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ORIGINAL PAPER

SCoMHA: a framework to analyse process-level sediment connectivity in multi-hazard events

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Abstract

A slope saturated from prolonged rainfall suddenly fails and connects to the channel; while high runoff mobilizes loose sediments into a debris flow, a landslide supplies more material that clogs channels and floods areas downstream—a hazard-chain in motion. Multi-hazard events in mountains often involve such complex process-dynamics that are tied together by sediment connectivity. Yet, this important conduit is rarely accounted for in hazard analysis. This study addresses that gap by developing a new framework that integrates sediment connectivity into multi-hazard analysis in mountain catchments. It adopts a data-agnostic structure that incorporates both qualitative and quantitative data through a fuzzy logic scheme. This is then used to calculate a sediment connectivity weight (SCW) for each process comprising a multi-hazard event. Applying it to eight Alpine events reveals how proficiently each underlying process shapes the propagation and distribution of a hazard cascade. Sediment-heavy flows and severe channel erosions received high-SCW scores, indicating strong functional connectivity and a dominant role in event dynamics. Conversely, depositional processes or those reaching beyond the source-catchment score low, indicating gradual termination of the cascade. It also captures abrupt transitions like overtopped structures turning from barriers to connectors and disconnected areas being suddenly reactivated. Such patterns affirm that sediment connectivity is a dynamic catchment property continuously interacting with hazard processes—highlighting the need for holistic assessments. The modular and flexible design of the framework enables wide applicability and integration of additional indicators or logic to effectively analyse complex multi-hazard dynamics.

Keywords Sediment connectivity · Multi-hazards · Process-based framework · Mountain catchments · Hazard-interactions

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1 Introduction and rationale

Sediment connectivity is the fundamental mechanism through which hazards connect, interact, and evolve in multi-hazard events. These dynamics are particularly critical in mountain landscapes, which are characterized by some unique natural processes and phenomena. Mountains across the world are subjected to extensive and increasing impacts of climate change, which eventually lead to an increase in natural hazard occurrences and their intensities (Nogués-Bravo et al. 2007; Keiler et al. 2010; Huggel et al. 2012; Beniston et al. 2018; Kirschbaum et al. 2020; Rubinato et al. 2020). The most recurrent natural hazards in the Alpine region are mountain hazards, such as landslides, avalanches, floods, and debris flows (Metternicht et al. 2005; Keiler et al. 2010; Lepuschitz 2015). Given the increasing influence of climate change and human intervention, the recurrences and impacts of these hazards are projected to intensify in the upcoming years (Beniston 2003; Lehning and Wilhelm 2006; Bernardie et al. 2021; Mani et al. 2023; APCC 2025; Haslinger et al. 2025; Fan et al. 2025).

Assessing and dealing with one specific type of natural hazard in isolation usually refers to a single-hazard approach (Tilloy et al. 2019; Julià and Ferreira 2021) and is commonly used in disaster risk reduction (DRR) practices (Fleming et al. 2016). Especially, Alpine countries have traditionally relied on such approaches, through isolated, single-hazard mapping and pre-defined scenario-based zoning to delineate areas at risk (a product of hazard, vulnerability, and exposure (Dewan 2013; UNISDR 2015), and thus often overlooking the dynamics and interconnectedness of multiple hazards (Keiler and Fuchs 2018). In such contexts, single-hazard approaches can underestimate the actual risk in place, whereas multi-hazard approaches are more efficient and appropriate in terms of addressing the complex interactions among different hazards, better risk management, improved mitigation and preparedness, and overall a greater understanding of the hazard context and interactions (Papathoma-Köhle et al. 2011; Kappes et al. 2012; Fuchs et al. 2013; van Westen et al. 2014; Saha et al. 2021). Events that involve multiple coexisting or interacting natural hazards or hazardous processes over a certain spatio-temporal scale refer to (and regarded in this study as) multi-hazard events (Sadegh et al. 2018; Pourghasemi et al. 2019; Wang et al. 2020). In practice, multi-hazard events are often assessed as the simple sum of individually assessed hazards, a method proven inadequate to capture the true hazard situation (Kappes et al. 2012; Fan et al. 2025). Although recent years have seen some methodological developments focusing on hazard interactions (Gill and Malamud 2014; Liu et al. 2016; Dunant et al. 2021; Bebbington et al. 2025), data acquisition and integration of heterogeneous data types remain major challenges (Kappes et al. 2012; Graff et al. 2019). Among these, process-based models such as r.avaflow (Mergili et al. 2017) can simulate cascading mass flow processes in mountain catchments, but typically require detailed inputs and focus on dynamic simulation. Given the variety of approaches and inherent challenges, the importance of developing more holistic frameworks has been widely recognized (Kappes et al. 2012; Barrantes 2018; Tilloy et al. 2019).

Notably, geomorphic processes such as multi-hazard events are fundamentally intertwined with sediment storage, mobilization, and transport (Korup et al. 2004; Owens et al. 2010; Korup 2012; Prancevic et al. 2014), which significantly influence hazard assessment through their highly variable interactions with the terrain and geomorphic processes (Wolman 1977; Anthony and Julian 1999; Förstner and Salomons 2008). To account for this, the concept of ‘sediment connectivity’ can aid in assessing such basin-scale geomorphic processes (e.g., natural hazards) and their interlinkages (Kuo and Brierley 2014; Cavalli et al. 2019; Lisenby et al. 2020). The term ‘connectivity’—referring broadly to the exchange of energy or material across different components of a system (Johnson 1995; Fryirs 2013)—is relevant to many other research fields (Brierley et al. 2006), including ecology (LaPoint et al. 2015; Bishop et al. 2017), pollutant and nutrient dispersion (Chartin et al. 2013; Soranno et al. 2015), geomorphology (Wohl et al. 2019; Singh et al. 2021), and also to the field of natural hazards (Cavalli et al. 2013; Tiranti et al. 2016; Sá et al. 2022; Sharma et al. 2023). In geomorphology, ‘connectivity’—mostly referring to geomorphic/sediment connectivity (Cienciala 2021)—is relatively new (Cossart and Fressard 2017) but not an innovation (Bracken et al. 2015). Sediment connectivity, as conceived in this study, can be defined as the degree of a geomorphic system’s capability to facilitate sediment movement across its components (Heckmann et al. 2018). In other words, it refers to the material transport between two zones (each comprising a morphologic and cascading system) over a variety of spatial and temporal scales through the transport vectors of the system (Schumm 1981; Peters et al. 2008). Though some studies tend to use the terms ‘sediment connectivity’ and ‘sediment coupling’ interchangeably (Harvey 2012), they are conceptually quite distinct; as the concept of ‘coupling’ is based on the location-specific morphological setting, whereas the continuity of the cascading systems sets the basis for the ‘connectivity’ concept (Bracken et al. 2015). Thus, ‘sediment coupling’ can be a subset of ‘sediment connectivity’ (Heckmann and Schwanghart 2013). In a catchment scale, sediment movement can be on hillslopes, between hillslopes and channels, and within channels (Bracken et al. 2015); and they are defined as structural, lateral/functional, and longitudinal/vertical connectivity, respectively (Fryirs et al. 2007a). While all types of connectivity shape catchment behaviour, functional connectivity—consisting of the volumetric and temporal aspects—is particularly crucial for hazard assessment because it directly affects hazard magnitude and frequency; high functional connectivity indicates a higher likelihood of geomorphic changes and often delineates hazard hotspots (Zingaro et al. 2020; Torresani et al. 2023). On the other hand, disconnectivity in a geomorphic system indicates long-term sediment storage (Messenzehl et al. 2014) with the potential of sediment mobilization in the case of an extreme event (Borselli et al. 2008; Owens et al. 2010). A thorough understanding of sediment connectivity can provide valuable insights into hazard magnitude and pathways, and therefore is crucial for natural hazard and risk studies (Crema and Cavalli 2018; Najafi et al. 2021). Sediment connectivity can also be abruptly altered by additional local factors such as large wood, which can eventually play a critical role in propagating complex hazard cascades (Ruiz-Villanueva et al. 2014; Steeb et al. 2017; Swanson et al. 2021).

However, studying sediment connectivity in the context of multi-hazards is a complex and challenging task, both when studied individually and especially together (Kappes et al. 2012; Heckmann et al. 2018; Cislaghi and Bischetti 2019; He and Weng 2020; Abatti et al. 2023). Substantial research work has been conducted in the direction of relating sediment connectivity and natural hazards, especially during the recent years (Li et al. 2016; de Walque et al. 2017; Bordoni et al. 2018; Kalantari et al. 2019; Martini et al. 2019; Zingaro et al. 2020); but they mostly adopted a so-called ‘single-hazard approach’ (Caputo et al. 2015; Mesa-Gómez et al. 2020; Hussain et al. 2023). Wichmann et al. (2009) employed a random walk algorithm-based modelling approach to delineate potential sediment transport pathways—a crucial component of sediment connectivity; while this method considers geomorphic process interactions to some extent, it cannot address the temporal aspect, which is another crucial component of sediment connectivity (Saletti et al. 2015; Heckmann et al. 2018). Additionally, the mere use of geomorphic process units (GPUs) and map overlays (Wichmann et al. 2009) is not sufficient to address the dynamic nature of hazard interactions. Connectivity indices are one of the popular means to address sediment connectivity, of which the raster-based Borselli index (Borselli et al. 2008), later developed further by Cavalli et al. (2013), is one of the most prominent methods (Heckmann et al. 2018). Besides the raster-based methods, object or network-oriented methods (Heckmann and Schwanghart 2013; Cossart and Fressard 2017; Wohl 2017) and catchment area-based approaches (Fryirs et al. 2007b; Kumar et al. 2014; Nicoll and Brierley 2017) also exist, but Heckmann et al. (2018) show that the existing methods predominantly focus on the structural aspects of the sediment connectivity concept. Although several efforts aim to address the functional aspect of sediment connectivity (Lane et al. 2017; Kalantari et al. 2017; Mahoney et al. 2018; López-Vicente and Ben-Salem 2019; Zingaro et al. 2019), they are often confined within the structural component and/or remain untested or inadequate for capturing the complexities of multi-hazard dynamics.

