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Key Points:
- A wide range of interactions exist between natural hazards
- Interactions challenge the appropriateness of single hazard assessments
- Visualization frameworks are developed to communicate interaction information

Supporting Information:
- Readme
- Tables S1–S3 and Figures S1–S6

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Reviewing and visualizing the interactions of natural hazards

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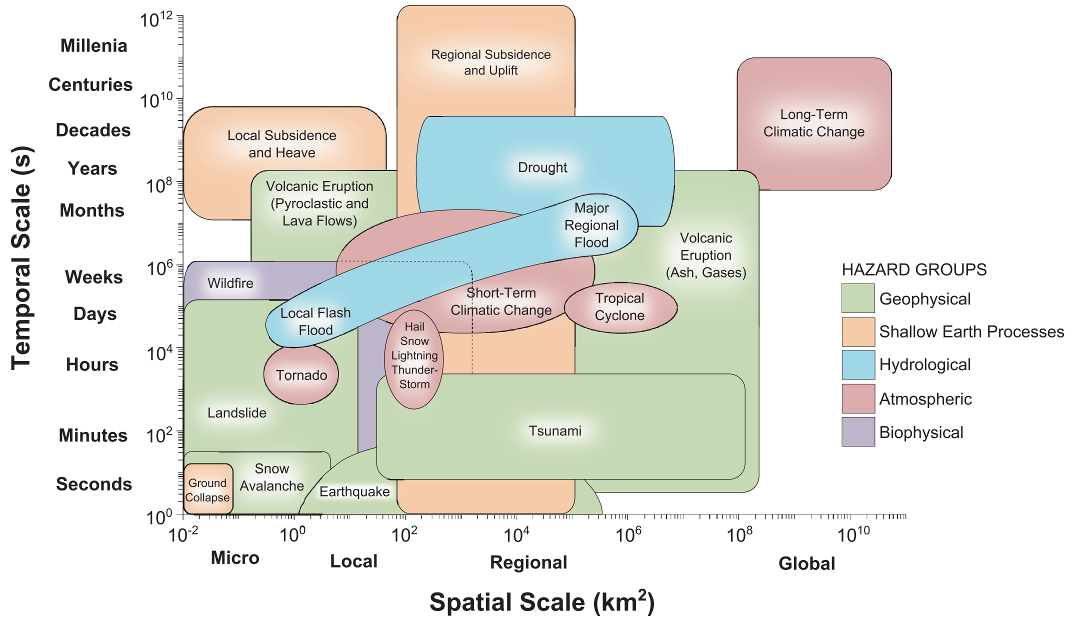
Abstract This paper presents a broad overview, characterization, and visualization of the interaction relationships between 21 natural hazards, drawn from six hazard groups (geophysical, hydrological, shallow Earth, atmospheric, biophysical, and space hazards). A synthesis is presented of the identified interaction relationships between these hazards, using an accessible visual format particularly suited to end users. Interactions considered are primarily those where a primary hazard triggers or increases the probability of secondary hazards occurring. In this paper we do the following: (i) identify, through a wide-ranging review of grey- and peer-review literature, 90 interactions; (ii) subdivide the interactions into three levels, based on how well we can characterize secondary hazards, given information about the primary hazard; (iii) determine the *spatial overlap* and *temporal likelihood* of the triggering relationships occurring; and (iv) examine the relationship between primary and secondary hazard intensities for each identified hazard interaction and group these into five possible categories. In this study we have synthesized, using accessible visualization techniques, large amounts of information drawn from many scientific disciplines. We outline the importance of constraining hazard interactions and reinforce the importance of a holistic (or multihazard) approach to natural hazard assessment. This approach allows those undertaking research into single hazards to place their work within the context of other hazards. It also communicates important aspects of hazard interactions, facilitating an effective analysis by those working on reducing and managing disaster risk within both the policy and practitioner communities.

