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Earth System Dynamics Discussions

Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies

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Abstract. This paper combines research and commentary to reinforce the importance of integrating hazard interactions and interaction networks (cascades) into multi-hazard methodologies. We present a synthesis of the differences between 'multi-layer single hazard' approaches and 'multi-hazard' approaches that integrate such interactions. This synthesis suggests that ignoring interactions between important environmental and anthropogenic processes could distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate disaster risk. In this paper we proceed to present an enhanced multi-hazard framework, through the following steps: (i) describe and define three groups (natural hazards, anthropogenic processes and technological hazards/disasters) as relevant components of a multi-hazard environment; (ii) outline three types of interaction relationship (triggering, increased probability, and catalysis/impedance); and (iii) assess the importance of networks of interactions (cascades) through case-study examples (based on literature, field observations and semi-structured interviews). We further propose visualisation frameworks to represent these networks of interactions. Our approach reinforces the importance of integrating interactions between different aspects of the Earth system, together with human activity, into enhanced multi-hazard methodologies. Multi-hazard approaches support the holistic assessment of hazard potential, and consequently disaster risk. We conclude by describing three ways by which understanding networks of interactions contributes to the theoretical and practical understanding of hazards, disaster risk reduction and Earth system management. Understanding interactions and interaction networks helps us to better (i) model the observed reality of disaster events, (ii) constrain potential changes in physical and social vulnerability between successive hazards, and (iii) prioritise resource allocation for mitigation and disaster risk reduction.

1 Introduction

In this article we combine research and commentary to discuss the importance of integrating hazard interactions and their networks (cascades) into multi-hazard methodologies. Building on the work of others (Delmonaco et al., 2006; Kappes et al., 2010; Kappes et al., 2012; Gill and Malamud, 2014) we advocate for a multi-hazard approach that goes beyond the simple overlay of multiple single hazards, to an approach that also encompasses interactions between these hazards. We present here an enhanced framework for considering such interactions and integrating these into multi-hazard methodologies, supporting efforts to improve management of those aspects of the Earth system that are relevant to disaster risk reduction.

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Examples from primary research and published literature, together with commentary about multi-hazard approaches, are included throughout.

Following this introduction, **Sect. 2** examines the differences between single hazard, multi-layer single hazard, and full multi-hazard approaches. In **Sect. 3** we define and describe relevant groups of hazards and processes that can be considered in multi-hazard methodologies. This is followed by **Sect. 4** which discusses and visualises the principal interactions between these hazards and processes. Then in **Sect. 5** we discuss four case studies (three from Guatemala and one from Nepal), introduce two visualisation frameworks to demonstrate how individual interactions can join together to form networks of hazard interactions (cascades), and commentate on the benefits of assessing such networks of hazard interactions to support disaster risk reduction efforts. Conclusions are outlined in **Sect. 6**.

2 Single vs. Multi-Hazard

Single hazard approaches to assessing hazard potential, in which hazards are treated as isolated and independent phenomena, are commonplace. Their prevalence, however, can distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate risk (Tobin and Montz, 1997; ARMONIA, 2007; Kappes et al., 2010; Budimir et al., 2014; Mignan et al., 2014). If a community is susceptible to more than one hazard, management decisions will benefit by reflecting the differential hazard potential and risk from each of these, and not just focus on them as individual entities. Focusing on a small portion of the whole Earth system, rather than the dynamics of its entirety, may result in decisions being made that increase people's vulnerability to other, ignored hazards. The development of enhanced 'multi-hazard' approaches could offer a way by which the disaster risk reduction community can address these problems.

Multi-hazard approaches are widely encouraged in key government and intergovernmental initiatives and agencies, but rarely defined. For example, the Hyogo Framework for Action (2005–2015) called for *"an integrated multi-hazard approach to disaster risk reduction"* (UNISDR, 2005, p. 4). The Sendai Framework for Disaster Risk Reduction (2015–2030) states that *"disaster risk reduction needs to be multi-hazard"* (UNISDR, 2015, p. 10). Despite the emphasis on multi-hazard approaches within these international agreements, both the Hyogo and Sendai Frameworks do not define what a multi-hazard approach involves. The term also does not appear in the descriptions of terminology published by UNISDR (2009). Further examples of multi-hazard approaches being advocated for, but not clearly defined, can be found in United Nations (2002) and Government Office for Science (2012).

The term 'multi-hazard' may appear to be unambiguous to some and not require a definition. It is, however, a term that is frequently used in different contexts by different members of the natural hazards and disaster risk reduction community. It has been used to describe the independent analysis of multiple different hazards (e.g., landslides, earthquakes, pyroclastic density currents, tephra fall, flooding) relevant to a given area (e.g., Granger et al., 1999; Perry and Lindell, 2008). It has also been used when referring to the identification of areas of spatial overlap, by superimposing hazard layers (e.g., Dilley et al.,

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2005; Shi et al., 2015). These can be better thought of (Gill and Malamud, 2014) as 'multi-layer single hazard' approaches, where an 'all-hazards-at-a-place' framework (Hewitt and Burton, 1971) seeks to understand the discrete risks due to multiple natural hazards.

The identification of all possible and spatially relevant hazards is an important feature of a full multi-hazard assessment, but we believe should not be the sole defining characteristic of such an approach. Multi-hazard assessments may also recognise the non-independence of natural hazards (Kappes et al., 2010), noting that significant interactions exist between individual natural hazards. In a previous study (Gill and Malamud, 2014) we took 21 different natural hazards and identified 90 possible interactions between the 441 (21 × 21) combinations. Here, we will further consider (**Sect. 3–4**) interactions that may also exist between natural hazards, anthropogenic processes (human activity) and the built environment. We will also consider (**Sect. 5**) interactions that can occur successively to form networks of hazard interactions, also referred to as hazard cascades or chains (e.g., Xu et al., 2014; Choine et al., 2015).

We now highlight five possible types of hazard interactions that may occur if an inhabited location is susceptible to multiple hazards, using as exemplars four hazards (tropical storms, floods, landslides and volcanic eruptions):

i. *Natural hazards triggering other natural hazards*: For example, tropical storms may trigger secondary hazards, such as flooding, landslides or lahars if there has been a recent volcanic eruption of tephra.
ii. *Human activities triggering natural hazards:* For example, road construction may destabilise a slope and trigger a landslide.
iii. *Human activities exacerbating natural hazard triggering*: For example, deforestation may exacerbate the triggering of landslides or floods during a tropical storm.
iv. *Networks of hazard interactions (cascades):* For example, a tropical storm may trigger hundreds of landslides, some of which may dam rivers and exacerbate flooding. This is turn could cause slope erosion and trigger further landslides.
v. *The concurrence of two (or more) hazard events*: For example, the spatial and temporal overlap of a volcanic eruption and tropical storm event may result in flooding of a greater severity than would have occurred otherwise, due to volcanic ash blocking drainage systems.

The above five interaction types, based on just four natural hazards and select human activities, are taken from a much broader range of possible hazard interactions and their networks. Even with these limited examples, they demonstrate the limitations of assuming independence of single hazards within a multi-layer single hazard approach.

Multi-hazard methodologies, therefore, should ideally evaluate all identified individual hazards relevant to a defined spatial area and characterize all possible interactions between these identified hazards. **Figure 1**, from Gill and Malamud (2014) shows four distinct factors required to transition from a multi-layer single hazard approach to a detailed, full multi-hazard approach. In addition to identifying all hazards and their interactions, this working framework also proposes an assessment

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of concurrent hazards (such as a tropical storm and volcanic eruption coinciding spatially and temporally), and the recognition that vulnerability is dynamic (which we discuss more in **Sect. 5.3**).

Many current hazard assessments that are labelled as 'multi-hazard' do not consider all the factors given in **Figure 1**, in either a qualitative or quantitative manner. This may be a consequence of limited existing methodologies to assess each of the steps proposed in **Figure 1** (Gill and Malamud, 2014) of a multi-hazard approach. Those methodologies that do exist are sometimes complex, requiring significant amounts of data. Some accessible methodologies to allow the comparison of natural hazards, however, can be found within the literature (e.g., Granger et al., 1999; Van Westen et al., 2002; Greiving, 2006; Grunthal et al., 2006; Marzocchi et al., 2009). Methodologies to identify and visualise potential natural hazard interactions also exist (e.g., Tarvainen et al., 2006; Han et al., 2007; De Pippo et al., 2008; Kappes et al., 2010; van Westen et al., 2014, Gill and Malamud, 2014).

As further multi-hazard approaches are developed, and integrated into research and practice, we believe that it is important to recognise (i) natural hazards do not operate in isolation and (ii) enhanced multi-hazard approaches would also likely benefit from considering how human activity can influence the triggering of hazards and initiation of networks of hazard interactions. We now proceed to define and describe three principal groups of hazards and processes that enhanced multi-hazard frameworks may consider including.