To ensure improved assessment of multi-hazard events, it is vital to understand how the involved hazard processes originate and interact (e.g., among themselves and with the sediment cascade), while the event propagates through a geomorphic system (Fan et al. 2025), for which sediment connectivity is an optimal framework (Cossart et al. 2018). While the significance of sediment connectivity in understanding landscape processes (e.g., natural hazards) and their interactions has been widely acknowledged (Parsons et al. 2015; Keesstra et al. 2018; Baartman et al. 2020; Cho et al. 2023), the critical need for further research and methodological development in this field, with a special focus on the functional connectivity, still remains (Crema and Cavalli 2018; Heckmann et al. 2018; Baartman et al. 2020; Najafi et al. 2021). Assessing the process/hazard interactions is crucial for studying both multi-hazard events (Gill and Malamud 2016) and sediment connectivity (Piva et al. 2011), for which a holistic approach is important (Keesstra et al. 2018). In fact, no such framework exists that explicitly integrates sediment connectivity in the assessment of multi-hazard events, leaving a critical gap in current hazard and risk analysis. Motivated by this shortcoming, this study strives to develop a sediment connectivity indexed multi-hazard assessment (*SCoMHA = Sediment Connectivity for Multi-Hazard Assessment*) framework that addresses the complex interrelationship between sediment connectivity and multi-hazard events in mountain catchments (hereafter referred to as SCoMHA). At the core of this framework is a reproducible, process-level metric that quantifies functional sediment connectivity within multi-hazard cascades, which enables a transparent ranking of the influential process-segments, cross-event comparison, and integration in event analysis. The following research questions guide the research: (i) how can a conceptual framework facilitate the assessment of sediment connectivity in the context of multi-hazard events while supporting the integration of both its structural and functional aspects? (ii) How do the fundamental processes involved in a multi-hazard event influence sediment dynamics, and how do these dynamics in turn characterize the evolution and propagation of multi-hazard events? (iii) How can sediment connectivity be systematically embedded into holistic approaches for evaluating multi-hazard scenarios in mountain catchments? To address these, the study pursues three key objectives, to:

- identify the underlying processes that drive interactions between sediment connectivity and multi-hazard events;
- develop a comprehensive and data-inclusive framework that incorporates the concept of sediment connectivity within multi-hazard assessment; and
- establish an approach for incorporating heterogeneous data in ways that support adaptability and transferability across different mountain catchment and hazard settings

Collectively, these research questions and objectives guide the study towards the development of a novel and holistic framework that, besides advancing the theoretical understanding of sediment connectivity in multi-hazard contexts, strengthens our practical capacities for assessing and managing multi-hazard events in complex mountain catchments. To operationalize and illustrate the applicability of the proposed conceptual framework, it is applied to eight multi-hazard events. These case studies help to demonstrate how integrating sediment connectivity through process-segmentation, relevant indices, and expert-informed evaluation can offer new insights into multi-hazard events.

2 Methods

To address the objectives, this study employed a systematic approach aimed at setting the basis for integrating both qualitative and quantitative approaches, thereby enabling a holistic analysis. Figure 1 depicts the conceptual process flow of the SCoMHA framework.

2.1 Event selection and data analysis

The study focused on several multi-hazard events in Alpine catchments in Austria and Switzerland, selected based on three criteria. Firstly, the scale of analysis was prioritized, as sediment connectivity is inherently spatial (Parsons et al. 2015; Lu et al. 2019). The chosen scale was sufficiently large to accommodate multi-hazard interactions and connectivity networks, but not so extensive that external processes (e.g., originating elsewhere) became dominant. Secondly, data availability was essential; catchments with adequate qualitative and/or quantitative data to ensure sufficient coverage of the event characteristics and progression (location and sequence) were selected. Thirdly, the multi-hazard definition and scope, as elaborated in Sect. 1, guided the selection. Accordingly, this study is restricted to multi-hazard events that occur in the mountain systems (Chakraborty 2021; Vij et al. 2021).

Based on these criteria, eight multi-hazard events in Alpine catchments across Austria (five cases) and Switzerland (three cases) were selected to demonstrate and test the applicability of the SCoMHA framework. While selecting the events (occurred between 2005 and 2020), the availability of detailed documentation describing the process-level interactions (crucial for evaluating sediment connectivity) was an important consideration among other factors. The selected catchments (event year in parentheses) are Schallerbach (2015), Seigesbach (2015), Schnannerbach (2018), Maierhofgraben (2017), and Firschnitzbach (2012) in Austria, and Rotlauibach, Glyssibach, and Trachtbach (all 2005) in Switzerland (Fig. 2). For all the events, we obtained post-event reports from the responsible national or regional authorities and high-resolution (0.5 m) elevation models. Elevation data obtained for the Austrian events were provided by Land Tirol (2023) and Land Salzburg (2025), whereas

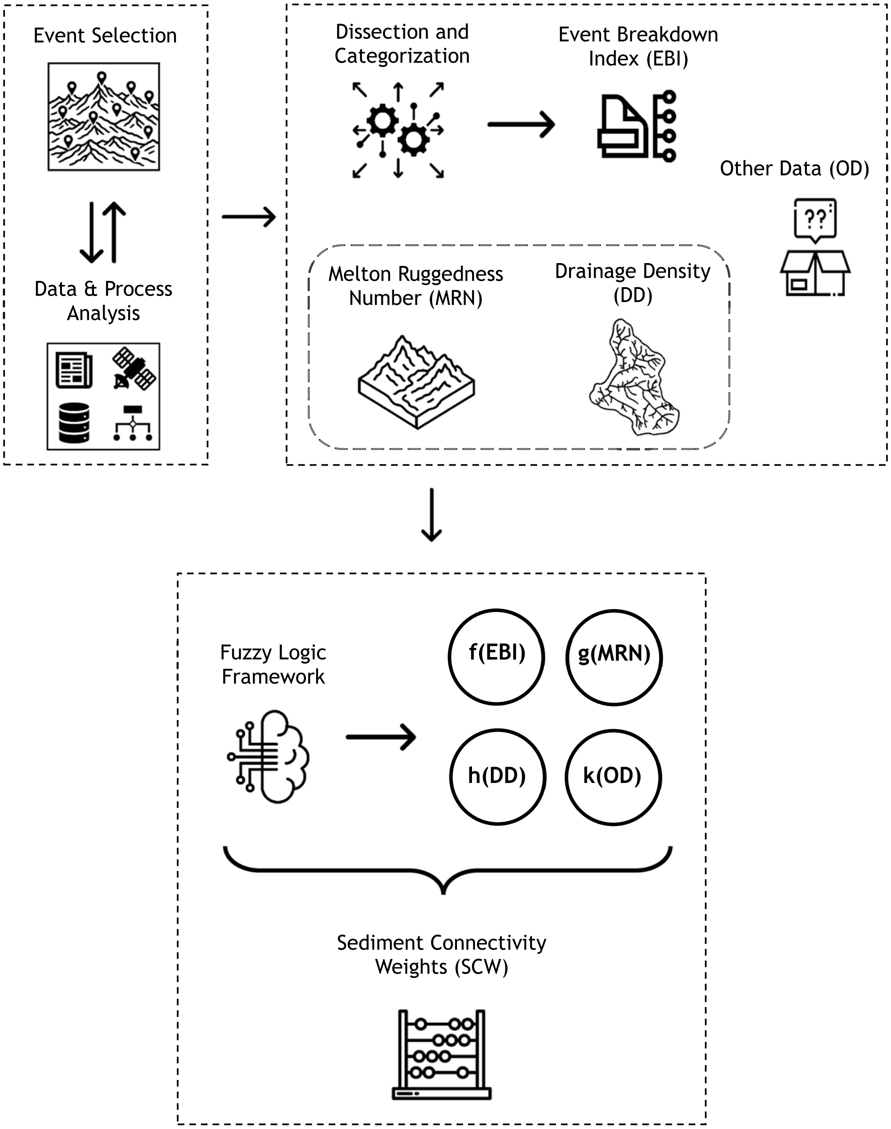
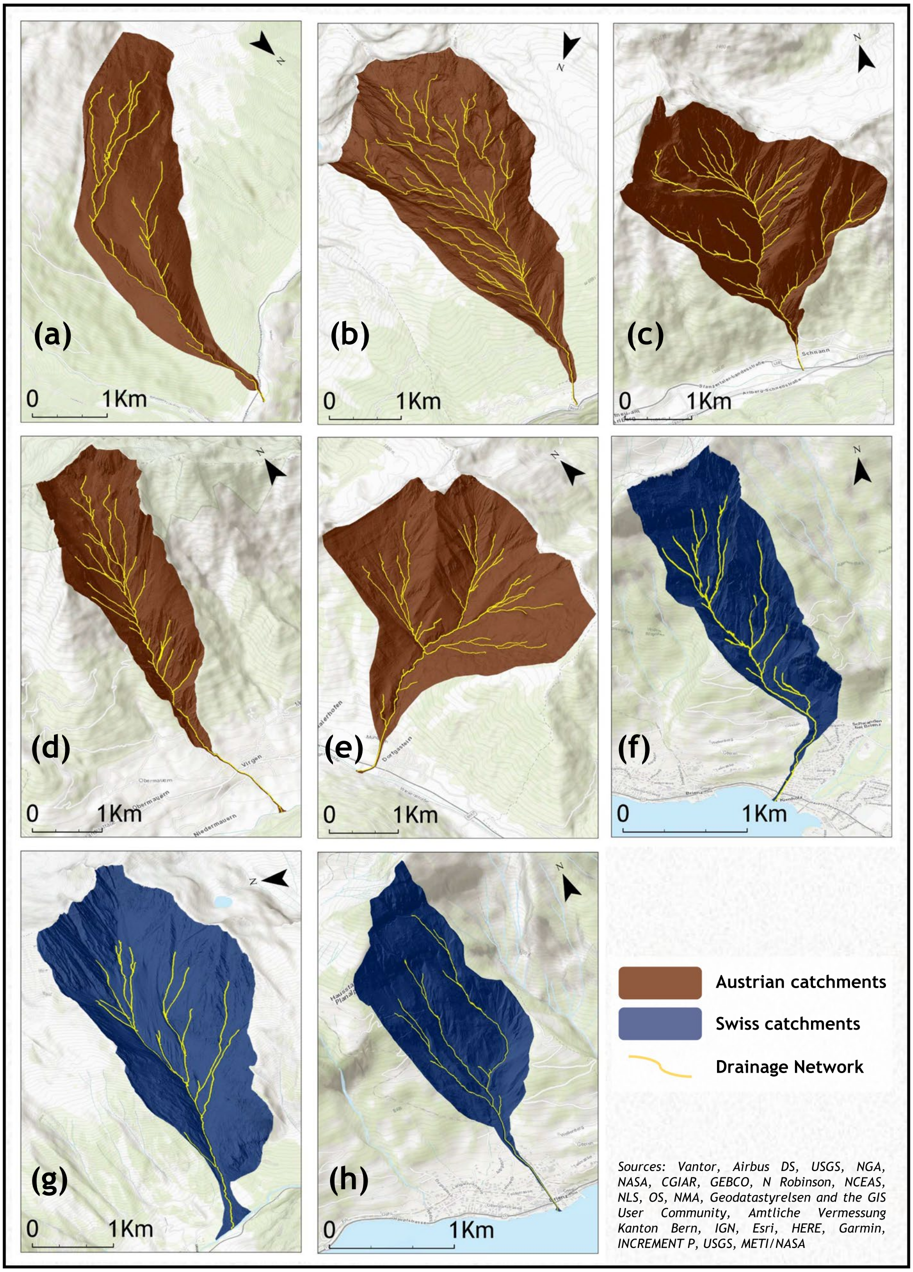


Fig. 1 Conceptual workflow of the proposed SCoMHA framework

the swissALTI3D (Swisstopo 2024) dataset was used for the Swiss events. Event reports were obtained from BMLFUW (2016) for Seigesbach and Schallerbach, WLV (2019) for Schnannerbach, BMLRT (2021) for Firschnitzbach, and BMNT (2018) for Maierhofgraben. For the Swiss events from the year 2005, we obtained documentation from BAFU and WSL (2007).