1. Introduction

The term "natural hazards" encompasses numerous different physical phenomena, including earthquakes, tsunamis, landslides, floods, volcanic eruptions, severe storms, tornadoes, and many more [see *Alexander*, 1993; *Tobin and Montz*, 1997; *Smith and Petley*, 2009]. The key aims of this paper are to review the interactions between 21 different natural hazards, place these interactions into a visualization framework, and reinforce the importance of incorporating natural hazard interactions into a multihazard approach. Here we use the term *hazard* as defined by *UN-ISDR* [2005] to refer to a natural process or phenomenon that may have negative impacts on society. We also use the term *hazard interactions* to refer to the effect(s) of one hazard on another and the term *multihazards* to refer to all possible and relevant hazards, and their interactions, in a given spatial region and/or temporal period. The term *multihazard risk assessment*, including its history and various uses, will be discussed and described toward the end of this paper (section 7). In this introduction, we will first examine the spatial and temporal aspects of 16 natural hazards, then highlight the challenges of assuming that hazards can be treated as discrete and independent events, and finally summarize the paper's organization.

The spatial and temporal scales over which natural hazards impact upon the natural environment cover many orders of magnitude. Through a broad consultation of the literature, we have estimated the spatial scale (area that the hazard impacts) and the temporal scale (the time duration over which the hazard acts on the natural environment). In Figure 1, the spatial versus temporal scales over which 16 selected hazards act are presented, along with a summary of the literature consulted and synthesized to generate this figure. These hazards, many of which will be among the 21 natural hazards studied later in this paper, are divided into five hazard groups:

1. *Geophysical* (earthquake, tsunami, volcanic eruption, landslide, and snow avalanche).
2. *Hydrological* (flood and drought).
3. *Shallow Earth Processes* (regional subsidence and uplift, local subsidence and heave, and ground collapse).
4. *Atmospheric* (tropical cyclone, tornado, hail, snow, lightning and thunderstorm, long-term climatic change, and short-term climatic change).
5. *Biophysical* (wildfire).



Group	Hazard	References
Geophysical	Earthquake	*Dixon* [1991]; *Ilk et al.* [2005]; *Minster* [2013]
	Tsunami	*Chelton* [2001]; *Ilk et al.* [2005]
	Volcanic Eruption	*Dixon* [1991]; *Ilk et al.* [2005]
	Landslide	*Waugh* [2000]; *Malamud et al.* [2004]; *Winter et al.* [2005]
	Snow Avalanche	*Waugh* [2000]; *Winter et al.* [2005]; *Lemke et al.* [2007]
Hydrological	Flood	*Hirschboeck* [1988]
	Drought	*Edwards* [1999]
Shallow Earth Processes	Regional Subsidence and Uplift	---
	Local Subsidence and Heave	---
	Ground Collapse	*Cooper* [1998]
Atmospheric	Tropical Cyclone	*Edwards* [1999]; *Grenci and Nese* [2006]; *Laing and Evans* [2011]; *Hirschboeck* [1988]
	Tornado	*Grenci and Nese* [2006]; *Laing and Evans* [2011]
	Hail, Snow, Lightning, Thunder Storm	*Edwards* [1999]; *Grenci and Nese* [2006]; *Laing and Evans* [2011]; *Hirschboeck* [1988]
	Long-Term Climatic Change	*Edwards* [1999];*Chelton* [2001] ; *Laing and Evans* [2011]
	Short-Term Climatic Change	*Chelton* [2001]; *Laing and Evans* [2011]; *Hirschboeck* [1988]
Biophysical	Wildfire	*Malamud et al.* [1998]; *Hincks et al.* [2013]

Figure 1. Spatial and temporal scales of 16 selected natural hazards. Shown on logarithmic axes are the spatial and temporal scales over which the 16 natural hazards act. Here spatial scale refers to the area that the hazard impacts and temporal scale to the timescale that the single hazard acts upon the natural environment. Hazards are grouped into geophysical (green), hydrological (blue), shallow Earth processes (orange), atmospheric (red), and biophysical (purple). The figure is compiled from an analysis of various references (outlined within the figure) and the authors' judgment. For details and definitions of the included hazard groups and individual hazards, see section 2.4.