3 Hazard and Process Groups

Here we discuss the characterisation of hazard potential for an applied multi-hazard approach that includes an assessment of at least three distinct groups: natural hazards, anthropogenic processes and technological hazards/disasters. All of these can be considered to be processes and/or phenomena with the potential to have negative impacts on society. In the context of this article, these terms are defined as follows:

i. *Natural hazards.* A natural process or phenomenon that may have negative impacts on society (UNISDR, 2009). Examples include earthquakes, volcanic eruptions, landslides, floods, subsidence, tropical storms and wildfires.

ii. *Anthropogenic processes.* Intentional human activity that is non-malicious, but that may have a negative impact on society through the triggering or catalysing of other hazardous processes. The word process here (and used in many other places in the text) is taken to mean "*a continuous and regular action or succession of actions occurring or performed in a definite manner, and having a particular result or outcome; a sustained operation or series of operations*" (OED, 2015). Examples include groundwater abstraction, vegetation removal, quarrying and surface mining, urbanisation and subsurface construction (tunnelling).

iii. *Technological hazards/disasters.* The unintentional, non-malicious or negligent failure of technology or industry. Examples include structural collapse, nuclear reactor failure, urban fires, chemical pollution and dam collapse.

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A more detailed list of examples for each of these three groups (natural hazards, anthropogenic processes, technological hazards/disasters), based on the definitions set out above, are given in **Table 1**. We now discuss in more detail (**Sect. 3.1–3.3**) each of these three groups, particularly potential overlap between the words 'anthropogenic process' and 'technological hazard' with additional brief comments in **Sect. 3.4**.

3.1 Natural Hazards

The meaning of the phrase natural hazards, considered both individually and as a group of processes is reasonably well understood (e.g., Alexander, 1993; Smith and Petley, 2009). The broad definition of a natural hazard, as set out by UNISDR (2009), is well accepted and encompasses those natural processes that are widely considered to potentially have a negative impact on society and the natural environment. Differences may exist in the level of organisation, or the resolution of classification, used to describe each single hazard. For example, floods may be divided into coastal flooding and in-land flooding. Differences may also exist in how single hazards are clustered. For example, landslides may be clustered with other single hazards within one or more of geophysical hazards, geomorphological hazards, hydrological hazards, and/or hydro-meteorological hazards. These differences in resolution of classification and clustering are normally due to different purposes and characteristics of interest to a specific project, rather than any significant differences of understanding in the process.

3.2 Anthropogenic Processes

Anthropogenic processes are less well defined and characterised as a group, compared to the group labelled natural hazards. There are numerous references to individual human activities exacerbating or triggering particular natural hazards in the literature. For example, Owen et al. (2008) refers to the role of road construction in exacerbating landslide initiation during the 8 October 2005 Kashmir earthquake; Glade (2003) refers to the role of land cover changes in the triggering of landslides during rainstorms in New Zealand; and Knapen et al. (2006) refers to the role of vegetation removal in triggering landslides in Uganda. Each of these examples involves an intentional, non-malicious human activity that has the potential to have a negative impact on society through the triggering or catalysing of hazards. UNISDR (2009) defines the occurrence of specific natural hazards arising from overexploited or degraded natural resources as 'socio-natural' hazards. By definition, these are generated by the interaction of anthropogenic processes with the natural environment. The inclusion of anthropogenic processes within multi-hazard approaches is therefore important and justified. They are very relevant to the modelling of Earth system dynamics and hazardous environments.

3.3 Technological Hazards/Disasters

Although often referred to in the context of disaster studies (e.g., Fleischhauer, 2006; Tarvainen et al., 2006; Bickerstaff and Simmons, 2009), technological hazards/disasters are also less well defined and characterised than the group 'natural hazards'. Some definitions or descriptions of technological hazards and disasters do exist (e.g., Kasperson and Pijawka,

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1985; Gunn, 1990; UNISDR, 2009), but these often lack clarity, or conflict with one another. For example, some definitions include intentional anthropogenic activities within their definition of technological hazards/disasters. Gunn (1990) refers to technological disasters as being human-initiated consequences of breakdown, technical fault, errors, or involuntary and voluntary human acts that have negative consequences. The latter (voluntary human acts) includes those examples that we have defined in **Sect. 3.2** as anthropogenic processes. Subsurface mining, for example, is a voluntary human act that can result in environmental damage, such as subsidence. This subsidence can vary in intensity from slight to severe (Bell et al., 2000).

The UNISDR definition (UNISDR, 2009) of technological hazards also appears to include examples that we have categorised as anthropogenic processes. The definition of technological hazards given by UNISDR (2009) states that they originate from technological or industrial conditions, including human activities that may cause environmental damage, health impacts, economic disruption and other negative consequences. This could include human activities such as subsurface mining, groundwater abstraction and vegetation removal.

Other authors make a clearer distinction between anthropogenic processes and technological hazards. Kasperson and Pijawka (1985) outline three categories of technological hazards:

i. *Routine hazard events of technology*, where there is exposure to underlying chronic hazardous activity over an extensive time period. These can normally be managed by established procedures.

ii. *Technology failures*, resulting in the need for an emergency response.

iii. *Technological disasters*, resulting in significant loss of life or injury, social disruption or relocation.

The latter two (technology failures, technological disasters) are distinguished based on the scale of impact, with technological failures able to evolve into technological disasters if losses are sufficiently large. Although included within the broad category of technological hazards in Kasperson and Pijawka (1985), similarities exist between the *routine hazard events of technology* and the definition of anthropogenic processes we outline in **Sect. 3.2.**

Whereas technological failures and disasters are generally *unintentional* (i.e., not a result of a conscious choice or a desired process), anthropogenic processes are generally *intentional*, and are a result of conscious decisions that may subsequently result in negative consequences. Although such consequences can often be managed using established procedures, anthropogenic processes sometimes still result in the triggering or catalysing of a natural hazard. In the context of this article, therefore, technological hazards are taken to be unintentional, non-malicious or negligent failures of technology or industry.

3.3 Additional Hazards or Processes

In **Sect. 3.1–3.3** it was noted that both anthropogenic processes and technological hazards/disasters are non-malicious; the negative consequences are not the desired outcome. Events that are malicious or deliberately destructive (e.g., terrorism,

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arson, aspects of warfare and criminal activity) are not included within either 'anthropogenic processes' or 'technological hazards/disasters', but may trigger the occurrence of other hazards or processes. For example, the deliberate, and malicious detonation of a bomb close to a dam (this is not an anthropogenic process, as it is malicious) may trigger the dam to collapse (technological hazard), resulting in substantial flooding (natural hazard).

In the context of the rest of this article we focus on interaction relationships between natural hazards (**Sect. 3.1**), anthropogenic processes (**Sect. 3.2**) and technological hazards/disasters (**Sect. 3.3**), and the development of possible networks of hazard interactions (cascades).

4 Interaction Relationships

Multiple interactions exist between the hazard and process examples outlined in the three groups (natural hazards, anthropogenic processes, technological hazards/disasters) discussed above. Kappes et al. (2012) notes a wide variety of terms used to describe such interactions (e.g., interrelationships, interconnections, coupled events) and specific sets of interacting hazards (e.g., coinciding hazards, triggering effects). Here we use the term interactions to refer to the effect(s) of one hazard/process on another hazard/process (Gill and Malamud, 2014), and note examples of three distinct interaction relationships:

i. *Triggering relationships* (e.g., an earthquake triggering a landslide; groundwater abstraction triggering regional subsidence).

ii. *Increased probability relationships* (e.g., a wildfire increasing the probability of landslides; ground subsidence increasing the probability of flooding).

iii. *Catalysis/impedance relationships* (e.g., urbanisation catalysing storm triggered flooding; storms impeding urban fire triggered structural collapse).

We now discuss each of these three interaction relationships in more detail, giving examples and introducing two visualisations. These interaction relationships are also used in **Sect. 5**, when discussing networks of interactions (cascades).

4.1 Triggering Relationships

Triggering relationships are causal relationships, where the occurrence of one primary event results in secondary events occurring. For example, a tropical storm or hurricane (a primary natural hazard) may trigger many landslides (a secondary natural hazard) due to the rapid increase in ground saturation, such as in the case of Hurricane Mitch in 1998 where heavy rain associated with the hurricane resulted in thousands of landslides being triggered in Guatemala (Bucknam et al., 2001). Triggering interactions can occur between a diverse range of hazards and processes. Gill and Malamud (2014) considered just natural hazards, and identified 78 possible triggering pairings between 21 natural hazards (the same natural hazards as

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those given in **Table 1**). The inclusion of both anthropogenic processes and technological hazards/disasters would result in many more triggering relationships than the 78 identified by Gill and Malamud (2014) for natural hazards, as not only would there be triggering relationships within each of the additional groups of 'anthropogenic processes' and 'technological hazards/disasters', but also a significant number would arise between the three groups.

When considering triggering relationships, relative timing of different stages is an important element and adds complexity. For example, some anthropogenic processes may involve multiple stages, including an initial decision-making or survey stage before ground disturbance. In this example, it is possible that a given anthropogenic process may trigger other processes to occur before, simultaneously with, or after any ground disturbance has occurred. Where an associated process is stated to occur 'before' a primary anthropogenic process, it is normally occurring after at least one preliminary stage of the primary anthropogenic process. Associated processes can therefore be considered to be triggered by an occurrence of a primary anthropogenic process. For example, subsurface construction, such as tunnelling, may require drainage and dewatering to take place before the tunnelling commences. The need for drainage or dewatering would be determined during preliminary ground reconnaissance and site investigation.