The selected catchments share typical characteristics of highly dynamic Alpine environments, while also exhibiting significant differences in scale, geology, topography, and land cover. The catchment areas are predominantly small in size, ranging from 4.1 km^2 (Sei-



Sources: Vantor, Airbus DS, USGS, NGA, NASA, CGIAR, GEBCO, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen and the GIS User Community, Amtliche Vermessung Kanton Bern, IGN, Esri, HERE, Garmin, INCREMENT P, USGS, METI/NASA

Fig. 2 Selected case-study sites from Austria (in brown, Seigesbach (**a**), Schallerbach (**b**), Schnannerbach (**c**), Firschnitzbach (**d**), Maierhofgraben (**e**)) and Switzerland (in blue, Glyssibach (**f**), Rotlauibach (**g**), Trachtbach (**h**)). SCoMHA_OR2 contains a webapp for spatial exploration of the case-study sites gesbach) to 8.5 km^2 (Maierhofgraben), and are characterized by high relief and gradient. According to our manually delineated catchment boundaries extending to the confluence with the main river, the elevation differences range from approximately 990–1600 m (above sea level), resulting in steep longitudinal profiles that facilitate high-energy sediment movement (Fig. 3). Beyond the geomorphological differences, the events also vary considerably in magnitude, providing us with diverse conditions for testing the methodological framework. Based on the documented mass balances, mid-range events such as Maierhofgraben involved erosion of approximately 49,000 m^3, whereas Schallerbach had about 126,000 m^3 of sediment mobilized. Exceptionally, the Rotlauibach event was documented to involve roughly 320,000 m^3 of sediment mobilization—the highest among the studied events (BAFU and WSL 2007; BMLFUW 2016; BMNT 2018; WLV 2019; BMLRT 2021). This heterogeneity in geomorphic setting and sediment flux ensures that the proposed SCoMHA framework is tested for its ability to capture sediment connectivity dynamics in complex, high-magnitude multi-hazard events in Alpine catchment systems. Therefore, these selected events serve as illustrative case studies, while the primary focus of the study remains on the methodological framework rather than on an exhaustive analysis of each event.

However, quantitative data on mountain multi-hazard events are often quite limited (Chen et al. 2016) and fragmented, posing major constraints on research and adding uncertainty. To tackle this, we propose making use of the comparatively more available qualitative sources (e.g., event reports, news archives) in an integrated manner with the quantitative datasets, where feasible. In this illustrative study, the acquired qualitative data were interpreted using the framework of Brugnach (2005), which is suitable for such complex process-based interactions. Additionally, we evaluated the possibility of complementing the qualitative

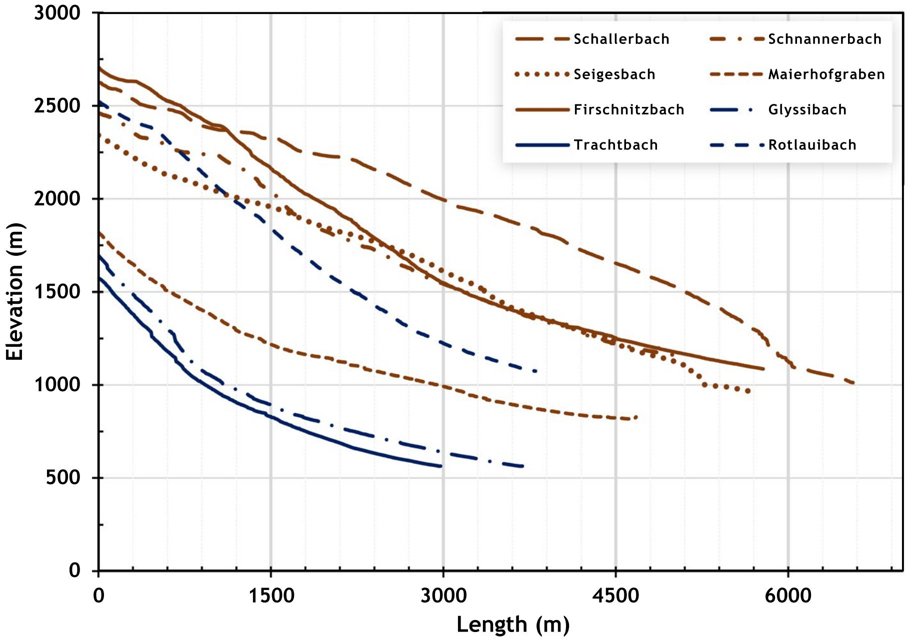


Fig. 3 Extended longitudinal profiles of the main stream to the outlet for the selected catchments (brown: Austrian, blue: Swiss)

information with various quantitative sources, e.g., remotely sensed datasets—as they could provide vital insights regarding the sediment cascades of the study area(s) (Foerster et al. 2014; Martini et al. 2022). The analysis focuses primarily on mass-movements (e.g., slides, debris flows) and floods, which are the most prominent mountain hazard processes with significant influence over sediment dynamics (Korup et al. 2004; Croke et al. 2013; Schopper et al. 2019). Both naturally occurring and triggered hazard processes, along with their underlying interactions were considered, with particular attention to their relevance to sediment connectivity and the overall scope of this study.

2.2 Dissection and categorization of events

Geomorphic systems have a hierarchical structure, where the underlying small processes interact and form larger processes and the system itself (de Boer 1992). In this regard, guided by data-driven insights, selected events are systematically disintegrated, considering their actual progression across space and time into generalized small segments to facilitate the analysis and comparability. The complete list of dissected process-segments for all events is provided as supplementary material (SCoMHA_OR1). The segmentation into smaller unitary segments or processes is conducted in a manner coherent with sediment transportation and/or connectivity. We assumed a cascading process flow across the events for this study, which is understood as a reconstruction of the dominant chronological propagation pathway of a multi-hazard event. In addition to the linear sequences, non-linear processes (e.g., feedbacks) are also taken into account (Mani et al. 2023). The segmented processes are subsequently classified according to a defined set of criteria, providing a structured basis for interpretation.

2.2.1 Categorization criteria

Table 1 summarizes the categorizing steps for interpreting the process segments, starting with their generalization and followed by classification into interaction type, sediment transport phase, and sediment connectivity weights.

2.2.1.1 Process generalization criteria: Generalizing the dissected segments or the underlying processes can provide substantial advantages, especially in terms of transferability (Green and Glasgow 2006; Polit and Beck 2010). This criterion serves as a structured framework to identify and evaluate the commonality among the underlying interactions and processes involved in the multi-hazard events. By adhering to this, we aim to standardize the analysis of pre-event conditions, triggering mechanisms, material mobilization, and

Table 1 Categorization criteria

Step	Criterion	Categories
Generalization	Process generalization criteria	Based on event conditions and propagation (see section a for the full list)
Categorization	Interaction type	Process-process, process-structure, process-topography, feedback
	Sediment transport phase	Erosion, transport, deposition, and disconnectivity
Weighting	Sediment connectivity weight	Derived using a fuzzy logic framework (see section d)

subsequent impact on topography and infrastructure. Through this approach, not only is the comparability of the studied events ensured, but also the propagation and understanding of the sediment connectivity weights along each stage of the events are facilitated. The components of this criterion are as follows (not in any specific order):

i) *Unstable pre-event conditions* Existing loose sediment, retention zones, environmental conditions, etc.
ii) *Triggering event* Heavy rainfall, rapid snowmelt events, etc.
iii) *Material mobilization* Sediment-rich runoff fills retention basins, channels, and sedimentation areas.
iv) *Favourable topography* Topographical features that enhance sediment movement and flow.
v) *Alteration of channel dynamics* Channels realign, split, or overflow due to sediment deposition and erosion.
vi) *Natural dam failure* Overflow and erosion of naturally occurring dams, causing probable or actual failure.
vii) *Sediment surge* Debris flow transports sediment and water, with contributions from landslides.
viii) *Geomorphic changes* Erosion and deposition reshape the landscape and create new channels.
ix) *Role of permanent or temporary infrastructure* Potential influence on the hazard processes from permanent and temporary measures, with regard to both the facilitation and blockage/diversion of the process propagation by the measures.
x) *Post-event redistribution* Sediment redistribution and long-term landscape changes.

2.2.1.2 Sediment transport phase: As discussed above, each process is categorized by its contribution to sediment transportation. Establishing these categorizations is vital for providing a better understanding of sediment connectivity in mountain catchment systems, where sediment transport processes and the morphological conditions in the catchment can be categorized with four distinct states: i) erosion, ii) transportation, iii) deposition, and iv) disconnectivity.

2.2.1.3 Interaction types:

Following the dissection of the selected multi-hazard events, the segments are categorized into three key types and their feedback, namely:

i) Process-process interaction: One process triggering or altering the other, i.e., the next (as this study assumes a cascading process flow);
ii) Process-structure: A process interacts with a human-made structure on its natural path, e.g., check dams.
iii) Process-topography: A process interacts merely with the topography and thus gets altered, e.g., deposition of mass movement over a wide valley.
iv) Feedback: Processes characterized by altered interactions that do not follow the natural downstream progression (non-linear processes), e.g., backwater effects.