In Figure 1, lower bounds of 10^{-2} km^2 (spatially) and 10^0 s (temporally) are artificially set, and both the spatial and temporal axes are placed on logarithmic scales. Upper bounds are determined from our literature consultation. In Figure 1, it can be observed that natural hazards influence a range of spatial areas, from fractions of kilometers squared (what is termed here to be a micro scale) to hundreds of million kilometers squared (a global scale). The durations of these 16 natural hazards range from seconds to millennia. The natural hazards taken together, even with an artificial lower bound of 10^{-2} km^2 and 10^0 s, impact over 12 orders of magnitude both spatially (in area) and temporally.

There are distinct and broad ranges, spatially and temporally, over which each of the 16 different natural hazards presented in Figure 1 have an impact. This assessment of spatial and temporal scales does not consider interactions between different hazards, instead focusing on single hazards. For example, the temporal influence of an earthquake is suggested to be on the order of seconds to minutes, i.e., the duration of shaking for an individual earthquake. The subsequent earthquake aftershocks, triggering of landslides and the possible alteration of stresses within a slope so as to increase the susceptibility of that slope to future landslides, means that there may be an impact from the original earthquake that lasts for months or years after its initiation.

These observations, along with significant variations in terms of hazard frequency and return periods, measures of intensity and impact, and the measurement, scales, instrumentation, and field techniques required, make it a challenging process to compare the spatial and temporal scales of one hazard with another. These complexities mean that hazard and risk assessments often take a "single hazard" approach, in which the hazard potential or risk from one particular physical phenomenon is constrained [e.g., *Aoudia et al*., 2000; *Hsu et al*., 2011; *Wastl et al*., 2011]. Such approaches often treat hazards as isolated or independent phenomena. An Earth system sciences approach, however, indicates significant interactions between various component systems (such as the lithosphere, atmosphere, hydrosphere, and biosphere) and thus the inadequacy of always treating hazards as independent [*Kappes et al*., 2012]. This lack of a holistic approach can lead to the distortion of management priorities, increased vulnerability to other spatially relevant hazards, or an underestimation of risk [*Tobin and Montz*, 1997; *ARMONIA*, 2007; *Kappes et al*., 2010; *Budimir et al*., 2014; *Mignan et al*., 2014].

In the context of reviewing, classifying, and visualizing hazard interactions between a broad range of natural hazards, this paper is organized as follows: Section 2 presents key aspects of background information that highlight the relevance of hazard interactions, define different types of hazard interaction, and reviews past research into this topic. Section 3 presents the results of a systematic review to identify and visualize interactions between 21 different natural hazards. Section 4 discusses our ability to characterize secondary hazards in terms of location, timing, and magnitude, given information about the primary hazard. Section 5 then proceeds to classify the *spatial overlap* and *temporal likelihood* of each of the identified hazard-triggering interactions occurring, given that the primary hazard has already taken place. Section 6 presents an initial analysis of the relationship between the intensity of the primary hazard and the intensity of the secondary hazard. Further discussion, limitations, and conclusions are presented in section 7, including the integration of hazard interactions into a multihazard framework. In addition, we provide extensive supporting information in a spreadsheet: (i) six of the ten figures found in the text are provided in high resolution, (ii) four additional tables expanding on the main text, and (iii) a list of over 200 references to support the tables, with many additional case studies to those noted in the main text.

2. Hazard Interactions Background

As introduced in the previous section, identifying and constraining hazard interactions can help us to better understand the hazard potential faced by a region, and thus the overall risk. In this section we begin by outlining four case studies that demonstrate the need for this holistic understanding of hazard interactions (section 2.1), followed by a discussion of four types of hazard interaction (section 2.2), an overview of previous research into hazard interactions (section 2.3), a description of the six hazard groups and 21 individual hazards selected for this study (section 2.4), and the importance of visualization techniques for organizing and presenting a wide array of complex information (section 2.5).

2.1. Case Studies

Here, four diverse case studies from the 18th to the 21st century are presented, each highlighting a range of hazard types and interactions. The illustrative case studies we use are as follows:

1. *Japan* (1792, volcanic eruption, earthquake, landslide, and tsunami).
2. *USA* (1964, earthquake, landslides, tsunami, and flooding).
3. *Philippines* (1991, volcanic eruption, typhoon, and lahars).
4. *Guatemala* (2010, tropical storm, landslides, flooding, ground collapse, and volcanic eruption).