When considering combinations of natural hazards, anthropogenic processes and technological hazards/disasters, we identify nine possible triggering relationships between these three groups as visualised in **Figure 2**. Triggering relationships are illustrated using block arrows, with the internal arrow fill colour indicating the group of hazards or processes to which the 'trigger source' belongs to. Medium grey is used for natural hazards (labelled **A**), dark grey is used for anthropogenic processes (labelled **B**), and light grey is used for technological hazards/disasters (labelled **C**). We use a prime labelling (**A′**, **B′**, **C′**) to indicate secondary hazards/processes triggered by the same primary hazard or process (**A**, **B**, **C**). Examples of all nine possible interactions are given in a table below **Figure 2**, with codes (i.e., $\mathbf{A_1}$–$\mathbf{A_3}$, $\mathbf{B_1}$–$\mathbf{B_3}$, $\mathbf{C_1}$–$\mathbf{C_3}$) relating to arrow labels. These arrow labels are derived from the hazard or process type of the 'trigger source' (i.e., **A**, **B**, **C**), and followed by sequential subscript numbering. Numbering starts ($\mathbf{A_1}$, $\mathbf{B_1}$, $\mathbf{C_1}$) with the triggering relationship between the same primary and secondary hazard or process type (e.g., a primary *natural hazard* triggering a secondary *natural hazard*) and progresses clockwise. These nine possible triggering relationships demonstrate an important set of interaction relationships that could be included within a multi-hazard methodology.

4.2 Increased Probability Relationships

In addition to a primary natural hazard, anthropogenic process or technological hazard directly triggering a secondary natural hazard, anthropogenic process or technological hazard, they may also increase the probability of another such event occurring. These situations involve a primary hazard or process altering one or more environmental parameters so as to change the frequency or extent of the secondary hazard or process (Kappes et al., 2010; Gill and Malamud, 2014). Examples relating to specific natural hazards include an earthquake increasing the susceptibility of a slope to landslides, regional subsidence increasing the probability of flooding, or wildfires increasing the probability of ground heave. In Gill and

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Malamud (2014), we took the 21 different natural hazards identified in Table 1, and identified 75 possible relationships where a primary natural hazard could increase the probability of a secondary natural hazard. The inclusion of anthropogenic processes and technological hazards/disasters will result in many more increased probability relationships.

4.3 Catalysing and Impedance Relationships

We have discussed above that one hazard/process may trigger another hazard/process. It is possible for these triggering relationships to be catalysed or impeded by further processes. For example, tropical storms can often trigger floods. This triggering relationship can be catalysed by other specific anthropogenic processes (e.g., vegetation removal, urbanisation), natural hazards (e.g., wildfires) or technological failures (e.g., blocked drainage). Conversely a volcanic eruption can trigger wildfires, but this triggering relationship may be impeded by other specific anthropogenic processes (e.g., deforestation) or natural hazards (e.g., tropical storms).

In addition to the nine triggering interaction relationships previously identified (**Figure 2**), a further 12 possible catalysing and impedance relationships can be considered, as visualised in **Figure 3**. We contrast triggering relationships (thick block arrow with a solid outline), and catalysing/impedance relationships (thin block arrow and dashed outlines). The internal arrow fill colour again indicates the group of hazards or processes to which the catalyst/impeder belongs (dark grey: anthropogenic processes; medium grey: natural hazards; light grey: technological hazards/disasters).

Figure 3 highlights the range of possible interaction relationships between three broad groups of hazards and processes. Some of the block arrows represent interaction relationships that have been shown to include large numbers of frequently-occurring interactions (e.g., specific natural hazards triggering other natural hazards). Others represent interaction relationships that are considered to be less common (e.g., specific technological hazards/disasters triggering natural hazards). Overall, the differential likelihood of each of these relationships will depend on a range of parameters in any given location. Only through the careful assessment of all possible single hazards and processes can relevant interactions be identified and assessed.

Examples of some interaction relationships (catalysing and impeding) are presented below. Here we state which hazard or process group (e.g., anthropogenic process) is acting as the catalysing or impeding agent, whether it is a catalysis or impedance relationship, and which triggering relationship identified in **Sect 4.1** is being catalysed or impeded (e.g., $\mathbf{A_1}$, $\mathbf{B_1}$, $\mathbf{C_1}$, as labelled and described in **Sect. 4.1**). We then give a more specific example.

i. *Anthropogenic processes impeding triggering relationship* $\mathbf{A_1}$: Example: urbanisation catalyses storm triggered flooding.

ii. *Technological hazards/disasters catalysing triggering relationship* $\mathbf{A_1}$: Example: dam collapse catalyses flood triggered landslides.

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iii. *Natural hazards catalysing triggering relationship* $\mathbf{B_1}$: Example: floods catalyse urbanisation triggered agricultural practice change.

iv. *Natural hazards impeding triggering relationship* $\mathbf{C_1}$: Example: storm impedes structural collapse triggered urban fires

5 Networks of Hazard Interactions (Cascades)

In the last section, we discussed three different interaction relationships (triggering, increased probability, catalysing/impedance) between specific natural hazards, anthropogenic processes and technological hazards/disasters. However, in addition to having a paired relationship (e.g., one primary hazard triggering a secondary natural hazard) these interactions can be joined together to form a network of hazard and/or process interactions. For simplification of language, we will call these just 'networks of hazard interactions' or 'interaction hazard networks'. Such networks have also been referred to as hazard chains (e.g., Han et al., 2007; Xu et al., 2014), cascades (e.g., Choine et al., 2015; Pescaroli and Alexander, 2015) or multi-hazard networks of interacting hazards (Gill and Malamud, 2014). Networks of hazard interactions may consist of short or long chains of interactions, and may include single or multi-branches.

In this section we first introduce four case studies of networks of hazard interactions (**Sect. 5.1**), then present two ways of visualising the networks (**Sect. 5.2**), and finally discuss why we believe evaluating networks of hazard interactions are important (**Sect. 5.3**).

5.1 Case Study Examples

Networks of hazard interactions can extend over many orders of magnitude both spatially and temporally (Gill and Malamud, 2014). For example, a tropical storm (lasting several days) may trigger landslides across an entire region (e.g., Central America). One of these triggered landslides may block a river causing a small, localised flood. In a further example, volcanic activity may impact a national or sub-national level, but persist for many decades. The Santiaguito dome in Guatemala, for example, has seen unsteady, extrusive activity since 1922 (Bluth and Rose, 2004), mainly impacting the southwest of Guatemala. The combination of this sustained (albeit unsteady) eruptive activity and regular rainfall can result in the regular triggering of lahars (Harris et al., 2006).

Networks of hazard interactions can also vary in terms of frequency and impact. For example, they can be observed in low frequency, large events such as the 2015 M_w = 7.8 'Gorkha earthquake, Nepal'. These internationally-publicised events help to raise the profile of networks of hazard interactions (cascades). They can also, however, be observed in localised, high-frequency, low-impact events, such as the regular eruptions of Santiaguito in Guatemala.

Here we introduce two case studies, one from Nepal and one from Guatemala, which demonstrate some of the variation in spatial and temporal extent, frequency and impact of networks of hazard interactions:

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i. *M_w = 7.8 Nepal earthquake, April 2015*. The 25 April 2015 M_w = 7.8 Gorkha earthquake in Nepal impacted several Himalayan nations, triggering a M_w = 7.3 aftershock on 12 May 2015 (Bilham, 2015; Collins and Jibson, 2015). The initial earthquake is reported to have triggered more than 400 aftershocks with $M_w > 4$ as of 13 December 2015, almost eight months after the initial earthquake (National Seismological Centre, 2015). The main shock and aftershocks rapidly triggered snow avalanches and multiple landslides, with some of the landslides blocking rivers which in some cases triggered upstream flooding (Collins and Jibson, 2015). The earthquake sequence also increased the probability of further landslides, triggered by subsequent monsoon rains (Bilham, 2015, Collins and Jibson, 2015).

ii. *Tropical Storm Agatha and eruption of Volcano Pacaya, Guatemala, May 2010).* Tropical Strom Agatha impacted several nations within Central America, hitting the Pacific coastline of Guatemala on 29 May 2010 (Beven, 2011). It was associated with strong winds and torrential rains (Stewart, 2011; Stewart and Cangialosi, 2012). Within Guatemala, the storm triggered landslides (Wardman et al., 2010) and flooding across much of the Southern Highlands of Guatemala, and contributed to a rare, localised (20 m), rapid-onset ground collapse event (Beven, 2011; Stewart, 2011) in Guatemala City. The effects of Tropical Storm Agatha in Guatemala were exacerbated by the near-simultaneous eruption of Pacaya, a complex volcano located 30 km southwest of Guatemala City. Pacaya erupted two days prior to the onset of Tropical Storm Agatha on 27 May 2010 (Wardman et al., 2010), ejecting ash and debris across much of Guatemala City. As ash blocked the inadequate drainage system, it increased the intensity of flooding during Tropical Storm Agatha (United Nations, 2010). The combination of fresh ash, volcanic debris and heavy rain, generated lahars (a natural hazard) and structural collapse (a technological hazard/disaster) (Wardman et al., 2010; Daniell, 2011).

Guatemala is an example of a location where multiple different networks of hazard interactions can be identified. Guatemala is affected by a wide range of specific natural hazards, including: earthquakes, volcanic eruptions, landslides, floods, droughts, tropical storms, extreme temperatures, subsidence and wildfires. Relevant anthropogenic processes include deforestation, inadequate drainage, agricultural practices and building/road construction practices. Technological hazards/disasters of relevance include structural collapses, urban fires, chemical pollution and transport accidents. Specific hazards or processes impacting Guatemala may last for decades (e.g., eruptive activity of Santiaguito) or days (e.g., Tropical Strom Agatha), impacting large areas (e.g., drought across 100s km^2) or small areas (e.g., 20 m ground collapses). A wide range of possible interactions exist between specific natural hazards, anthropogenic processes and technological hazards/disasters.