2.2.1.4 Sediment connectivity weights: To formulate a flexible yet structured framework for holistically studying mountain multi-hazards, calculating sediment connectivity weights (SCW) forms a central part of this study. SCW is conceptualized as a metric reflecting the degree of functional connectivity among the process-segments, which enables the identification and categorization of the crucial processes in a cascade and facilitates the evaluation of process-interactions across different events and catchments.

As highlighted in the research gap, existing methodological approaches (both stand-alone and combined) offer ways to assess sediment connectivity, but they very often lack sufficient emphasis on or room for integrating the functional aspects of connectivity—particularly in multi-hazard contexts involving hazard interactions. Moreover, most existing methods are not designed to accommodate diverse data sources, thereby introducing additional uncertainties when analysing events with limited or heterogeneous datasets.

To tackle these challenges, we adopted a fuzzy logic-based multimodal approach to calculate sediment connectivity weights for each dissected process segment. Soft-computing techniques such as fuzzy logic are particularly effective for handling imprecise or vague information and for supporting approximate deductions (Zadeh 1975; Leung 2009); therefore, they have been extensively applied in earth sciences (Demicco 2004), including several instances in the study of sediment dynamics (Nordlund 1999; Demicco and Klir 2001).

This study implemented a simplified yet robust fuzzy logic framework to assess the sediment connectivity weights for the dissected process segments. The framework is designed to be multimodal, flexible, and transferable, allowing diverse datasets to be incorporated while maintaining a consistent focus. For this purpose, we used three indices: event breakdown index (EBI) and two geomorphic indices, e.g., Melton ruggedness number (MRN) and drainage density (DD) (hereafter EBI, MRN, and DD, respectively). At this stage, we introduce the notion of other data (OD) in a conceptual sense, highlighting the adaptability and flexibility of the framework to accommodate additional indices into the calculation of sediment connectivity weights when and if such datasets are available, while noting that they are not included in the present (demonstrative) analysis.

EBI:

For a multi-hazard event, EBI contains the dissected process segments, their respective generalized class, and their role towards sediment connectivity through three categories: contributing, neutral, and limiting—the values of which were obtained through an expert survey conducted among regional and local experts in geomorphology, natural hazards, and related fields spanning both academic and practitioner domains. The survey involved a total of 10 experts (5 for Austrian events and 5 for the Swiss) and was conducted online (via Google Forms), consisting of event narratives, lists of process segments and chronology, an elaborate definition of sediment connectivity, detailed scoring instructions with examples, and maps. For each unit process, experts specified the degree of membership, i.e., the degree to which it was contributing, neutral, and/or limiting to sediment connectivity, with each membership and the total for each set to within 1. Since EBI could require qualitative assessments, obtaining a crisp value might often be difficult or inappropriate. Therefore, expert-defined degrees of membership offer a way forward to a more flexible and context-sensitive approach. Such expert-based approaches are also particularly valuable for tackling data deficiencies common in mountain hazard events (Chen et al. 2016).

To reduce subjective bias, we applied a reliability-based weighted fuzzy aggregation approach, adapted from the commonly used expert aggregation frameworks (Cooke 1991; Cooke and Goossens 2004; O'Hagan 2019; Marozzi et al. 2024). In this approach, expert assessments (x) on the influence of each process segment on sediment connectivity were expressed as fuzzy membership in three categories: contributing (C), neutral (N), and limiting (L). For each process, the median membership values across all experts were used as central references (C_m, N_m, L_m). Deviations of the experts' values for all three categories from the group consensus were quantified as their Euclidean distance from the respective medians:

$$d_i = \sqrt{(C_i - C_m)^2 + (N_i - N_m)^2 + (L_i - L_m)^2} \tag{1}$$

Internal consistency of each expert is represented by their mean deviations across all processes ($\overline{d_i}$); whereas their reliability was computed as the inverse of this mean deviation ($r_i = 1\big/\overline{d_i} + \varepsilon$), and normalized to generate weighting factors (w_i) that sum to 1. Thus, higher weight/influence was assigned to experts who deviated less from the consensus (O'Hagan 2019; Marozzi et al. 2024).

$$w_i = \frac{1/\left(\overline{d}_i+\varepsilon\right)}{\sum_j 1/\left(\overline{d}_j+\varepsilon\right)}, \text{where}\, \varepsilon = 10^{-6} \text{prevents division by zero}\ (0) \tag{2}$$

Weighted fuzzy memberships (EBI values) were then aggregated using the expert-reliability weights for each process segment.

$$EBI_k = \sum_i w_i x_{i,k}; k \in [C, N, L] \tag{3}$$

The deviations among the expert assessments were computed as unbiased weighted variance,

$$Var_k = \frac{\sum_i w_i (x_{i,k} - EBI_k)^2}{1 - \sum_i w_i^2}; U_k = \sqrt{Var_k} \tag{4}$$

U_k represents the epistemic uncertainty associated with the disagreements among experts. The larger the value, the weaker the consensus, and the higher the uncertainty in the derived fuzzy membership values. However, though the EBI values were derived in this study through utilizing expert elicitation, the framework is flexible and allows alternative data-driven or model-based inputs for these values where available.

Geomorphic indices:

Two geomorphic indices, widely used to represent catchment properties relevant to event propagation—Melton Ruggedness Number (MRN) and Drainage Density (DD) were used.

MRN is a dimensionless index calculated as dividing catchment relief by the square root of its area (Melton 1965). It is extensively used in mountain-hazard studies because it provides a simple yet effective indicator of dominant sediment transport processes – steeper and compact catchments with high MRN are typically more susceptible to rapid, high energy flows, whereas those with lower MRN values are characterized by fluvial dynamics (Marchi and Dalla Fontana 2005; Bertrand et al. 2013); however, this does not indicate actual sediment yield, which may vary independently. This study adopted the widely used thresholds of MRN$\leq$0.30 (fluvial), 0.30–0.60 (mixed), and$>$0.60 (debris-flow prone) (Wilford et al. 2004; Welsh and Davies 2011) to classify the MRN values into low, medium, and high membership classes, respectively; noting that the categories may reflect process characteristics rather than sediment volume.

Drainage density (DD), on the other hand, is the ratio of total channel length to area of the catchment (Horton 1932). It is an essential parameter for sediment connectivity studies because it directly reflects the degree of linkage between hillslopes and the channel network. High drainage density typically indicates a more connected landscape, facilitating sediment transportation and hazard propagation. We classified the DD values into three membership classes: Low ($<$5 km/km^2), medium (5–15 km/km^2), and high ($>$15 km/km^2), in line with commonly reported ranges (Mutzner et al. 2016; Bujak-Ozga et al. 2023).

High-resolution lidar DEMs (Digital Elevation Model) were obtained for each study area and processed using standard hydrologic conditioning. Consecutively, MRN and DD were calculated for the elevation zones delineated by naturally occurring statistical breaks in the elevation distribution (de Smith et al. 2025) in the elevation data. Each dissected process segment was then assigned to its respective elevation zone, thereby receiving the values of the geomorphic indices, which were classified into low, medium, and high membership classes.

The sediment connectivity weight (SCW) for each dissected process segment was then derived as a weighted sum of the indices within the fuzzy logic framework, expressed as:

$$SCW = W_1 * f\left(EBI\right) + W_2 * g\left(MRN\right) + W_3 * h\left(DD\right) + W_4 * k(OD) \qquad (5)$$

where f(EBI), g(MRN), h(DD), and k(OD) represent the membership functions of the respective indices and W_1, W_2, $W_{3,}$ and W_4 are their associated influence scores. The membership functions were calculated as the sum of products between the degree of membership values for each class (e.g., contributing, neutral, limiting for EBI; low, medium, and high for MRN and DD) and their respective influence scores. They were then aggregated using the relative weights of the indices to obtain the final sediment connectivity weights (SCW). Table 2 lists the influence scores and weights for the indices.

Influence scores for MRN and DD were derived from the midpoints of their respective class thresholds and normalized to a 0–1 scale to represent their relative influence. For MRN, midpoint values (0.15, 0.45, 0.90) were normalized by the maximum (approximated) value of 0.90, producing normalized scores of 0.17, 0.50, and 1, which were rounded to 0.2, 0.5, and 1 for low, medium, and high classes, respectively. For DD, the upper bound of the 'High' class was approximated to 25 km/km^2, and similarly, the influence scores of 0.2,0.5, and 1 were derived for low, medium, and high classes, respectively. In the present analysis, a higher weight (in SCW calculation) was assigned to EBI because it is the most representative

Table 2 Indices with corresponding influence scores and weights

Index	Membership classes	Influence scores	Weight (in SCW)
EBI	Contributing/neutral/limiting	1/0.5/0	0.5
MRN	Low/medium/high	0.2/0.5/1	0.25
DD	Low/medium/high	0.2/0.5/1	0.25
OD	N/A	N/A	N/A

of the event propagation, while the geomorphic indices capture catchment properties, and OD was used only for demonstrative purposes. To evaluate the robustness of this weighting scheme, a simple sensitivity analysis was conducted using alternative weights, including a balanced scenario with equal weights assigned to all indices and parameter-focused scenarios where the geomorphic indices (MRN and DD) were alternatively assigned equal weights to EBI. Geomorphic indices were not assigned higher weights than EBI to ensure that its event-specific representation of functional sediment connectivity remains central.

3 Results

3.1 Schnannerbach event example

To demonstrate the application of the SCoMHA framework, we first report the Schnannerbach multi-hazard event in detail, linking the methods to the event's sediment connectivity dynamics. Details of the other events are presented in the supplementary materials (SCoMHA_OR1 contains the events' data and SCoMHA_OR2 contains an interactive web application for spatial exploration). Schnannerbach is located in Pettneu am Arlberg, a municipality in the province of Tyrol, western Austria. The catchment, with an area of approximately 6.8 km^2, drains into the Rosanna River from the orographic left and is characterized by steep relief, limited forest cover (≈ 13%), and a landscape highly prone to debris flows and fluvial processes (BMLRT 2021). On 1 August 2018, an intense precipitation event triggered a complex sequence of geomorphic processes in Schnannerbach.