In the latter two, the 1991 Philippines and 2010 Guatemala case studies, the overall impact was increased by the simultaneous occurrence of two independent hazards. For these four case studies, we explore two types of hazard interactions: (i) a primary hazard triggering one or more secondary hazards, and (ii) a primary hazard increasing the probability of a secondary hazard. These secondary hazards can in turn trigger or increase the probability of further hazards to form a network of interacting hazards (similar to a domino or cascade system). Although in this section we limit our case study examples to just four, there are many other possible case studies involving different hazard types, some of which we present in sections 3–6 and in

Table S1 of the supporting information. We now discuss each of the four case studies in turn, before using them to provide a background to our method for classifying hazard interactions.

2.1.1. Mount Unzen and Mount Mayuyama, Japan, 1792

In the first case study, the Japanese volcano Mount Unzen erupted in 1792, triggering the collapse of the adjacent volcano, Mount Mayuyama [*Yoshida and Sugai*, 2007]. This collapse, in the form of a large landslide, resulted in large volumes of material being deposited in a nearby ocean, which in turn triggered a tsunami [*Yoshida and Sugai*, 2007]. The tsunami crossed the ocean and devastated communities on the opposite Japanese shoreline, killing more than 15,000 people [*Takarada and Melendez*, 2006].

2.1.2. Alaska, USA, 1964

In the second case study, an earthquake with a moment magnitude $M_w = 9.2$ [*Suleimani et al.*, 2009] occurred in the Prince William Sound region of Alaska in 1964. This earthquake triggered both submarine and subaerial landslides and a tsunami [*Eckel*, 1970; *Suleimani et al.*, 2009], and both regional uplift (or ground heave) and regional subsidence [*Eckel*, 1970]. These secondary hazards also triggered or increased the probability of further tertiary hazards, such that the submarine landslides (secondary) triggered further tsunami waves (tertiary) [*Suleimani et al.*, 2009], and regional subsidence (secondary) resulted in (and continues to result in) an increased probability of flooding (tertiary). Finally, the subsidence, together with the various stages of tsunami waves, caused serious flooding, leading to the loss of many lives [*Eckel*, 1970].

2.1.3. Mount Pinatubo, Philippines, 1991

In the third case study, Mount Pinatubo in the Philippines, an active stratovolcano, erupted in June 1991. Volcanic activity gradually increased at the volcano, with the eruption reaching its climax between 15 and 16 June 1991 [*Self et al.*, 1996]. This explosive eruption triggered many small earthquakes, both before and during the eruption [*White*, 1996; *Harlow et al.*, 1996]. These earthquakes were likely triggered by subterranean magma propagation [*Jones et al.*, 2001]. The volcanic eruption also triggered pyroclastic density currents and ejected significant quantities of ash, debris, gases, and aerosols into the atmosphere and surrounding environment [*Mori et al.*, 1996; *Antuña et al.*, 1998; *Scott et al.*, 1999]. The volcanic eruption resulted in the ejection of 17 megatons of sulfur dioxide [*Self et al.*, 1996] and ash into the stratosphere. Its rapid spread around the globe over the following three weeks is believed to have resulted in climatic consequences, including both warming of the lower stratosphere and global cooling effects [*Self et al.*, 1996; *Robock*, 2000].

The eruption of Mount Pinatubo in 1991 coincided with Typhoon Yunya [*Umbal and Rodolfo*, 1996; *Scott et al.*, 1999], which brought about intense rainfall. The combination of this rainfall and thick ash deposits triggered lahars [*Umbal and Rodolfo*, 1996; *Self*, 2006] and structural failures [*Chester*, 1993] due to the additional mass exerted by the wet ash. Lahars blocked the Mapanuepe River, causing flooding of the Mapanuepe Valley [*Umbal and Rodolfo*, 1996]. The volcanic blast also created a caldera at the summit of Mount Pinatubo, which filled with water during the seasonal rains [*Stimac et al.*, 2004]. This water and the deposited pyroclastic material continued to pose a threat to local communities after the eruption had finished, due to the potential for flooding, lahars, and landslide events [*Pierson et al.*, 1992].