5.2 Visualising Networks of Hazard Interactions (Cascades)

Given the prevalence of networks of hazard interactions, we consider here how these networks can be visualised in order to support multi-hazard assessments of interacting natural hazards. In Gill and Malamud (2014), we developed one method of

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visualising networks of hazard interactions, where we developed a 21 × 21 matrix, showing possible interactions between 21 different 'primary' and 'secondary' natural hazards, and then overlaid onto this relevant information about the network of hazard interactions.

In **Figure 4** we show this methodology using a hypothetical, but common, example of a network of hazard interactions formed exclusively from natural hazards. This network of hazard interactions is presented on a 21 × 21 matrix, from Gill and Malamud (2014), which includes both triggered relationships and relationships where one hazard increases the probability of another. It uses a two letter code for the 21 different natural hazards, which are the same as those given in **Table 1**. The vertical axis of the matrix in **Figure 4** displays the primary hazards (rows 1 to 21, **EQ** to **IM**). These are the initial hazards that trigger or increase the probability of another hazard occurring. The horizontal axis of the matrix presents these same hazards as potential secondary hazards (columns A to U, **EQ** to **IM**). These are the triggered hazards, or the hazards for which the probability of occurrence has been increased. The 21 hazard types are clustered into six hazard groups, identifiable with different colours as indicated in the key. Each matrix cell is divided diagonally so that there are two triangles in a cell. Shading in the upper-left triangle of a given cell indicates that the primary hazard could trigger an occurrence of the secondary hazard. Shading in the lower-right triangle of a given cell indicates that the primary hazard could increase the probability of the secondary hazard. It is, of course, possible for both of these triangles to be shaded for any given primary hazard-secondary hazard coupling.

The network of hazard interactions (cascade) presented within **Figure 4**, overlaying the 21 × 21 matrix, is initiated by a storm (row 12, **ST**) that triggers flooding (column F, **FL**). This flooding may (row 6, **FL**) subsequently trigger landslides (column D, **LA**) through the erosion of slope bases. These landslides (row 4, **LA**) could then trigger or increase the probability of further flooding (column F, **FL**) through the damming of rivers.

Using this visualisation framework we give two further examples of networks of hazard interactions from the Southern Highlands of Guatemala (**Figure 5**):

i. *M_w = 7.5 Guatemala earthquake, 1976.* **Figure 5 (top)** visualises some of the hazards and hazard interactions relevant to the 1976 M_w = 7.5 Guatemala earthquake. This event triggered multiple aftershocks, as well as triggering movement on other faults close to Guatemala City (Espinosa, 1976, Plafker, 1976). The earthquake triggered some rapid subsidence or ground collapse (Plafker, 1976) and more than 10,000 landslides, rock falls and debris flows (Harp et al., 1981). Many of these mass movements occurred along poorly-built road and rail cuttings, blocking vital transport routes (Plafker, 1976). Some of the mass movements also blocked rivers and triggered upstream flooding (Plafker, 1976; Harp et al., 1981). Breaches of these landslide-dams also resulted in further flooding (Harp et al., 1981).

ii. *Santiaguito lahars and triggered flooding, approximately annual.* **Figure 5 (bottom)** visualises some of the hazards and hazard interactions associated with lahar triggered flooding around the volcano Santiaguito. In Guatemala,

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rainfall mobilisation of ash and tephra deposits on active volcanic flanks, such as Santiaguito, frequently result in lahars. These lahars subsequently trigger floods through increased sedimentation, the addition of large amounts of tephra material to the hydrological system (Harris et al., 2006). While in Guatemala in 2014, we confirmed this network of hazard interactions using personal field observations and discussed in seven semi-structured interviews with hazard monitoring and civil protection officials. This network of hazard interactions (cascades) may be observed on an approximately annual basis, during the rainy season (month to month), while Santiaguito is active.

Many others examples of networks of hazard interactions (cascades) can be observed in the published scientific literature, technical reports, press releases and other forums. It is beyond the scope of this article to compile a comprehensive list of these cascades, however many can be found in the references noted at the end of this article.

Using the visualisations previously introduced in **Sect. 4** (**Figures 2** and **3**) we can also represent complex networks of hazard interactions involving a mixture of natural hazards, anthropogenic processes and technological hazards/disasters. The original figure outline (from **Figure 3**) can be used and replicated within the same figure to allow for longer and more complex networks of hazard interactions. The examples we present in **Figures 6** and **7** show all possible triggering interactions (thick block arrows with solid outlines) and relevant catalysing/impedance interactions (thin block arrows with dashed outlines). Possible networks of hazard interactions are visualised using light-blue boxes to highlight the relevant hazards/processes (i.e., nodes within a network), and dark-blue arrows to highlight the relevant interactions (i.e., links within a network).

The network of hazard interactions in **Figure 6** shows a primary anthropogenic process catalyse (**1**) the triggering relationship between a primary and secondary natural hazard (**2**), with the secondary natural hazard then triggering (**3**) a primary technological hazard, which in turns triggers (**4**) a primary anthropogenic process to occur. An analogous example of this interaction network would be urbanisation increasing overland flow and therefore catalysing (**1**) storm triggered floods (**2**), with the floods then triggering (**3**) an embankment to collapse, which in turn triggers (**4**) anthropogenic drainage and dewatering.

The network of hazard interactions in **Figure 7** is more complex, with three branches and five interaction relationships highlighted here. This example shows a primary natural hazard triggering (**1**) a primary technological hazard, which in turn triggers (**2**) a primary anthropogenic process. The same primary natural hazard may trigger (**3**) a secondary natural hazard. This secondary natural hazard could then trigger (**4**) a primary technological hazard and (**5**) tertiary natural hazards. An analogous example of this interaction network would be an earthquake triggering (**1**) a structural collapse, which in turn results in (**2**) increases in infilled (made) ground. The earthquake may also trigger (**3**) landslides, which could trigger (**4**) a road traffic accident and (**5**) flooding.

The overlay of networks of hazard interactions on matrices (**Figures 4** and **5**) and the construction of network diagrams (**Figures 6** and **7**) can be complemented by other visualisation techniques. For example, when a quantitative evaluation of

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possible outcomes of interaction relationships is possible, probability trees can be used to assess networks of hazard interactions (e.g., Neri et al., 2008; Marzocchi et al., 2009; Neri et al., 2013). Probability trees are used to visually represent the possible outcomes of an event and add associated probabilities. All three methods are useful for communicating information about specific chains of events. The two visualisation techniques that we have presented here, together with existing probability trees, allow simple and more complex networks of hazard interactions to be evaluated and visualised.

5.3 Importance of Networks of Hazard Interactions (Cascades)

We believe that the assessment and visualisation of possible interaction networks (cascades) within multi-hazard methodologies is of importance to both the theoretical and practical understanding of hazards and disaster risk reduction. Here we outline three principal reasons for identifying possible interaction networks.

5.3.1 Risk assessments and risk management benefit by better matching observed reality

An analysis of past occurrences of hazards and disasters shows that interaction networks are often part of the structure of disasters (Gill and Malamud, 2014). The need to better match observed reality, by including interaction networks, is applicable to events of diverse spatial and temporal extent, frequency and impact, as has been discussed in **Sect. 5.2**. The frequency of occurrence of specific networks of hazard interactions demonstrates that more could be done to understand and characterise them. Following the 2015 Gorkha (Nepal) earthquake, the European Geosciences Union (EGU) issued a statement (EGU, 2015) calling for a multi-hazard, integrated approach to risk assessment and the management of natural hazards. This statement also notes the need for agreement within the geoscience community on how to model cascades of natural hazards. This call joins many previous calls (Delmonaco et al., 2006; Kappes, 2011; Kappes et al., 2012; Gill and Malamud, 2014) encouraging the assessment of interacting natural hazards, and their integration into multi-hazard methodologies. Assessing interaction networks is therefore important as they are a fundamental part of hazard and disaster events.

5.3.2 Changes to social and physical vulnerability during links of a multi-hazard cascade event

As a network of hazard interactions (cascade) progresses, aspects of social and/or physical vulnerability may change following the occurrence of a specific natural hazard, anthropogenic process or technological hazard/disaster. If there is a succession of hazard events (i.e., a network of hazard interactions), there may be progressive changes in vulnerability during this succession. While some aspects of vulnerability may remain at the same level before and after the occurrence of a specific event, it is also possible that other aspects of vulnerability may increase as pressure is placed on society and infrastructure, thus reducing coping capacity or decrease. Other aspects of vulnerability could also decrease, especially if there are significant time intervals between successive events in a cascade. This could, for example, help facilitate a growth in community awareness and preparation.

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This changing vulnerability during a network of hazard interactions can be represented visually, as shown in **Figure 8**, where a series of three hazard events occur in succession and an assumption is made each hazard event will increase subsequent levels of vulnerability. Before and between these three hazard events, a representation of vulnerability is given, where we illustrate the vulnerability magnitude as proportional to the height of the rectangle. **Figure 8** shows the dynamic nature of vulnerability during a network of interacting hazards. In this representation, we have assumed that there are increases in vulnerability as the chain of events progresses, but we note that this will not always be the case. On the ground these changes to social and physical vulnerability may be observed in different ways. For example, buildings may have sustained significant damage so that they are more likely to collapse during an aftershock. Hospitals may be at maximum capacity following an earthquake and therefore not able to respond effectively if a subsequent typhoon results in further casualties. Injuries sustained by a community during an earthquake may mean they have a reduced capacity to evacuate if a tsunami is subsequently triggered.