A total of ten distinct process-segments and their tentative locations were identified from the dissection and categorization step (Sect. 2.2), see Table 3. These segments ranged from mass sediment mobilization to downstream channel blockages, each classified by its generalized category, interaction type, and sediment transport phase. To elaborate, the event began with previous landslide deposits being remobilized into the main channel (unstable pre-event conditions), followed by severe lateral and vertical erosion in the upper catchment (triggering event). Consequently, the next segments included feeder channels delivering large volumes of sediment into the catchment (material mobilization). This mobilized sediment passed through a narrow canyon section that amplified sediment transport (favourable topography). In the mid-catchment zone, a retention basin was filled and eventually overtopped, having retained a large volume of sediment before reaching its retention capacity. This marked a critical shift from controlled to uncontrolled sediment propagation (process-structure interaction). Downstream, a substantial amount of sediment was deposited across the alluvial cone and lower channel reaches (geomorphic change and alteration of channel dynamics).

Further downstream, near the confluence with the Rosanna River, a bridge was blocked with debris, causing backflow. Additionally, the event led to the failure of multiple other bridges and local control structures, resulting in extensive dispersion of sediment downstream and infrastructural damage. Subsequently, settlements in the valley, a railway underpass, and the adjacent commercial zones were flooded, and the Rosanna River underwent avulsion, with its flow partially rerouted through two road tunnels. Table 3 summarizes this breakdown and classification of the event, and corresponding SCW calculations for each segment are presented in Table 4.

Table 3 Schnannerbach (2018) event breakdown and categorization

Schnannerbach event: 1 August 2018

Process-segment	Generalized category	Elevation zone	Interaction type	Sediment transport phase
Previous landslide deposits remobilized into the main channel	Unstable pre-event conditions	2	Process-process	Transportation
Severe lateral and vertical erosion in the upper and middle stream sections	Triggering Event	2+3	Process-topography	Erosion
Feeder channels delivered large sediment volumes into Schnannerbach	Material Mobilization	3	Process-process	Transportation
Canyon section amplified erosion and sediment transport downstream	Favourable Topography	3	Process-topography	Transportation
Sediment retention basin filled and was overtopped by debris flow	Role of permanent or temporary infrastructure	3	Process-structure	Transportation
Massive sediment deposition on the alluvial cone and lower reaches	Geomorphic changes	3	Process-topography	Deposition
Bridge near Rosanna River became blocked by debris	Role of permanent or temporary infrastructure	3	Process-structure	Disconnectivity
Backflow from Rosanna River caused upstream flooding	Alteration of channel dynamics	Out of catchment	Feedback	Transportation
Rosanna River paved new flow path into road tunnels due to channel obstruction	Alteration of channel dynamics	Out of catchment	Process-structure	Transportation
Failure of bridges and control structures increased sediment dispersion	Role of permanent or temporary infrastructure	Out of catchment	Process-structure	Transportation

The Schnannerbach case illustrates how calculating sediment connectivity weights (SCW) provides insights into the internal mechanics of a multi-hazard event. Each process-segment was assigned an SCW score by integrating the expert-determined EBI values with geomorphic indices (MRN and DD) through fuzzy functions. This allows us to understand the extent to which each segment contributes to sediment transfer. Higher SCW scores indicate stronger process-level contributions to sediment connectivity; in other words, more efficient sediment transmission through the cascade.

In this event, the calculated SCW values reveal a logical and structured progression: the initial remobilization of sediments from hillslopes had a moderate connectivity (SCW $\approx$ 0.57), which increased to a peak as the event escalated. The most connected (most efficient in sediment transfer) phase was during the intense sediment input through feeder channels (SCW $\approx$ 0.71), indicating that once the material was fully mobilized in a steep, narrow setting, connectivity rose to very high. Although the following canyon segment had moderately high connectivity (SCW $\approx$ 0.59), it declined through the depositional segments

Table 4 Derived membership values of the indices and SCWs for Schnannerbach (2018) event

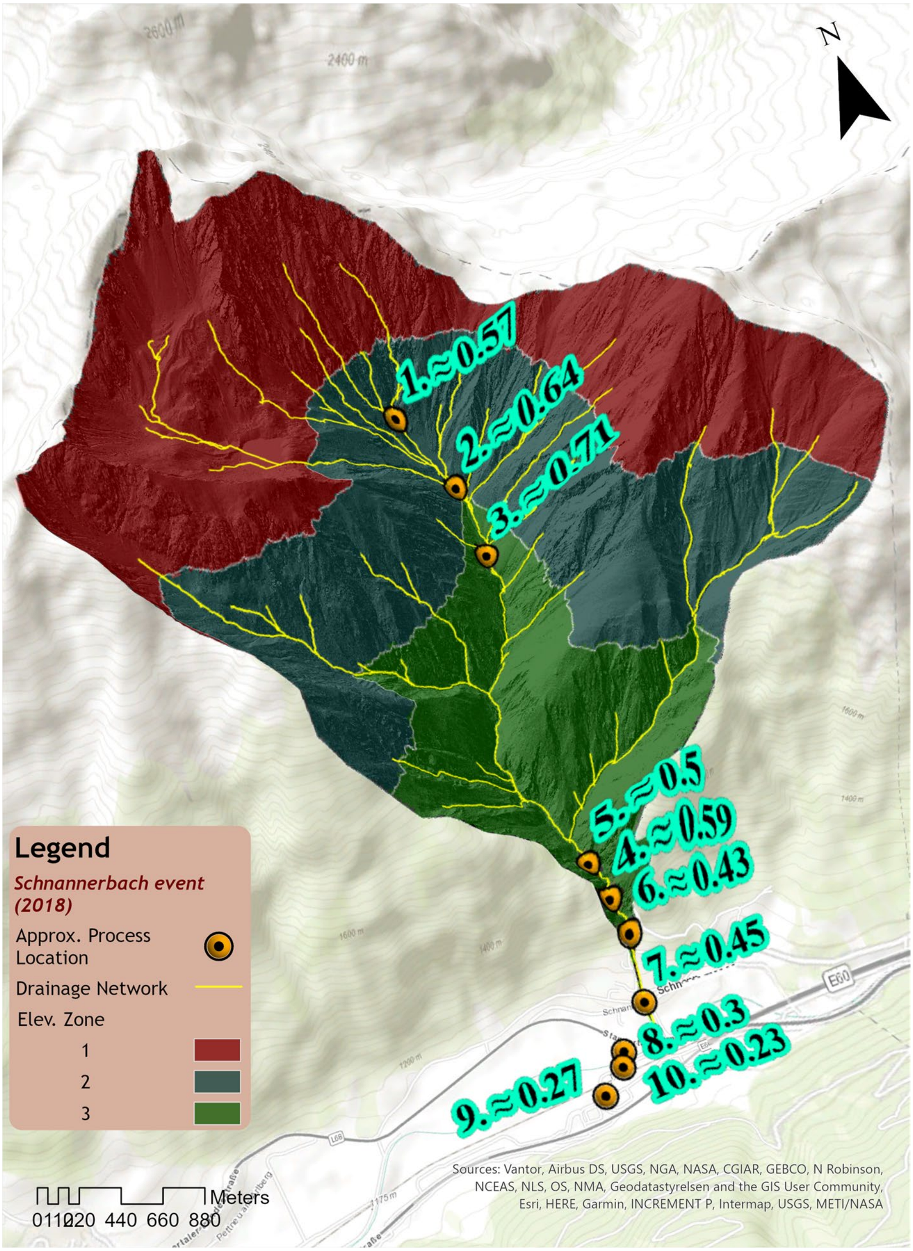
Process-segment	f(EBI)	g(MRN)	h(DD)	SCW
Previous landslide deposits re-mobilized into the main channel	0.80	0.20	0.50	0.57
Severe lateral and vertical erosion in the upper and middle stream sections	0.85	0.35	0.50	0.64
Feeder channels delivered large sediment volumes into Schnannerbach	0.93	0.50	0.50	0.71
Canyon section amplified erosion and sediment transport downstream	0.69	0.50	0.50	0.59
Sediment retention basin filled and was overtopped by debris flow	0.51	0.50	0.50	0.50
Massive sediment deposition on the alluvial cone and lower reaches	0.36	0.50	0.50	0.43
Bridge near Rosanna River became blocked by debris	0.39	0.50	0.50	0.45
Backflow from Rosanna River caused upstream flooding	0.60	0	0	0.30
Rosanna River paved new flow path into road tunnels due to channel obstruction	0.53	0	0	0.27
Failure of bridges and control structures increased sediment dispersion	0.47	0	0	0.23

and into disrupted out-of-catchment flow phases (SCW ≈ 0.43–0.23), which marked the effective termination of sediment transport from the source catchment. Figure 4 tentatively places these process-segments across the catchment.

Instead of considering the underlying process-segments of the event as a uniform flow, SCW improves our understanding of where and when sediment propagation was most efficient, for which types of processes, and where the cascade began to disintegrate. By systematically capturing this pattern, the SCoMHA framework reveals the intensity and internal transitions of the hazard propagation, thereby complementing process-level understanding to decode complex multi-hazard dynamics.

3.2 SCW patterns across events

Across the eight analysed multi-hazard events, the framework was applied across a total of 80 process segments (see *SCoMHA_OR1*). The calculated SCW values span the full range from 0 (complete functional disconnection) to 0.80 (very high connectivity). The highest process-level connectivity (≈ 0.80) was observed during an extreme channel erosion in Firschnitzbach, whereas the lowest values (≈ 0–0.23) occurred in process-segments that were effectively disconnected or outside the source catchment (e.g., in Maierhofgraben, Rotlauibach, Trachtbach). Most segments, however, fall in the intermediate range (≈ 0.4–0.7), indicating partial to strong sediment connectivity. Figure 5 shows the distribution of SCW values for each event, highlighting differences in median connectivity and spread. Notably, some events exhibit generally higher overall connectivity than others. For instance,



Sources: Vantor, Airbus DS, USGS, NGA, NASA, CGIAR, GEBCO, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen and the GIS User Community, Esri, HERE, Garmin, INCREMENT P, Intermap, USGS, METI/NASA

Fig. 4 Tentative process locations, their sediment connectivity weights (SCW) and elevation zones of Schnannerbach (2018) event

Firschnitzbach and Seigesbach have the highest median SCW values and broad ranges, whereas Trachtbach shows a more compact distribution. These cross-catchment comparisons underscore that each multi-hazard event has a distinctive sediment connectivity signature. SCW patterns remained consistent across alternative weighting scenarios and relative