2.1.4. Guatemala, 2010

In the final case study, Tropical Storm Agatha hit the Pacific coastline of Guatemala on 29 May 2010. The storm brought strong winds and torrential rains [*Stewart*, 2011; *Stewart and Cangialosi*, 2012]. This heavy rain triggered mass movements [*Wardman et al.*, 2010], flooding across Guatemala City and contributed to a ground collapse event. This collapse occurred due to a pseudo-piping phenomenon in the Quaternary volcanic ash and pyroclastic density current deposits underlying Guatemala City [*Waltham*, 2008; *Stewart*, 2011]. In this pseudo-piping process, subterranean water washes out the finer material within the pyroclastic deposits, followed by the coarser material eventually being eroded out and the formation of underground voids. The roofs of these subterranean voids can then collapse, resulting in ground surface deformation.

The effects of Tropical Storm Agatha were exacerbated by the near-simultaneous eruption of Pacaya, a complex volcano located 30 km southwest of Guatemala City. Pacaya erupted 2 days prior to the onset of Tropical Storm Agatha on 27 May 2010 [*Wardman et al.*, 2010]. Ash and debris, ejected from Pacaya, covered much of Guatemala City. Reports suggested that the ash blocked parts of the drainage system, increasing the intensity of flooding during Tropical Storm Agatha [*UN*, 2010]. Furthermore, the combination of fresh ash, volcanic debris, and heavy rain, generated lahars and structural collapse [*Wardman et al.*, 2010; *Daniell*, 2011].

2.2. Hazard Interaction Types

Building on the four case studies just discussed (section 2.1) and the wider literature, multiple hazard interactions can be identified, which we divide into four categories:

1. Interactions where a hazard is triggered.
2. Interactions where the probability of a hazard in increased.
3. Interactions where the probability of a hazard is decreased.
4. Events involving the spatial and temporal coincidence of natural hazards.

Although this study primarily focuses on the first two of these hazard interactions, each is briefly discussed in turn.

2.2.1. Interactions Where a Hazard Is Triggered

Any natural hazard might trigger zero, one, or more secondary natural hazards [*Tarvainen et al*., 2006; *Han et al*., 2007; *De Pippo et al*., 2008; *Marzocchi et al*., 2009; *Kappes et al*., 2010; *van Westen et al*., 2014], where the secondary natural hazard might be of the same type as the primary hazard or different. For example, an earthquake, a rainfall event, a snowmelt, or the erosion and undercutting of slopes during a flooding event, could each trigger multiple landslides. These secondary natural hazards could then potentially trigger further natural hazards, thus resulting in a network of interacting hazards, which can dramatically escalate the accumulated hazard potential in a given region. For example, in the Alaskan case study (section 2.1.2) a $M_w = 9.2$ earthquake triggered multiple secondary hazards, which in turn triggered further hazards. The earthquake triggered regional subsidence and both subaerial and submarine landslides [*Suleimani et al*., 2009]. These landslides in turn triggered tsunami waves, with water inundating the land surface causing flooding, including in areas subjected to the aforementioned regional subsidence.

The simultaneous occurrence of two (or more) hazards can also trigger secondary hazards. For example, the occurrence of lightning during a drought could result in the triggering of wildfires. Furthermore, it is possible that feedback mechanisms can be established, where the triggering of a secondary hazard exacerbates the primary hazard, therefore triggering further episodes of the secondary hazard. An example from Nepal [*Marston et al*., 1996] discusses the undercutting of slopes by river systems causing channel aggradation. This aggradation can trigger greater undercutting, thus developing a positive feedback or cyclic triggering.