These examples demonstrate that existing assessments of vulnerability may rapidly become out of date following a hazard event. The identification of possible interacting hazard networks in a given region would allow improved planning of possible changes in vulnerability during successive events. In turn, this could help to improve preparedness efforts.

5.3.3 Allocation of resources for disaster risk reduction

In addition to the risk reduction benefits that come from the last two points, understanding how chains of interacting hazards are initiated and propagated may help determine how to invest resources to minimise disruption should a specific network of interacting hazards occur. Scientific and management efforts can be focused to prevent the initiation of interaction networks, reducing the propagation of triggered hazards and the development of an interaction network. It may not always be possible to prevent an initial primary hazard from occurring, but sensible investments in structural and non-structural mitigation measures may reduce the likelihood of specific networks of hazard interactions propagating. While we cannot currently prevent a tropical storm from forming and hitting land, for example, measures may be taken to improve drainage and reduce flooding, reinforce certain slopes that are susceptible to failure, or improve urban management to reduce structural collapses, urban fires and water contamination.

6 Conclusions

In this research and commentary article, we have sought to advance the understanding of enhanced multi-hazard frameworks, which we believe to be of relevance to improved Earth-systems management. We advocate an approach that goes beyond multi-layer single hazard approaches to also encompass interaction relationships and networks of interactions (cascades). This study has described this integrated approach, noting that to do otherwise could distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate risk. The development of an enhanced framework to assess and characterise interactions and networks of interactions first required a description of three principal

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groups of hazards/processes, including natural hazards, anthropogenic processes and technological hazards/disasters. These three groups can interact in a range of different ways, with three interaction relationships discussed in the context of this article: triggering relationships, increased probability relationships, and catalysis/impedance of other hazard interactions. In addition to those circumstances where one stimulus triggers one response, it is highly likely that more than one of these interactions can be joined together to form a network of interactions, chain or cascade event. We have developed enhanced frameworks to visualise these interactions and networks of interactions (cascades). These frameworks, visualisations and associated commentary:

i. Reinforce the importance of enhanced multi-hazard approaches, integrating hazard interactions and networks of interactions to better model observed dynamics of the Earth system.

ii. Offer a more holistic approach to assessing hazard potential and disaster risk, helping to improve Earth system management.

Better characterisation and integration of interactions and networks of interactions into multi-hazard methodologies can contribute to an improved theoretical and practical understanding of hazards and disaster risk reduction.

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Table 1. Examples of hazard/process types, grouped into three categories: Natural Hazards (classification of 21 hazards from Gill and Malamud, 2014), Anthropogenic Processes and Technological Hazards/Disasters.

Hazard/Process Group	Examples
Natural Hazards	Earthquake, tsunami, volcanic eruption, landslide, snow avalanche, flood, drought, regional subsidence, ground collapse, soil (local) subsidence, ground heave, storm, tornado, hailstorm, snowstorm, lightning, extreme temperature (hot and cold), wildfire, geomagnetic storm, impact event.
Anthropogenic Processes	Groundwater abstraction, subsurface mining, subsurface construction, fluid injection, vegetation removal, urbanisation, surface mining, drainage and dewatering, chemical explosion.
Technological Hazards/Disasters	Structural collapse, nuclear reactor failure, urban fire, chemical pollution, dam collapse, industrial explosion, transport accident.

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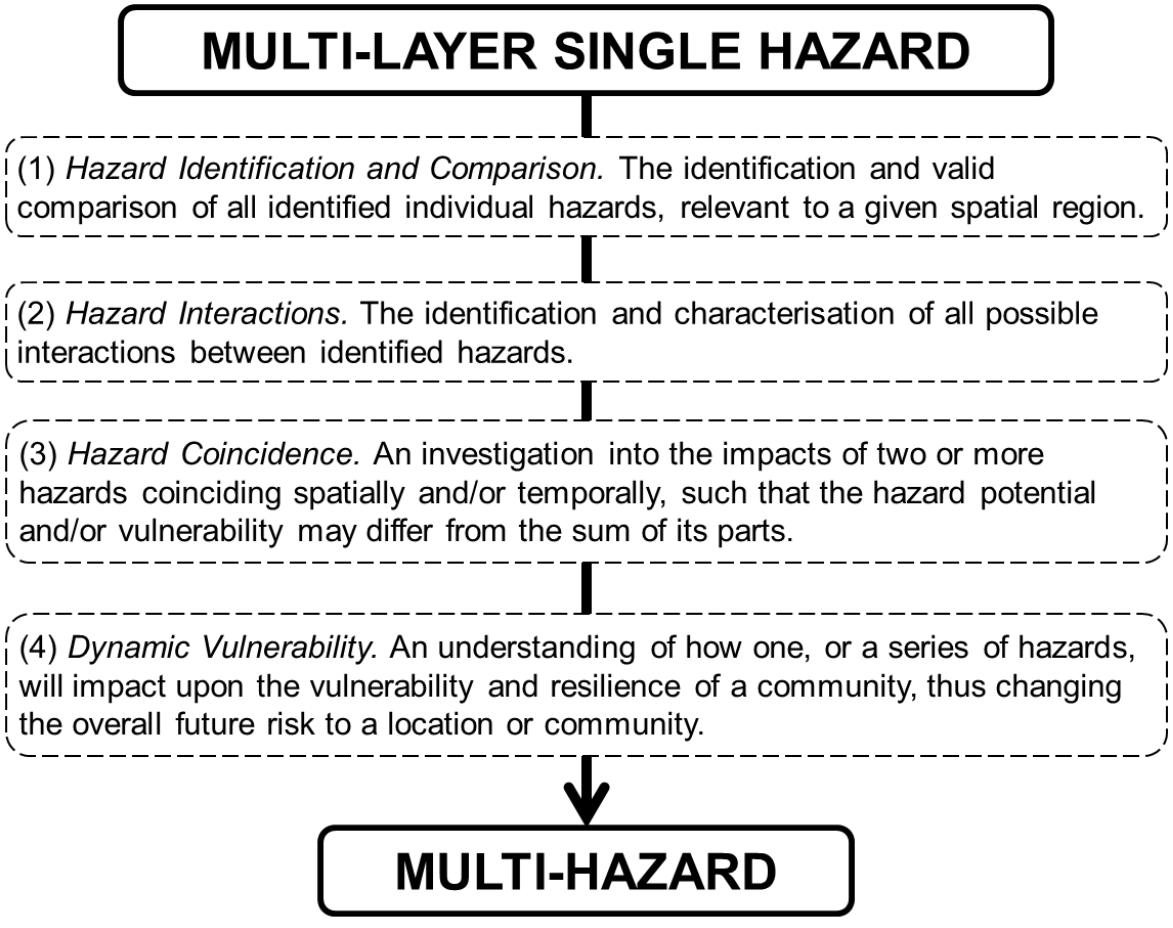

Figure 1. Multi-hazard framework (from Gill and Malamud, 2014). Shown is the progression from a multi-layer single hazard approach to a full multi-hazard approach that includes: (i) hazard identification and comparison, (ii) hazard interactions, (iii) spatial/temporal coincidence of natural hazards, and (iv) dynamic vulnerability to multiple stresses.

5

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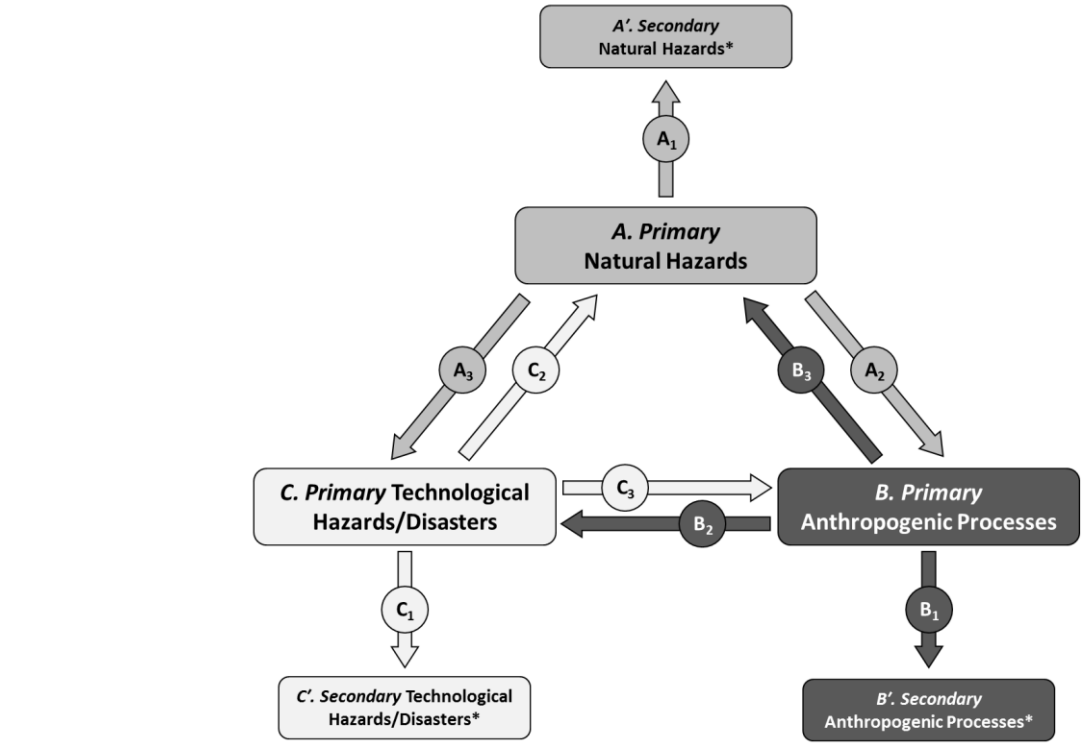