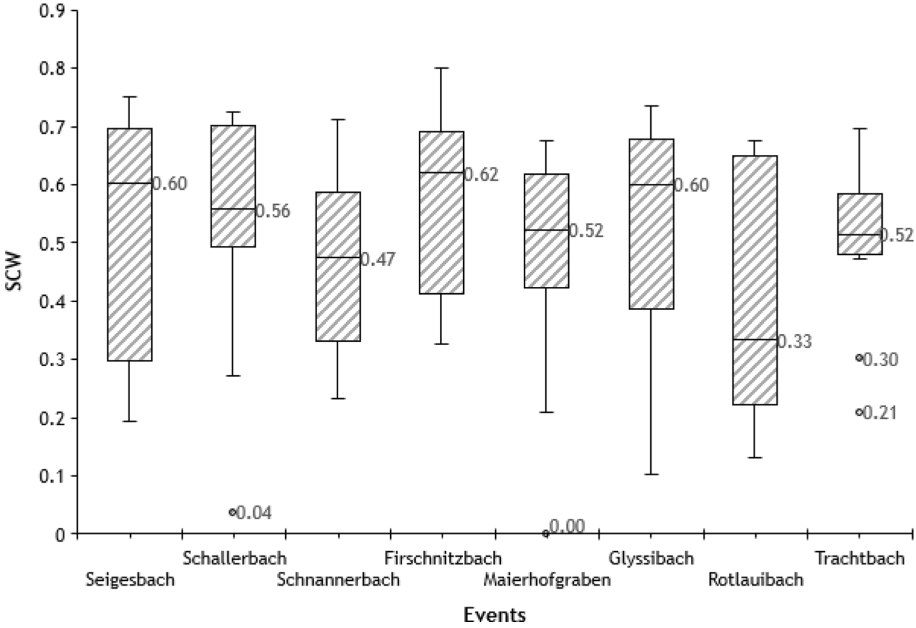


Fig. 5 Sediment Connectivity Weight (SCW) distribution across the analysed events (labelled as catchment names)

trends, with only minor variations. High correlation between the original and alternative configurations (r = 0.96–0.99) suggests limited sensitivity to weight selection.

The variability in SCW distributions among catchments also appears to be linked to each event's dominant process sequence. Events characterized by a long and uninterrupted chain of in-catchment processes (e.g., Maierhofgraben, Glyssibach) show a greater proportion of high-SCW process-segments (SCW≥0.60) and relatively few low-SCW ones. On the contrary, events that were highly influenced by out-of-catchment processes contain more low-SCW segments (e.g., Rotlauibach). These differences indicate that the continuity of sediment transport within the catchment (in comparison to early deposition or external flow routing) directs the overall sediment connectivity pattern of the event.

3.3 Categorical distinction

The framework's process-segmentation and categorization also allow comparison of sediment connectivity across different interaction types (e.g., process-process, process-topography, process-structure, feedback) and sediment transport phases (e.g., erosion, transportation, deposition, disconnectivity). Figure 6 presents the calculated SCW values for all process-segments grouped by interaction type and sediment transport phases. Looking at these dimensions together reveals some clear patterns. For instance, process-topography interactions appear most frequently, while feedback interactions are least common. Notably, process-structure interactions are the second most frequent, reflecting the significance of mitigation measures in the propagation of the sediment cascade. In addition, segments categorized as 'sediment surge' and 'material mobilization' (process generalization crite-

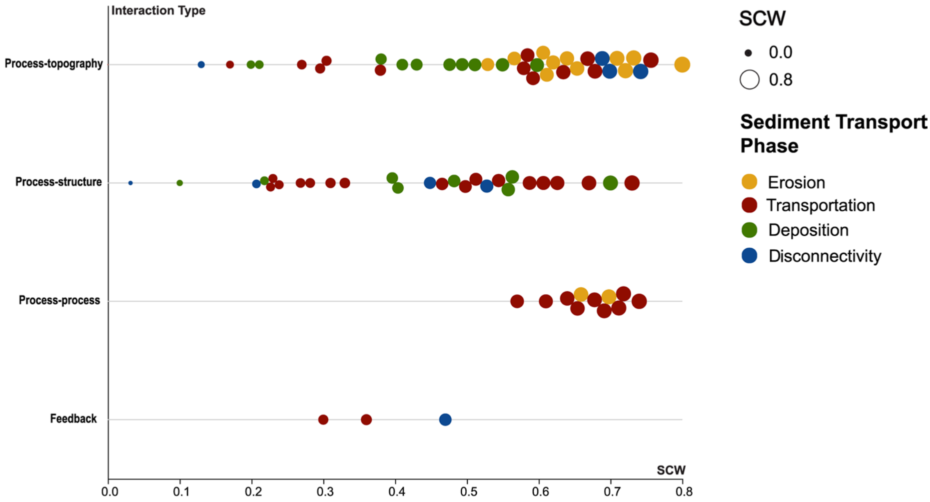


Fig. 6 Distribution of SCW against interaction types (Y-axis) and sediment transport phases (shown by colour), with bubble size (and X-axis) representing SCW value across all events

ria) are characterized by the highest SCW scores, e.g., debris flow surges in Seigesbach (SCW ≈ 0.75) and bed & lateral erosion in Firschnitzbach (SCW ≈ 0.80). These segments contain intense erosion and/or entrainment with substantial downstream transfer of sediments. 'Triggering events' (heavy rainfall, rainfall-snowmelt combinations) generally show moderately high SCW scores (≈ 0.58–0.74), as they might initiate the cascade but not immediately cause the highest connectivity until the channels and sediment storages are fully engaged. Among other generalizing criteria, 'geomorphic changes' (e.g., alluvial cone deposition in Schnannerbach) generally associate with partial decoupling of the cascade, where they still contribute to sediment transfer but locally store a considerable amount; therefore, they receive moderate SCW scores (≈ 0.43–0.60). 'Role of permanent or temporary infrastructure' (both positively or negatively contributing to sediment connectivity) and 'post-event redistribution' are among the criteria belonging to the lower end of the observed SCW range. This is evident in the out-of-catchment flooding and infrastructure damage in Glyssibach and Rotlauibach (SCW ≈ 0.10–0.31), and post-event valley bottom deposition in Seigesbach (SCW ≈ 0.20).

Additionally, segments that directly trigger or feed into another (process-process interaction) during active erosion or transport consistently yielded high SCW scores; such as debris flow formation in Firschnitzbach (SCW ≈ 0.69), previous deposit erosion in Glyssibach (SCW ≈ 0.66). These high values signify that direct cascading of processes efficiently transfers sediment downstream. Process-topography interactions, particularly in steep terrain during active sediment transport phases (e.g., large debris flow surge in Seigesbach: SCW ≈ 0.75, rocky midsection helping debris flow to gain energy in Rotlauibach: SCW ≈ 0.67, canyon section's amplification in Schnannerbach: SCW ≈ 0.59), also show moderate to high SCW. Therefore, topographic convergence and high relief enhance sediment connectivity when material is already mobilized. In contrast, process-structure interactions (involving retention basins, dams, bridges, etc.) exhibited more variable connectivity patterns. When structural measures functioned as designed by retaining or blocking sediment (e.g., protection barriers preventing debris flow from spreading during the Schallerbach event: SCW ≈ 0.04, deposition behind the barrier in Glyssibach: SCW ≈ 0.40), they noticeably reduced SCW. However, if these structures are overtopped or fail, their effect is reversed to increase sediment connectivity. For example, the overtopping of a retention basin in Schallerbach resulted in SCW ≈ 0.73, and a dam overtopping in Firschnitzbach yielded SCW ≈ 0.62. In such cases, stored sediment was suddenly released, or flows were redirected; therefore, the process-segment continued to transfer sediment efficiently despite the presence of protective infrastructure. Finally, segments categorized as ‘disconnectivity’ (often associated with blockages or feedback that halt or reverse flow) generally recorded low to moderate SCW scores—marking that they represent breaks in the sediment cascade. For instance, out-of-catchment ‘disconnectivity’ segments in Maierhofgraben and Rotlauibach had SCW of ≈ 0.21 and ≈ 0.13, respectively. Nonetheless, not all disruptions (disconnectivity) completely terminate connectivity. In the Trachtbach event, an obstructed road bridge and backwater blockage from feedback at Dindeln bridge still retained moderate SCW (≈ 0.53 and 0.47), indicating that some sediment continued to pass through or around these obstructions. Overall, these observations show how the different categories (elaborated in Sect. 2.2 and Table 1) regulate sediment connectivity across the analysed multi-hazard events.

3.4 Event breakdown index (EBI) and associated uncertainty

Another key component of the results is the expert-informed event breakdown index (EBI) and its associated uncertainty, which influences the SCW calculations. The EBI scores, expressed through fuzzy membership sets (contributing, neutral, limiting), reflect expert judgement on how much each process-segment contributes to or limits sediment connectivity. Across the events, we observed a strong correspondence between EBI values and resulting SCW scores; high SCW values were associated with high “contributing” and low “limiting” EBI membership. Whereas, the ones with high “limiting” or “neutral” membership almost always returned low SCW values.

Despite the overall agreement, experts also had some differences, which introduced notable uncertainty in some EBI scores. Figure 7 illustrates this with a reliability-weighted plot of ‘contributing’ EBI scores for one event (Schnannerbach, 2018). For certain process-segments, especially those explicitly involving sediment surges or mass movements, the EBI membership values are highly concentrated, indicating strong agreement among experts regarding their ‘contributing’ (to sediment connectivity) role. On the contrary, some process-structure interaction segments show diffuse EBI memberships, reflecting diverse interpretations. For instance, in segments involving partial blockage or overtopping, experts were split on whether these processes ultimately promoted or reduced connectivity, resulting in a wide spread in the EBI scores. The EBI estimation method based on reliability scoring helps account for these differences in the SCW calculation.