2.2.2. Interactions Where the Probability of a Hazard Is Increased

Kappes et al. [2010] describe the effects of one hazard altering the disposition of another. *Kappes et al*. [2012] further describe how one hazard may change environmental parameters so as to alter the frequency or magnitude of another hazard. In the context of our study, these interactions are categorized as the primary hazard changing one or more environmental parameters so as to drive the system toward a specific threshold or "tipping" point. In some situations, a primary hazard may not directly trigger a secondary natural hazard, instead it changes some aspect of the natural environment in order to increase the probability that another hazard will occur. For example, vegetation promotes slope stability by increasing slope shear strength. In the event of a wildfire, vegetation is destroyed and thus the shear strength of the slope is reduced. While this may not be enough to trigger a landslide, it will increase vulnerability of the slope to landslides in the event of a trigger, such as rainfall, snowmelt, or an earthquake [*Cannon et al*., 2008, 2010]. Wildfires therefore act to increase the probability of landslides occurring. A second example is the relationship between regional subsidence and flooding. While subsidence may not directly trigger flooding, it would increase the probability of it occurring. In the case study from Alaska (section 2.1.2), co-seismic regional subsidence (directly triggered by the 1964 $M_w = 9.2$ earthquake) increased the susceptibility of the land surface to subsequent flooding events [*Eckel*, 1970].

2.2.3. Interactions Where the Probability of a Hazard Is Decreased

Although not widely discussed in the context of hazard assessments, it is possible that the occurrence of a hazard could reduce the risk of other hazards. As previously outlined, natural hazards impact upon the natural environment and in doing so can change one or more environmental parameters. These changes could result in the risk of a particular secondary hazard being reduced. For example, a heavy rainfall event could increase surface moisture content and reduce the depth to the water table. This would decrease the probability of wildfires in the immediate aftermath. A further example can be seen in the relationship between long-term global cooling and volcanism. Long-term global cooling results in the greater accumulation of continental ice. If the explosive phase of volcanic eruptions takes place below the ice sheet, the hazard from ash fall and pyroclastic debris is likely to be reduced, as is the injection of sulfur dioxide into the stratosphere [*Tuffen*, 2010].

In some cases, a few smaller occurrences of a hazard event could reduce the probability of a larger event. The theoretical basis of prescribed burning, for example, is that smaller human-made fires are initiated which might reduce the risk of a larger wildfire by consuming available fuel [*Parsons et al*., 1986; *Fernandes and Botelho*, 2003]. Using similar logic, it is feasible that several smaller wildfires over a given area could reduce the risk of a larger wildfire by not allowing large amounts of fuel to build up. In an example described by *Parsons* [1976] in Sierra Nevada (California), the exclusion of smaller fires resulted in large amounts of mature wood building up which increased the likelihood of a fire of greater intensity and seriousness. Prescribed burning, however, is a controversial method as to whether or not it is effective in reducing the risk of large wildfires [*Fernandes and Botelho*, 2003].

While these primary and secondary hazard interactions may be of importance for the generation of techniques to minimize and manage (secondary) hazard events, they are not considered within the remainder of this study. An understanding of interactions that decrease the probability of an event could form part of a hazard mitigation strategy, but they are unlikely to be included within an overall risk assessment and scenario planning for interacting hazards (also called multihazard interactions, see section 7), where a conservative approach would often be implemented.

2.2.4. Spatiotemporal Coincidence of Hazards

In the event of more than one hazard occurring in the same general location and within a short timeframe, the risk and impacts may be different than the sum of their parts [*Tarvainen et al*., 2006; *Han et al*., 2007]. The precise extent of the location and timeframe depend on what is being considered and the magnitude of the events. When considering spatial overlap, the type of hazard being considered will influence whether the scale of interest is a city, country or intercontinental range. This is also likely to be affected by the event magnitude. For example, a large tsunami could have an influence over multiple countries and continents, whereas a small landslide is likely to only influence a district of a town or city. In considering the role of temporal overlap, this could be the time in which the hazard event occurs (i.e., the actual shaking of an earthquake) but is more likely to also relate to the impacts of the hazard event. For example, the time taken for infrastructure to be repaired or rebuilt, or the time taken for a population to recover from an earlier event. *Alexander* [1993] discusses aspects of both space and time within disasters, highlighting the various scales of interest that we may want to consider. It is important to recognize within this context that there could be a range of possible definitions of "before, during, and after" when considering the occurrence of a hazard or disaster event. This has implications for our understanding of this interaction type. If there are differences in how the "during" timeframe of a hazard event/disaster is defined, this is likely to impact upon the ways in which temporal overlap are considered. Furthermore, the defining of "before, during, and after" also impacts the mitigation strategies followed by disaster risk reduction practitioners.

