_ipcc	Google Scholar	Search Engine	Report	"extreme events" AND "ipcc reports"	E+G	N/A	14.12.25	1	1
G04_GO_paratus	Google	Search Engine	Technical Report	"paratus project" -> Official PARATUS project website -> Project library-> Deliverables ->D1.1	E+G	N/A	05.12.25	1	1
G05_GS_ic	Google Scholar	Search Engine	Journal Article	"impact chain analysis" AND "multi-hazard" AND "PARATUS"	E+G	2015-2025	05.12.25	44	1
S01_SD_brenner	Science Direct	Citation Database	Journal Article	"brenner pass" AND "hazards" AND "disruption"	E+G	2015-2025	06.01.26	170	2
S02_SD_rail	Science Direct	Citation Database	Journal Article	"brenner corridor" AND "rail vulnerability"	E+G	2015-2025	05.12.25	30	1
S03_SD_bbt	Science Direct	Citation Database	Journal Article	"brenner base tunnel" AND" natural hazard"	E+G	2015-2025	05.12.25	81	1
S04_SD_corridormanagement	Science Direct	Citation Database	Journal Article	"mountain corridor" AND "transport" AND "infrastructure management" AND "Brenner"	E+G	2015-2025	05.12.25	38	2
G06_GS_alps	Google Scholar	Search Engine	Journal Article	"brenner corridor" AND "multi-hazard" AND "alps"	E+G	2015-2025	30.12.25	18	1
G06_GS_mountaintransportcrds	Google Scholar	Search Engine	Journal Article	"mountain transport corridors" + "multi-hazard"	E+G	2015-2025	28.01.26	3800	0
G07_GS_NotoSlopeFailure	Google Scholar	Search Engine	Journal Article	"noto earthquake" AND "slope failure" AND "Satoyama"	E+J	2015-2025	02.02.26	43	0
U01_transferability	u:search	Search Engine	Journal Article	"scoping review methodological frameworks for transferability across systems", "cross-context multi-hazards", transferable "impact-chain"	E+G	2015-2025	16.02.26	13	3
G08_GS_ContentAnalysis	Google Scholar	Search Engine	Journal Article	"content analysis method geography"	E+G	2016-2026	22.02.26	38.900	0
PK01	prior knowledge	Manual Search/ Snowballing	Journal Article	N/A	N/A	N/A	N/A	N/A	11
SN01	Backward Citation Search	Manual Search/ Snowballing	Journal Article	N/A	N/A	N/A	N/A	N/A	11

Appendix B: Literature management overview

Author/Year	Search ID	Relevant chapter	Title	Journal/ Source
seneviratne2012	SN01	02_Theory	Changes in Climate Extremes and Their Impacts on the Natural Physical Environment	Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
Liu2016	SN01	02_Theory	Hazard Interaction Analysis for Multi-Hazard Risk Assessment: A Systematic Classification Based on Hazard-Forming Environment	Natural hazards and earth system sciences
Alexander2018	PK01	02_Theory	A magnitude scale for cascading disasters	International journal of disaster risk reduction
alexander2019	PK01	02_Theory	What are cascading disasters?	UCL open environment
deangeli2022	PK01	02_Theory	A multi-hazard framework for spatial-temporal impact analysis	International journal of disaster risk reduction
gillmalamud2014	PK01	02_Theory	Reviewing and visualizing the interactions of natural hazards	Review of geophysics
gillmalamud2016	PK01	02_Theory	Hazard interactions and interaction networks (cascades) within multi-hazard methodologies	Earth system dynamics
sakic2024	PK01	02_Theory	Challenges in assessing and managing multi-hazard risks: A European stakeholders' perspective	Environmental Science and Policy
pescalex2016	PK01	02_Theory	Critical infrastructure, panarchies and the vulnerability paths of cascading disasters	Natural Hazards
pescalex2018	PK01	02_Theory	Understanding compound, interconnected, interacting, and cascading risks: A holistic framework	Risk Analysis
ipcc2012	G03_GS_ipcc	02_Theory	Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation	Intergovernmental Panel on Climate Change
ostermann2017	SN01	03_Brenner	The Benner pass rock avalanche cluster suggests a close relation between long-term slope deformation (DSGSDs and translational rock slides) and catastrophic failure	Geomorphology
marini2025	SN01	03_Brenner	Innovations in the Brenner Base Tunnel project: From planning to operations	Tunnelling into a Sustainable Future – Methods and Technologies
EU_whitepaper	SN01	03_Brenner	White paper on transport – Roadmap to a single European transport area – Towards a competitive and resource efficient transport system	Publications Office of the European Union
2marini2025	SN01	03_Brenner	The Brenner Base Tunnel system: An overview of the main interferences between the different cavities	Tunnelling into a Sustainable Future – Methods and Technologies