Examples for Interaction Relationships A_1–C_3

	1	2	3
A	Earthquake triggers landslides	Drought triggers agricultural practice change	Earthquake triggers nuclear reactor meltdown
B	Subsurface mining drives dewatering	Subsurface mining triggers mine collapse	Fluid injection triggers earthquakes
C	Transport accident triggers chemical spill	Dam collapse triggers flooding	Structural collapse drives infilled (made) ground

Figure 2. Interaction relationships (triggering) framework. A framework for hazard/process interactions is given here, which highlights triggering relationships between three groups: (**A**) natural hazards, (**B**) anthropogenic processes and (**C**) technological hazards/disasters. Arrows are used to illustrate interaction relationships, with the arrow fill colour indicating

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the 'source' or initiation of the trigger (dark grey: anthropogenic processes; medium grey: natural hazards; light grey: technological hazards/disasters). We use a prime (**A′**, **B′**, **C′**) to indicate secondary hazards/processes triggered by the same primary hazard/process group (**A**, **B**, **C**). Arrows are labelled ($\mathbf{A_1}$–$\mathbf{A_3}$, $\mathbf{B_1}$–$\mathbf{B_3}$, $\mathbf{C_1}$–$\mathbf{C_3}$) according to the hazard or process type of the 'trigger source' (i.e., **A**, **B**, **C**), and followed by sequential subscript numbering. Numbering starts ($\mathbf{A_1}$, $\mathbf{B_1}$, $\mathbf{C_1}$) with the triggering relationship between the same primary and secondary hazard or process type (e.g., a primary natural hazard triggering a secondary natural hazard) and progresses clockwise. Examples of each interaction are given in the table at the bottom of the figure, where the vertical axis indicates the source of the primary hazard/process (**A**, **B**, **C**), and the horizontal axis indicates which subscript is being referred to (**1**–**3**).

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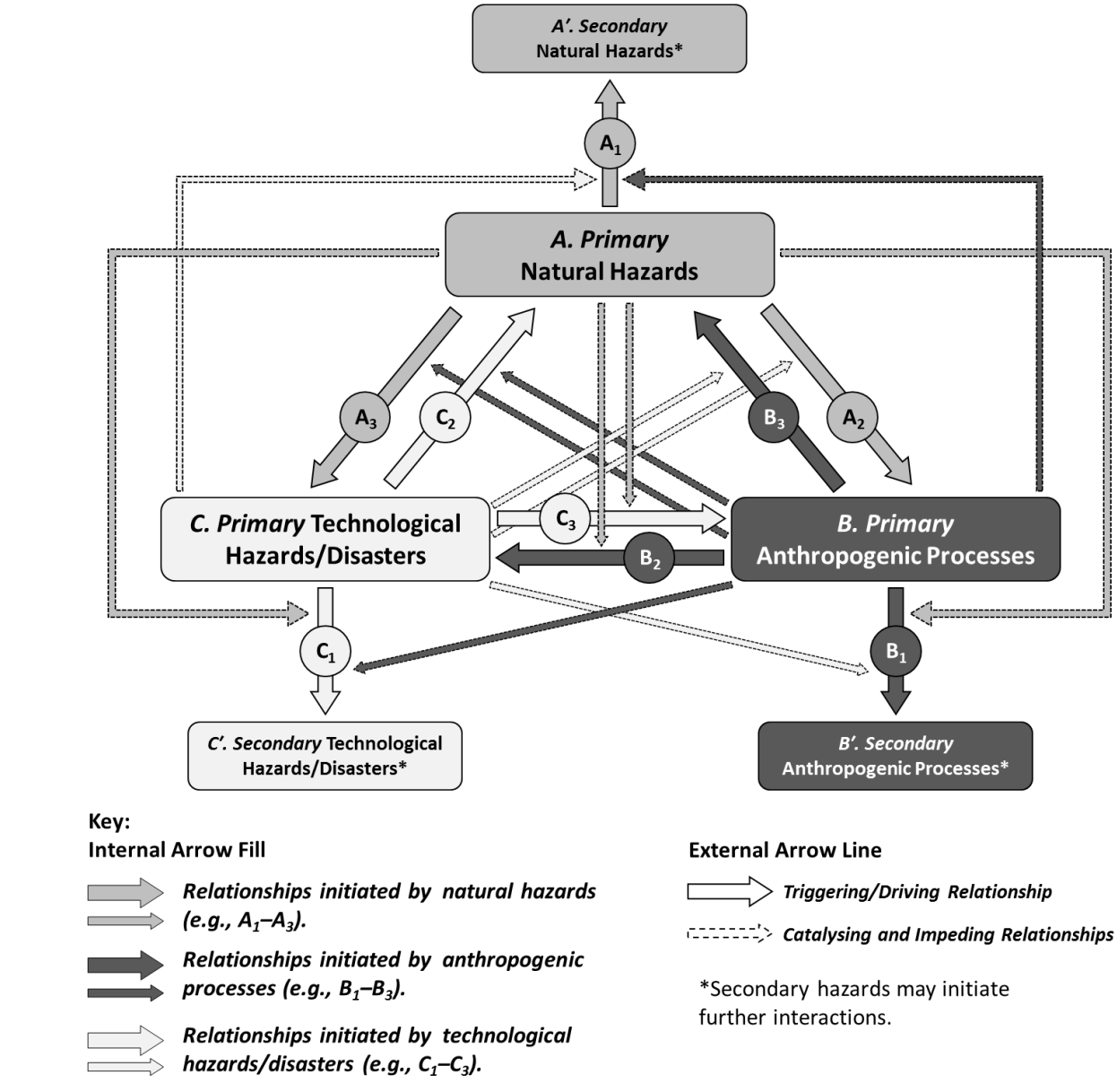

Figure 3. Interaction relationships (triggering, catalysing and impeding) framework. Interactions in the form of triggering relationships (**Figure 2**), and catalysing/impedance interactions are possible between (**A**) natural hazards, (**B**) anthropogenic processes and (**C**) technological hazards/disasters. We use a prime (**A**′, **B**′, **C**′) to indicate secondary hazards/processes triggered by the same primary hazard/process group (**A**, **B**, **C**). We contrast here triggering relationships (thick block arrows with solid outlines) and catalysing/impedance relationships (thin block arrows with dashed outlines). The internal arrow fill colour indicates the group of hazards or processes to which the catalyst/impeder belongs (dark grey: anthropogenic process;

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medium grey: natural hazard; light grey technological hazard/disaster). Descriptions of arrow labels (**A_1**–**A_3**, **B_1**–**B_3**, **C_1**–**C_3**) can be found in **Figure 2** caption. Examples of catalysing and impedance relationships are given in **Sect. 4.3**.

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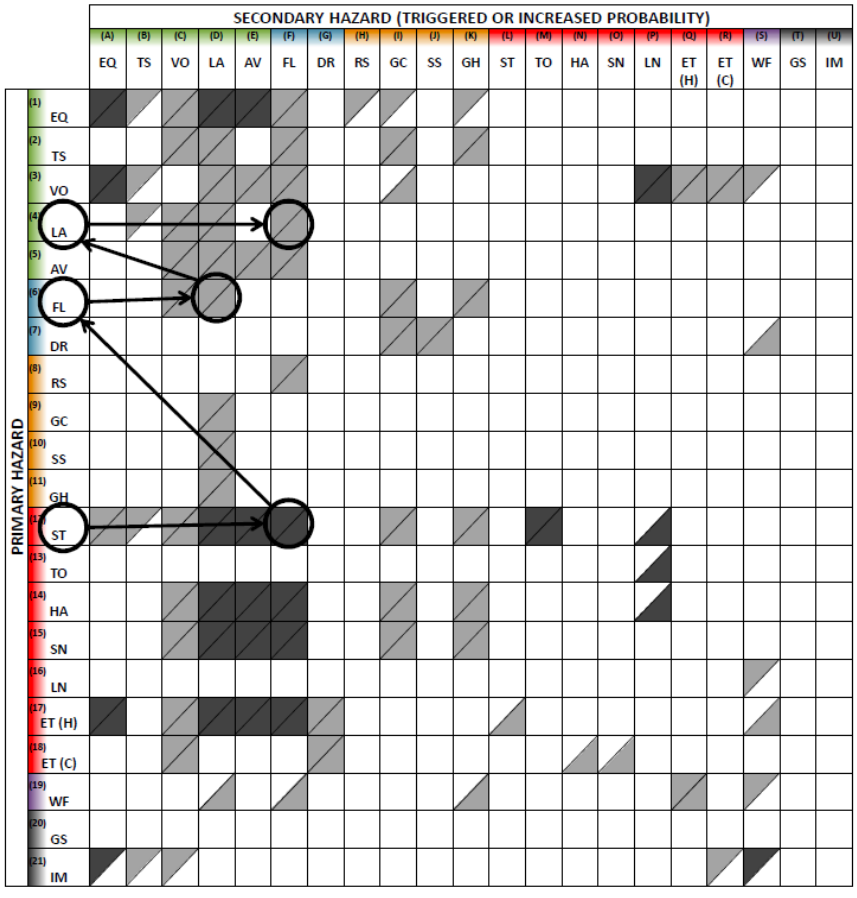