Interestingly, we also observed a few instances where experts appeared to interpret the segment’s contribution to the overall hazard impact rather than to sediment connectivity. Specifically, certain segments that actually created new sediment transport pathways (thus functionally increasing connectivity) were sometimes assigned low ‘contributing’ scores. This resulted in lower SCW values for those segments than anticipated based on their role. This discrepancy suggests that, in some cases, some experts may have focused on how a segment influenced the event or its consequences (as is often emphasized in hazard assess-

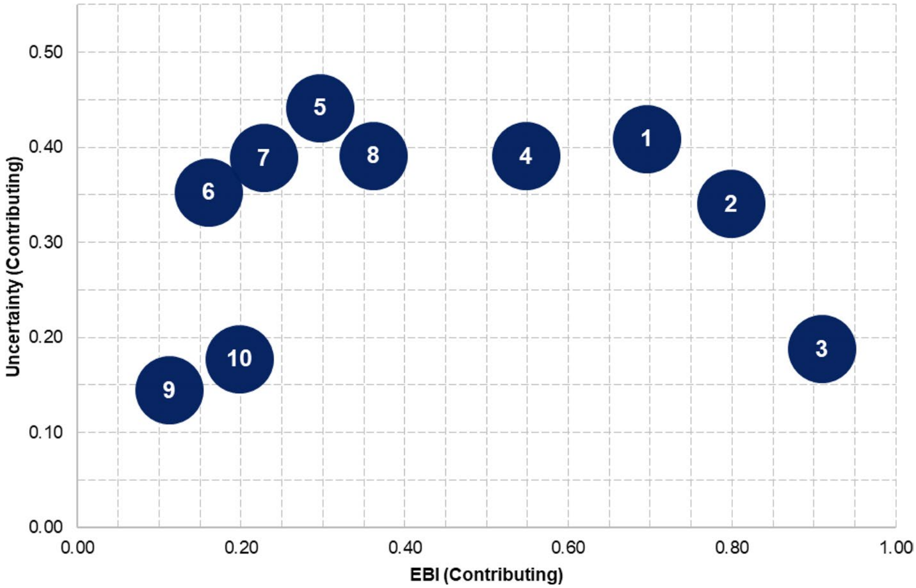


Fig. 7 Reliability-weighted EBI (contributing) scores for the Schnannerbach: 2018 event. The x-axis shows contributing scores and y-axis indicates uncertainty (contributing). Bubble numbers refer to process-segments listed in Table 4 (row order). Note: For each process, contributing, neutral, and limiting scores sum to 1

ment) rather than its role in intensifying sediment connectivity. Recognizing these differences is important for the conceptual clarity of sediment connectivity, and we address this issue further in the discussions.

3.5 Geomorphic indices

Finally, we evaluated how the catchment properties, i.e., geomorphic indices, influenced the observed sediment connectivity patterns. The fuzzy membership functions for MRN and DD, combined with the tentative elevation zones designated for the process-segments, provide a geomorphic context for the SCW patterns (Fig. 8). High MRN values predominantly cause the process-segments to receive high SCW scores, e.g., sediment surge in Schallerbach (MRN: 1, SCW $\approx$ 0.75). Whereas, the combination of high MRN and moderate to moderately high DD values—indicating steep, rugged terrain with well-developed channel networks, generally represent process-segments with elevated SCW (e.g., the steep middle section in Rotlauibach and Glyssibach containing material mobilization and channel erosion process segments with MRN scores of 0.5–1 and SCW$\geq$0.60). Low or zero MRN and DD values are associated with low SCW scores, especially in the out-of-catchment segments where the classification sets their values explicitly to zero, e.g., out-of-catchment flooding and infrastructure damage in Schnannerbach, Glyssibach, and Trachtbach exhibit SCW$\leq$0.30. Processes involved here indicate that, although the flow of sediment might still cause local damage, the functional connectivity with the source catchment is effectively disengaged. Within catchments, SCW often increases when moving from higher to mid elevation zones, then decreases towards the lower depositional areas. For instance, in

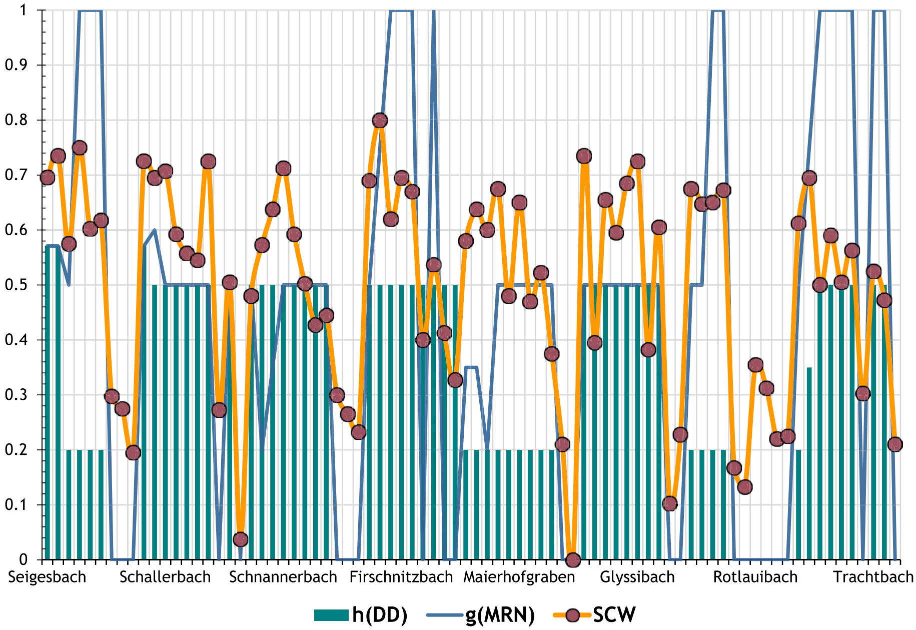


Fig. 8 Geomorphic indices (membership scores of MRN and DD) in relation to SCW values across all 80 process segments. X-axis represents the catchments, while Y-axis shows the corresponding values

Schnannerbach (Tables 3 and 4), SCW rises from an unstable pre-event condition segment (≈ 0.57) to a maximum during excessive sediment movement in the catchment (≈ 0.71), then declines through downstream routing and deposition (≈ 0.59–0.23). Figure 4 shows a visual overview of this pattern, plotting Schnannerbach's process-segments by elevation zones. In general, these patterns of geomorphic indices highlight that sediment connectivity is influenced not only by process-interactions and sequence, but also by the catchment settings. While the SCoMHA framework can incorporate structural connectivity metrics, this study focused predominantly on event-driven (functional) connectivity. Contextually, results indicate that extreme events can transiently activate sediment pathways that might appear disconnected under baseline geomorphic conditions.

4 Discussions

4.1 Sediment connectivity in multi-hazard events

The results clarify that the SCoMHA framework systematically captures the functional aspect of sediment connectivity at the scale of individual processes within multi-hazard events. Instead of inferring sediment connectivity solely from static terrain metrics, SCW scores reflect how strongly each process-segment contributes to the event propagation through transmitting sediment. In other words, the SCW metric reflects the degree of functional connectivity between process-segments. Higher SCW values, therefore, represent strong functional connectivity.

The proposed approach goes beyond the terrain-based assessments by identifying ‘where’ and ‘when’ sediment actually moves during a cascading event, not (just) where it ‘could move’ under pre-event baseline conditions. However, SCW scores in this current study cannot entirely determine whether a process-segment would lead to another. The actual cascading potential also depends on the availability of material (e.g., sediment volume); incorporating this in the framework would enable the SCW values to also represent the propagation likelihood. In that sense, SCW values can be regarded as a pathway-specific indicator. Moreover, in addition to the demonstrative indices used in this study, incorporating relevant additional datasets and refined fuzzy membership functions could further improve the accuracy and enhance our understanding of functional sediment connectivity during a multi-hazard event.

Across the studied events, high SCW values were consistent with material mobilization and sediment surge process-segments, often involving direct process-process chains in steep sections. The framework, therefore, highlights the phases where catchments are most efficient at transmitting sediment and consequently the impacts. On the other hand, process-segments categorized as disconnectivity, post-event redistribution, or out-of-catchment flooding show substantially low SCW values, which indicates that they mark the effective end of the cascade regardless of high local damage potential. These findings highlight that the most critical processes (from a sediment connectivity perspective) are not always the ones causing the most visible damage; rather, they are the ones that keep the multi-hazard chain active by efficiently transferring sediment to the next phase. In short, the framework identified the ‘connectivity backbone’ of the events as well as the segments that stopped or disintegrated the hazard cascades.

Another important insight is that sediment connectivity in a catchment is highly context-dependent and dynamic, reinforcing our initial assertion (see Sect. 1) that a comprehensive understanding of it demands moving beyond fixed terrain-based metrics. Accordingly, SCW values are event- and process-specific, meaning that similar processes may yield different SCW values across catchments or even within the same catchment under different events. We observed instances where presumably disconnected segments in a structural sense (e.g., a sediment storage, channel behind a retention basin) became functionally connected under extreme conditions. Such cases demonstrate that functional connectivity can temporarily exceed pre-determined structural connectivity (Fryirs et al. 2007b; Duvert et al. 2011), and hence, are difficult to analyse with static connectivity metrics. This implies that a catchment’s sediment connectivity cannot be regarded as a fixed property, as an extreme trigger can activate otherwise dormant pathways or even create new ones (e.g., Rosanna River flowing through tunnels during the Schnannerbach event). This perspective raises the question of the extent to which pre-determined static connectivity representations remain applicable under extreme conditions, a concern also discussed by Heckmann et al. (2018), underscoring the need for further investigation.

It is vital to clarify that our process-level perspective is not a replacement for structural connectivity concepts (in the context of hazard assessment), but rather a complementary view. Commonly used structural connectivity indices (based on morphology, landcover, etc.) indicate where sediment ‘could’ travel under general conditions (Crema and Cavalli 2018). Whereas, this framework describes where sediment ‘did’ move and ‘when’ in a particular multi-hazard scenario. The variations in SCW that we observed even among segments with similar settings (e.g., retention basin acting first as a sediment storage but later, when overtopped, acting as a strong connector), emphasize that sediment connectivity is not just a static landscape trait, but rather a dynamic attribute evolving with the progression of the event. Therefore, while structural connectivity indices remain essential for baseline assessments (providing a pre-event overview of connectivity potential), integrating the functional connectivity dimension (as our framework allows) provides a more realistic understanding of how a multi-hazard event can unfold. In this regard, our approach addresses a critical gap in current natural hazard research and provides a basis for further investigations into how functional sediment connectivity may respond under different hazard scenarios and catchment conditions, thereby strengthening hazard and risk assessment.

4.2 Influence of interactions and mitigation structures

The results also explain how different process interactions can shape sediment connectivity. Section 3.3 highlighted that process-process chains, i.e., cascading interactions during multi-hazard events in steep terrain, are the key drivers of high sediment connectivity, essentially forming the foundation of multi-hazard events. These high-SCW segments tightly link hazard processes together (e.g., a landslide immediately triggering a debris flow), resulting in a fast and efficient transmission of materials. Recognizing these ‘high-connectivity links’ is crucial for early warning and intervention, because they identify phases where the hazard escalates most rapidly. On the other hand, process-structure interactions often act as control or buffering points. When mitigation structures function as expected, they significantly lower the SCW for those segments by slowing or stopping the sediment transport and protecting downstream areas, at least temporarily. Nevertheless, if these structures collapse or are overtopped, their role shifts rapidly: they may stop functioning as buffers, suddenly release large volumes of stored sediment, or even divert flows into vulnerable and previously unaffected areas (as observed with the torn-away barriers in Glyssibach and the overtopped basin in Schnannerbach). It is crucial to recognize this ‘duality’, as structures may alternate between acting as buffers or connectors (Fryirs et al. 2007a; Fryirs 2013; Marchi et al. 2019) depending on event magnitude and sequence. Our framework makes this behaviour visible (as reflected in the results through contrasting low SCW for functioning structures with high SCW for failed ones) and underscores the importance of time-dependent, scenario-based analysis of sediment connectivity. Accounting for this connectivity flip in risk assessment, mitigation strategies, or emergency protocols could improve resilience, for example, by preparing downstream regions for different overtopping scenarios.