cavallaro2022	S04_SD_corridormanagement	03_Brenner	Are transport policies and economic appraisal aligned in evaluating road externalities?	Transportation Research Part D: Transport and Environment
cavallaro2024a	S04_SD_corridormanagement	03_Brenner	Sustainable pathways for mitigating externalities in long-distance terrestrial transport	Transport Policy
laimer2017	S03_SD_bbt	03_Brenner	Anthropogenically induced landslides – A challenge for railway infrastructure in mountainous regions	Engineering Geology
fikar2016	S02_SD_rail	03_Brenner	Impact of transalpine rail network disruptions: A study of the Brenner Pass	Journal of Transport Geography
pfurtscheller2019	S01_SD_brenner	03_Brenner	The Felbertauern landslide of 2013 in Austria: Impact on transport networks, regional economy and policy decisions	Case Studies on Transport Policy
simeoni2024	S01_SD_brenner	03_Brenner	Mobile Terrestrial LiDAR survey for rockfall risk management along a highway	Procedia Structural Integrity
wenzel2024	PK01	03_Brenner	Local Natural Hazards, Cascading to Cross-Regional Risks and Impacts Along the Main Transit Route from North and South in the Austrian Alps	Proceedings of the 7th International Conference on Earthquake Engineering and Seismology
chen2016	G06_GS_alps	03_Brenner	Integrating expert opinion with modelling for quantitative multi-hazard risk assessment in the Eastern Italian Alps	Geomorphology
cavallaro2014	G02_GS-tnet	03_Brenner	An Approach To Manage Conflicts In The Construction Of New Transport Infrastructures: The Case Of The Brenner Hs/hc Railway Line	WIT Transactions on Ecology and the Environment
schiavo2014	SN01; Backwards_Wenzel et al., 2024	03_Brenner	Geology of the Brenner Pass-Fortezza transect, Italian Eastern Alps	Journal of Maps
yamakoshi2024	SN01	04_Noto	Road Disaster Prevention Measures in Response to the 2024 Noto Peninsula Earthquake: Considering the Geographical Disadvantages of a Peninsula	Legislation and Research 469
peng2025	G01_GS_initial	04_Noto	Brief report of a field investigation in Noto Peninsula, Japan, after the 2024 Noto earthquake	Geoenvironmental Disasters
morimoto2017	G01_GS_initial	04_Noto	Embankment Failure of the Noto Satoyama Kaido (Former Noto Toll Road) Caused by the Noto Peninsula Earthquake and Estimation of Groundwater Levels: A Proposal of a Simplified Seismic Stability Evaluation Method for Road Embankments in Mountainous and Hilly Areas	Japanese Geotechnical Journal
chiba2024	G01_GS_initial	04_Noto	Traffic Facilities Damages Caused by the 2024 Noto Peninsula Earthquake, Ishikawa Prefecture, Japan	Journal of Japan Society for Natural Disaster Science
baxter2019	U01_transferability	06_Methodology	Towards greater understanding of implementation during systematic reviews of complex healthcare interventions: the framework for implementation transferability applicability reporting (FITAR)	BMC Medical Research Methodology
baills2020	U01_transferability	06_Methodology	The ESPREssO Action Database: Collecting and assessing measures for disaster risk reduction and climate change adaptation	International journal of disaster risk reduction
albulescu2026	U01_transferability	06_Methodology	Shared Floods, Shared Lessons: An Impact Chain and Metrics-Based Cross-Country Analysis of the 2021 Floods as a Blueprint for Improved Disaster Risk Management	Earth's Future
snyder2019	SN01	06_Methodology	Literature review as a research methodology: An overview and guidelines	Journal of Business Research
scolobig2014	SN01	06_Methodology	From Multi-risk assessment to multi-risk governance: recommendations for future directions	-
Petutschnig2023	SN01	06_Methodology	Research Advancements for Impact Chain Based Climate Risk and Vulnerability Assessments	Frontiers in Climate
mayring2014	PK01	06_Methodology	Qualitative Content Analysis. Theoretical Foundation, Basic Procedures and Software Solution	-
Page2021	PK01	06_Methodology	The PRISMA 2020 statement: an updated guideline for reporting systematic re-views	BMJ372
albulescu2024	G05_GS_ic	06_Methodology	An impact-chain-based exploration of multi-hazard vulnerability dynamics: the multi-hazard of floods and the COVID-19 pandemic in Romania	Natural hazards and earth system sciences
cocuccioni2023impact	G04_GO_paratus	06_Methodology	D1.1 Impact chains for the Application Case Studies	-