KEY		
HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfires	WF
SPACE	Geomagnetic Storm	GS
	Impact Events	IM

COLOUR CODE	NATURE OF SECONDARY HAZARD (FOLLOWING ONE OCCURRENCE OF PRIMARY HAZARD)
	Potential for a small number of hazard events (individual or a few occurrences)
	Potential for a large number of hazard events (multiple occurrences)

SYMBOL	EXPLANATION
	Hazard Triggers Secondary Hazard
	Hazard Increases Probability of Secondary Hazard
	Hazard Both Triggers and Increases the Probability of Secondary Hazard

Footnotes

[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17A,D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large numbers of events, and are thus analysed in this way.
[1C] There is disagreement in the literature about the nature of this relationship .
[2,6,12,14,15C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.
[3I] Volcanism increases the acidity of rain, promoting dissolution of carbonate material.
[12A] Low pressure systems have been shown to trigger or increase the probability of slow earthquakes on faults that are already close to failure (Liu *et al.*, 2009).
[17A,C-F] Secondary hazards triggered or have an increased probability over a range of time-scales, through snow and glacial melting.
[18C] Long term reductions in temperature can increase glaciation and thus decrease sea-levels. This reduction in sea-levels can reduce confining pressures, promoting volcanic eruptions.

Figure 4. An example of a network of hazard interactions (a cascade system) (from Gill and Malamud, 2014). A 21 × 21 matrix with primary natural hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded, as explained in the key. This matrix shows cases where a primary hazard could trigger a secondary hazard (upper-left triangle shaded) and cases where a primary hazard could increase the probability of a secondary hazard being triggered (bottom-right triangle shaded). Where both triangles are shaded, this indicates that the primary hazard could both trigger and increase the probability of a secondary hazard. Also distinguished are those relationships where a primary hazard has the potential to trigger or increase the probability of multiple occurrences of the secondary hazard (dark grey), and few or single

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occurrences of the secondary hazard (light grey). Hazards are grouped into geophysical (green), hydrological (blue), shallow Earth processes (orange), atmospheric (red), biophysical (purple) and space/celestial (grey). Footnotes give further information about some of the relationships. This matrix can be used to present an example of a network of hazard interactions (cascade). In this example, a storm event (**ST**) triggers flooding (**FL**), which then triggers landslides (**LA**). These landslides (**LA**) may then trigger or increase the probability of further flooding (**FL**) through the blocking of a river or the increase of sediment within the fluvial system.

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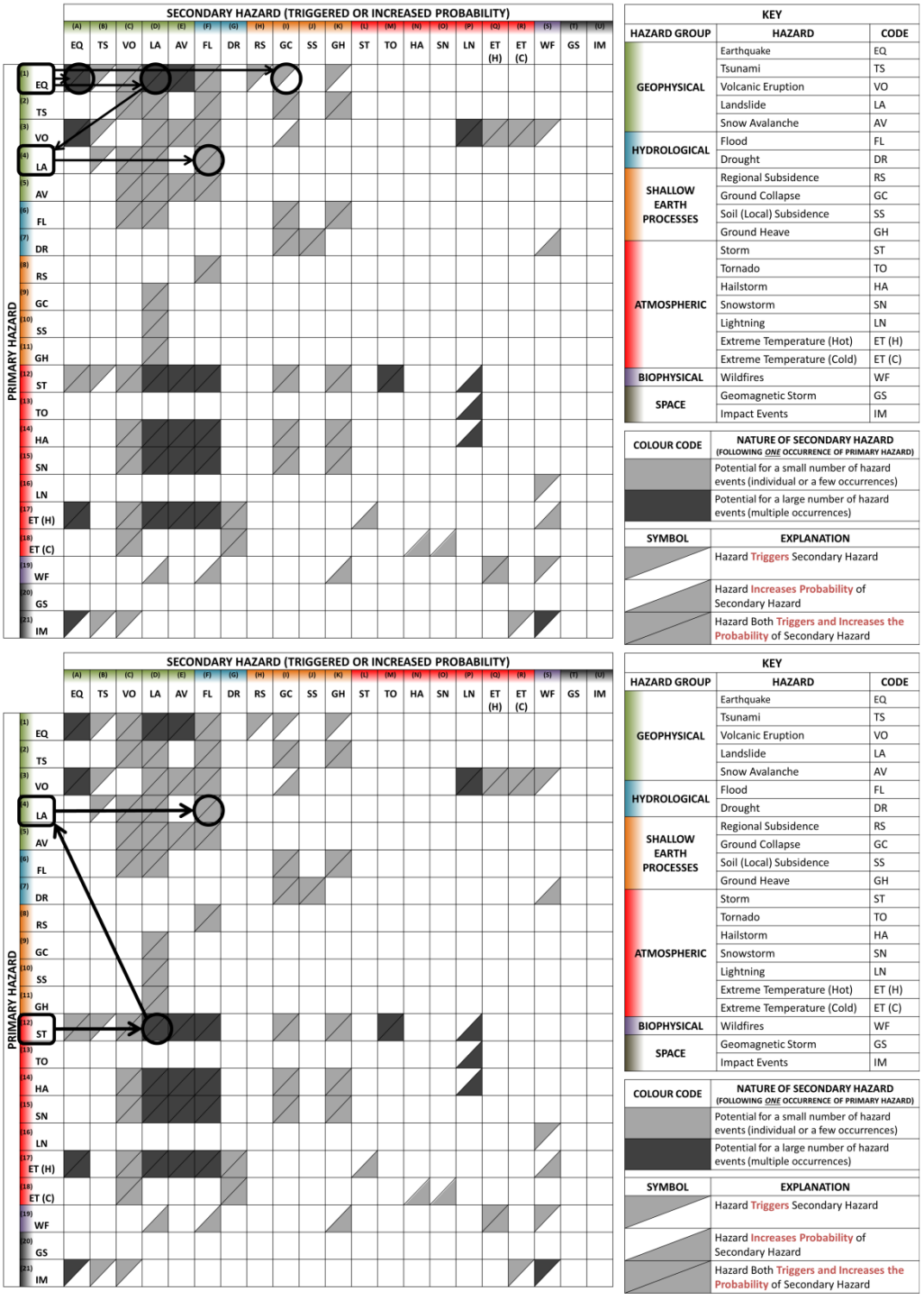

Figure 5. Two examples of networks of hazard interactions (cascade systems). Hazard interaction networks based on (*top*) the 1976 Guatemala earthquake sequence, and (*bottom*) lahar triggered flooding associated with Santiaguito, Guatemala.

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Both network examples are place on a 21 × 21 matrix, adapted from Gill and Malamud (2014), and described in detail within the caption of **Figure 4**. In the top example (described in **Sect. 5.2**), based on information from Espinosa (1976), Plafker (1976) and Harp et al. (1981), an earthquake (**EQ**) triggers further earthquakes (**EQ**), landslides (**LA**) and rapid subsidence/ground collapse (**GC**). The Landslides (**LA**) were then noted to have blocked rivers, causing flooding (**FL**). The bottom example (also described in **Sect. 5.2**), is based on information from Harris et al. (2006) and confirmed by personal field observations and seven semi-structured interviews with hazard monitoring and civil protection officials while the authors were in Guatemala in 2014. The bottom example shows rain storms (**ST**) triggering lahars (**LA**) on the flanks of Santiaguito. These lahars enter the hydrological system and result in flooding (**FL**) downstream.