4.3 Novelty, adaptability, and significance of the framework

SCoMHA introduces several novel elements to multi-hazard assessment, notably the integration of sediment connectivity. Additionally, it advances the understanding of the often discussed but rarely addressed functional aspect of process-level sediment connectivity (Heckmann et al. 2018; Najafi et al. 2021). Using a fuzzy-logic scheme, we integrated heterogeneous information sources, such as qualitative event reports, expert interpretations, combined with quantitative geomorphic indices. This design allows the application of a consistent mathematical structure (SCW calculation) to a wide variety of process-segments, each with unique characteristics.

A key strength of the framework is its modularity and adaptability. In this study, MRN and DD were used to characterise catchment steepness-relief and stream-network organisation, but in other settings, they could be replaced or complemented by additional and locally suited indices when available (e.g., erodibility, sediment supply indices, glacial cover, landslide inventories, sediment deposition volumes, field-mapped indices, structural connectivity indices, etc.). Likewise, the EBI values can be calibrated/derived using local-expert knowledge, post-event reports, news articles, model outputs, etc. Depending on the chosen indices, the fuzzy membership functions can also be modified to address more complex patterns and data structures (Araya-Muñoz et al. 2017). Therefore, the SCoMHA framework is deliberately structured as "plug-and-play"—allowing users to replace or expand input layers while maintaining the overall logic and compatibility of the outputs. This highly adaptable design makes the framework transferable to areas beyond the Alpine examples presented here.

The framework is also kept operationally focused, by utilising a limited set of inputs typically available after major events, it can provide an improved understanding of process-level interactions and the role of sediment connectivity in multi-hazard propagation. As conventional hazard assessments, rooted in historical return periods and recurrence intervals, become increasingly inadequate for mountain multi-hazards (Terzi et al. 2019), a shift toward impact-based, scenario-led assessments that identify upstream triggers and trace their propagation pathways is imperative (Fan et al. 2025). The SCoMHA framework aligns with this notion by dissecting cascading multi-hazard events into distinct process segments as well as evaluating their role in sediment and hazard propagation through the system. Therefore, it is suitable not only for research case-studies, but also for post-event analysis and planning, e.g., scenario-based testing, event-tree analysis, rapid post-event analysis, etc. SCW values combined with other detailed spatial information can help identify hotspots where slight changes might cause disproportionate impacts downstream.

Overall, the novelty of the framework lies both in 'what' it addresses (functional sediment connectivity in multi-hazard events) and 'how' it can be tailored to a wide range of contexts and applications. Regarding its significance, the framework does not claim to provide a complete representation of functional sediment connectivity or to transform multi-hazard assessments fundamentally. Rather, it provides a comprehensive, operational, and transparent basis that can be readily adopted, modified, and further developed across diverse contexts while retaining a consistent structure, thereby supporting progress toward these ambitious aims. By explicitly incorporating sediment connectivity, the framework represents a concrete step toward holistic multi-hazard assessment and, as the case studies demonstrate, uncovers critical insights that conventional methods often overlook.

4.4 Limitations and future developments

Alongside its contributions, the study has certain limitations that point to avenues for further improvement. For instance, despite adopting a reliability scoring technique, the EBI scores still rely on expert judgement, which introduces subjectivity. The spread we observed between contributing, neutral, and limiting memberships for some segments (see Sect. 3.4**)** shows that experts do not always agree on a process's role, and as mentioned before, some may have occasionally and inadvertently focused on the event itself instead of sediment connectivity. We pre-emptively attempted to mitigate this by providing detailed event descriptions, clarifications on the sediment connectivity concept, and the intended use of the experts' inputs, but ambiguity in interpretation cannot be ruled out. Future applications could aim to reduce this subjectivity, for example, by incorporating trial runs to ensure conceptual consistency, iterative review, e.g., Delphi rounds (Hasson et al. 2000), to align their interpretation of each segment's role, or calibrating it with additional data where available.

Furthermore, this study adopted an elevation-based zonal segmentation (3 zones) across the case studies, which keeps the framework simple and well-aligned with qualitative data, facilitates cross-catchment comparison, and is easy to communicate. However, it may not fully capture the fine-scale variability within each zone. Geomorphic indices derived at this zonal scale may overlook important local differences in slope, channel geometry, and other parameters that influence sediment connectivity. A more detailed or process-specific segmentation (e.g., segmenting by geomorphic unit or using shorter elevation intervals) could reveal additional patterns of functional (sediment) connectivity, though perhaps at the expense of simplicity and consistency. Besides, the current study does not explicitly account for large-wood dynamics, which may play a critical role in shaping sediment transport and associated hazard processes. Where relevant, future studies could incorporate it as an additional metric within the SCoMHA framework.

In addition, the assumption of a simplified cascading process flow across the events may underrepresent the complex multi-hazard process sequences (e.g., mutually exclusive, concurrent, or parallel, etc.) that exist in reality (Liu et al. 2016; Wang et al. 2020; De Angeli et al. 2022). Independent process chains within an event are recommended to be analysed separately until interaction occurs, while dominant bifurcations (branching processes) (Mani et al. 2023) may be followed as distinct pathway segments. Extending the framework to handle concurrent or branching process-interactions is a challenging but important next step.

Moreover, while the framework is designed to be adaptable, this study focuses exclusively on its development and operationalization. As such, it hasn't been tested (on this occasion) in combination with structural connectivity indices (e.g., IC by Cavalli et al. (2013)) or hazard intensity metrics; both of which could complement the calculation of SCW in future applications. Likewise, the purposefully simplified fuzzy membership functions and aggregation scheme may be limited in capturing the complete range of dynamics present in complex settings. Future studies may therefore build upon these foundations and replace or incorporate different indices or functions where feasible.

Furthermore, the proposed framework is event-centric in design; specifically, we evaluated sediment connectivity within each event, but how one event might alter connectivity in subsequent events within the same catchment (e.g., the second Firschnitzbach event in 2020; BMLRT 2021) was beyond the scope of this study. Our findings demonstrate that a large event can cause persistent geomorphic changes in a catchment (depositing sediment, altering channels), thereby changing the baseline structural connectivity. Therefore, in the event of a second occurrence in the same catchment, the process-level functional connectivity patterns could be significantly different, given the altered starting conditions. Investigating how both structural and functional connectivity differ between pre- and post-event contexts is an intriguing avenue for future research. For example, comparing the SCW patterns (with integrated structural connectivity indices) for two successive events in the same catchment could reveal how the aftermath of the first event affects the second. This would provide a multi-event perspective on sediment connectivity, which could be useful for examining different climate change scenarios where repeated extreme events may become more common (APCC 2025; Fan et al. 2025).

Finally, we encourage testing the framework in diverse settings and for diverse applications. Applying it in different mountainous regions, in larger catchments (where other multi-hazard dynamics, e.g., concurrent, independent process-chains may exist), or even in non-mountainous multi-hazard or just hazard-prone settings are important next steps, as that would help evaluate its robustness. Different environments may introduce new processes (e.g., volcanic lahars, glacial lake outburst floods), which would expand the event-breakdown categories, possibly requiring additional indicators. Developing a more consistent or semi-automatic segmentation method, combined with cross-regional testing and context-informed fuzzy rulesets, would help the framework evolve towards a more universal and potentially automated tool capable of aiding hazard management and decision making.

5 Concluding remarks

This study presents a novel framework that explicitly integrates functional sediment connectivity into multi-hazard analysis, addressing a critical gap and emphasizing the need to move beyond static connectivity metrics and single-hazard approaches to assess complex multi-hazard dynamics. Specifically, the proposed framework examines the underlying hazard processes in multi-hazard events and assesses their role in event propagation through functional sediment connectivity weights (SCW). Its data-agnostic design allows the integration of both qualitative (event report, expert opinion) and quantitative (geomorphic indices: MRN and DD) inputs through a fuzzy logic framework. The results (from applying the framework to eight multi-hazard events) demonstrate that sediment connectivity is not merely a fixed catchment parameter; rather, it is highly context-driven and dynamic in the context of such events. Additionally, the framework provides a process-level perspective on the sediment cascades by identifying the critical high-connectivity processes that keep the event together as well as the ones that interrupt or disintegrate the cascades. For instance, steep topography and direct process-process interactions emerge as key drivers of strong functional connectivity. In short, the framework reveals the actively evolving patterns of the underlying processes that facilitate sediment transport through the system (connectivity) during multi-hazard events.

Another crucial aspect of the framework is its flexibility and modular design, which makes it widely adaptable. It is structured as a “plug-and-play” system where the core input layers (indices, fuzzy logic ruleset) can be replaced or complemented with context-specific indicators if available. This adaptability marks its robustness by ensuring its transferability across different environmental settings regardless of plausible data heterogeneity. Nonetheless, this study partially relies on expert judgement and broad zonal divisions, which introduces some subjectivity and simplification. Additionally, framing the events as a cascading sequence of processes may be limited in fully capturing complex multi-hazard dynamics, e.g., concurrent or parallel processes. However, the framework’s transparency and robustness compensate for these constraints and pave the way for future improvements, including, for example, an improved segmentation approach, EBI calibration (to reduce subjectivity and ambiguity), or integrating different connectivity and intensity metrics.

By explicitly integrating sediment connectivity with multi-hazard processes, this framework has significant implications for both natural hazard science and practice. It provides an improved understanding of hazard cascades and their geomorphic consequences, which can offer vital insights for mitigation planning (e.g., by identifying strategic intervention points), post-event analysis (e.g., to identify when, where, and how sediment movement amplified downstream impacts), preparedness planning, etc. Collectively, SCoMHA not only advances the methods of multi-hazard and sediment connectivity assessments but also offers a practical, modular basis for strengthening risk management strategies and decision-making amid escalating and complexly interconnected natural hazards.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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