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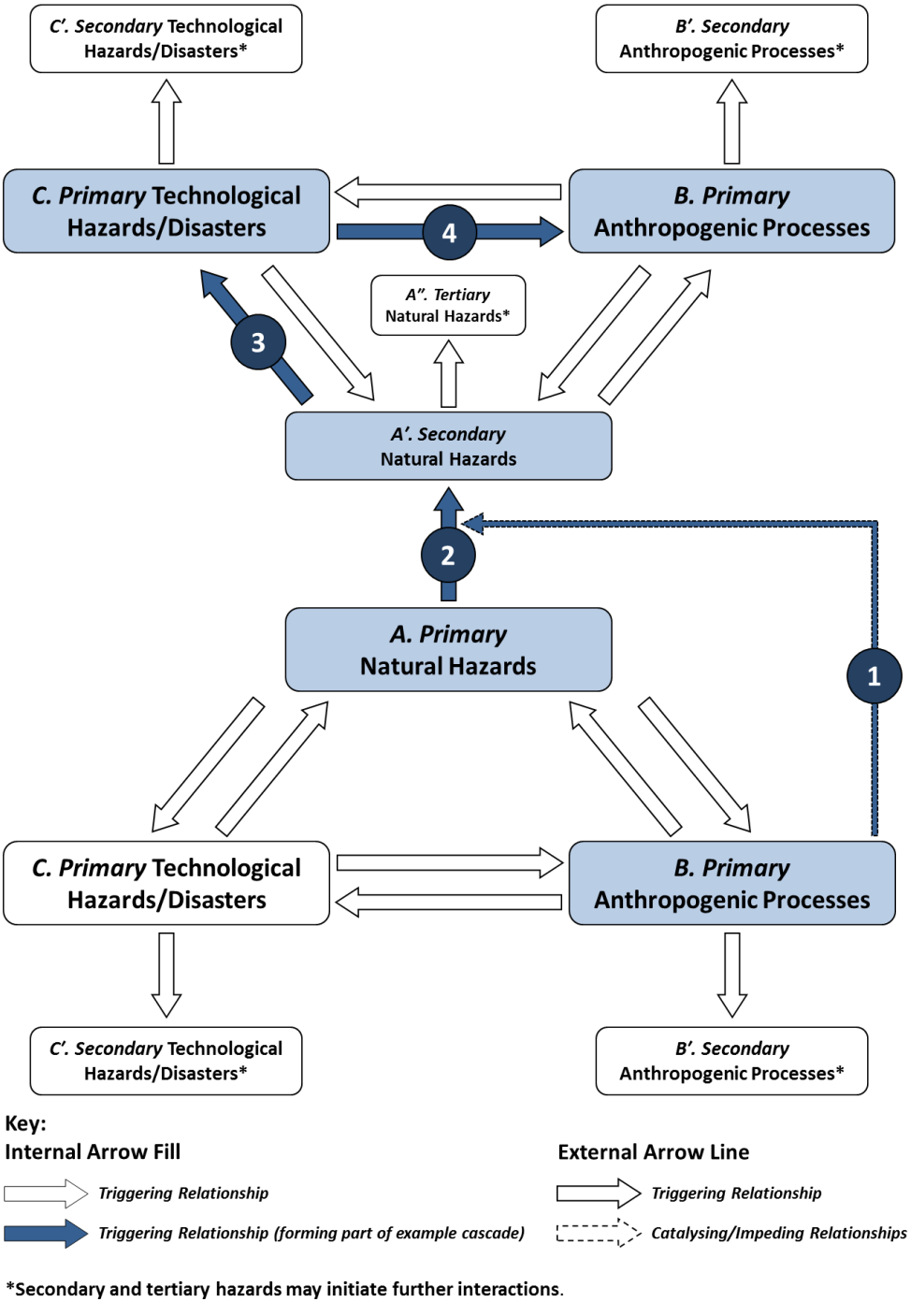

Figure 6. Network of hazard interactions (Example 1). Using the visualisation frameworks constructed in **Figures 2** and **3**, an example of an interaction network (cascade) can be presented. Three hazard/process groups are included: (**A**) natural

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hazards, (**B**) anthropogenic processes and (**C**) technological hazards/disasters. Arrows are used to illustrate interaction relationships, with both triggering relationships (thick block arrows with solid outlines) and relevant catalysing/impedance relationships (thin block arrows with dashed outlines). For clarity of communication, those catalysing/impedance relationships not of relevance to the specific example are not included. See **Figures 2** and **3** caption explanations for further details. Arrows within the example network of hazard interactions are labelled (**1**–**4**) and shaded dark blue to highlight the relevant pathway. In this example, a primary anthropogenic process catalyses (**1**) the triggering relationship between a primary and secondary natural hazard (**2**), with the secondary natural hazard then triggering (**3**) a primary technological hazard, which in turns triggers (**4**) a primary anthropogenic process to occur.

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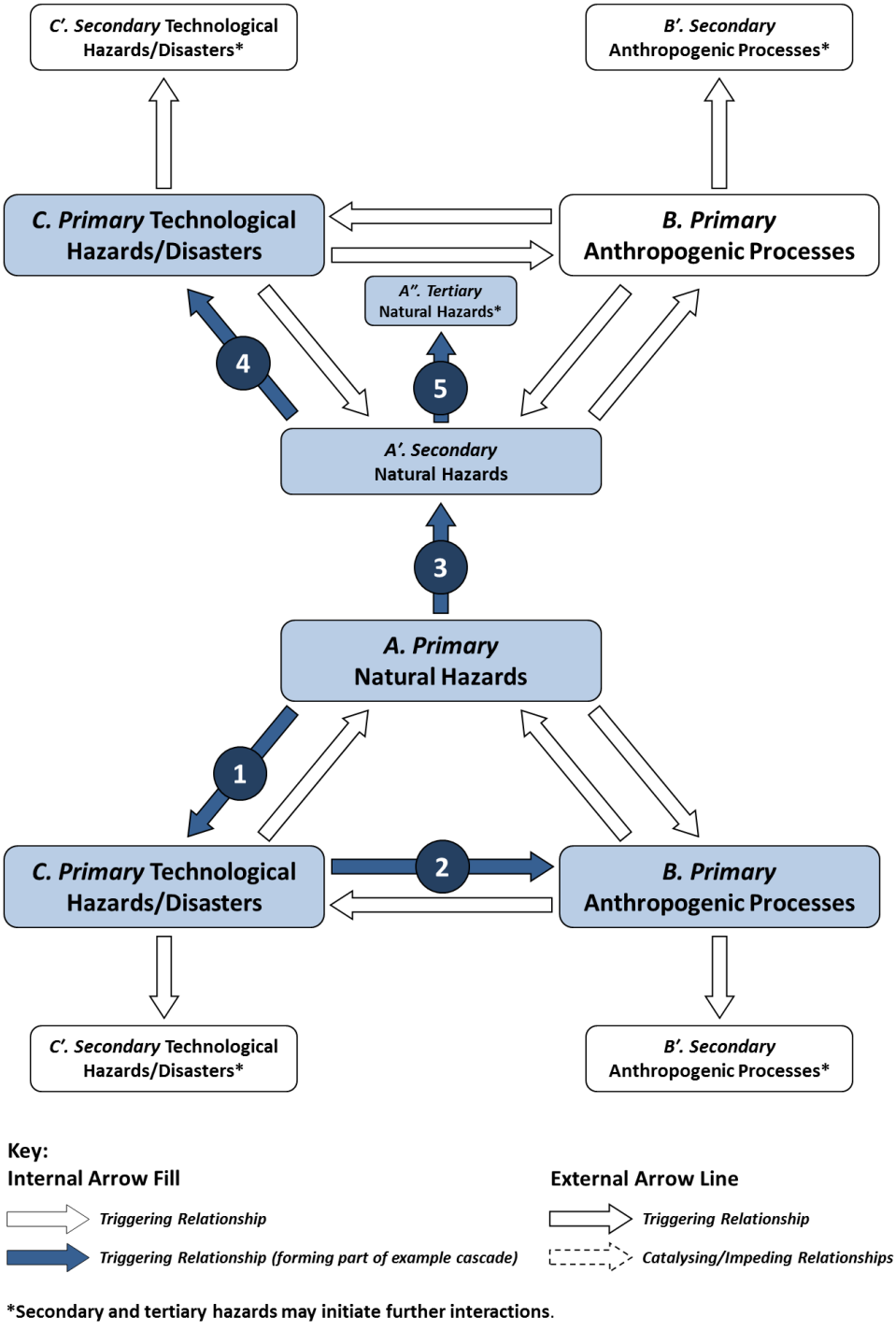

Figure 7. Network of hazard interactions (Example 2). Using the visualisations constructed in **Figures 2** and **3**, an example of an interaction network (cascade) can be presented. In this example the network is more complex than in Example 1

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(**Figure 6**), with three branches and five interaction relationships highlighted here. Three hazard/process groups are included: (**A**) natural hazards, (**B**) anthropogenic processes and (**C**) technological hazards/disasters. Arrows are used to illustrate interaction relationships, with both triggering relationships (thick block arrows with solid outlines) and relevant catalysing/impedance relationships (thin block arrows with dashed outlines). For clarity of communication, those catalysing/impedance relationships not of relevance to the specific example are not included. See **Figures 2** and **3** caption explanations for further details. Arrows within the example network of hazard interactions are labelled (**1**–**4**) and shaded dark blue to highlight the relevant pathway. This example shows a primary natural hazard triggering (**1**) a primary technological hazard, which in turn triggers (**2**) a primary anthropogenic process. The same primary natural hazard may trigger (**3**) a secondary natural hazard. This secondary natural hazard could then trigger (**4**) a primary technological hazard and (**5**) tertiary natural hazards.

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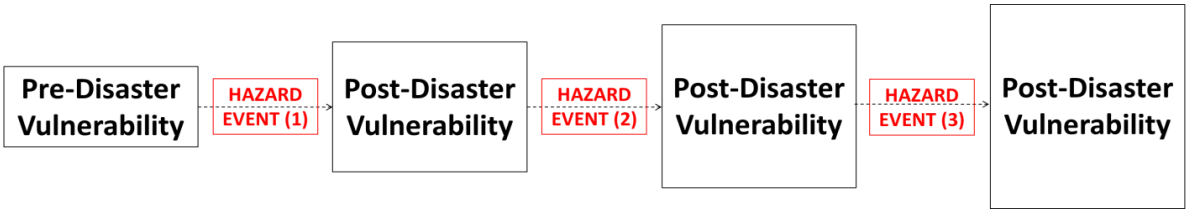

Figure 8. Example of vulnerability changes during a network of hazard interactions (cascade). A representation of changing vulnerability during a hazard cascade, where the magnitude of vulnerability is proportional to the size of the box. Following a disaster event, pressures on society, infrastructure and coping capacity are likely to be increased, and thus the vulnerability of a community and its systems/assets to further shocks or hazards may increase.