Spatiotemporal coincidence can be applicable to triggered hazards (where the primary and secondary hazards occur within a short timeframe of each other) or independent hazards occurring within a relevant timeframe and with appropriate spatial overlap. In the event of two or more hazards occurring in the same location, physical infrastructure and human populations may be placed under greater stress than if the hazards had occurred in different locations. The impact of one hazard on the physical infrastructure of a location could increase its vulnerability to secondary or future hazard events, therefore potentially amplifying the effects of a secondary or future hazard. For example, an earthquake may weaken housing making it more susceptible to collapse in the event of a further earthquake if repairs are not completed. The impact of one disaster on a population could also increase their vulnerability for a significant period of time afterward, thus exacerbating events in the near and distant future. For example, injuries or mental health problems caused by an earthquake, or the spread of disease and loss of earning capacity in the aftermath, may limit the ability of people to evacuate to a safe place in the event of a following hazard event. It is also possible that spatiotemporal coincidence may not increase the impacts or risk beyond the sum of components. For example, in the merging of two storm systems, the overall impact may be more than the impact of one storm, but less than the sum of the impacts of two separate storms.

Examples of the spatiotemporal coincidence of hazards can be seen in the case studies from the Philippines (section 2.1.3) and Guatemala (section 2.1.4). The eruption of Mount Pinatubo in the Philippines in 1991 coincided with Typhoon Yunya [*Umbal and Rodolfo*, 1996; *Scott et al*., 1999], which produced intense rainfall. The combination of rainfall and thick ash deposits triggered both lahars [*Umbal and Rodolfo*, 1996; *Self*, 2006] and structural failures due to the additional mass exerted by the wet ash [*Chester*, 1993]. The spatial and temporal coincidence of these two hazards resulted in greater hazard potential than the component sum of the two hazards. In the case study from Guatemala in 2010, the spatiotemporal coincidence of the eruption of Volcano Pacaya and Tropical Storm Agatha also resulted in greater hazard potential.

2.2.5. Some Additional Points

In sections 2.2.1–2.2.4 we outlined the four main types of hazard interactions that may occur. In assessing the types of hazard interaction that are possible, we note two other important considerations:

1. *The importance of anthropogenic processes*. Our discussion of interaction types has focused on interactions between natural hazards, but we also recognize the importance of anthropogenic processes. Anthropogenic processes could trigger or increase the probability of a hazard event (e.g., groundwater abstraction triggering regional subsidence). Alternatively, a natural hazard may impact on infrastructure so as to trigger or increase the probability of a further hazard (e.g., an earthquake damaging a gas pipeline and triggering major urban fires). These are both important situations for future consideration; however, the work presented in this paper focuses on the interactions between natural hazards.
2. *Timescales*. It is important to consider timescales of interest when analyzing sequences or chains of hazard events. As we have discussed above, the importance or impact of the spatial coincidence of hazard events may be strongly dependent on the time required for repair, recovery, and reconstruction. Timescales of interest may also influence whether an event increases or decreases the likelihood of a secondary event. For example, while heavy rain may reduce the likelihood of forest fires in the short term, it could increase the fuel load and subsequent fire risk in the long term.

We now discuss past research that has been done on hazard interactions.

2.3. Past Research on Hazard Interactions

The existence and importance of hazard interactions has been widely commented on [*ARMONIA*, 2007; *Han et al*., 2007; *Kappes et al*., 2010, 2012; *Government Office for Science* (UK), 2012; *Mignan et al*., 2014]. There are, however, very few detailed reviews or broad characterizations of hazard interactions within the scientific literature. Many examples exist of particular case studies where it is noted that one hazard has triggered or increased/decreased the probability of another hazard (such as those presented in section 2.1). There have also been a number of "bottom-up" studies (summarized in Table 1 and discussed in detail below) of interacting hazards, focusing on specific regions, landscapes, or end users.

The eight studies set out in Table 1 suggest three broad qualitative and quantitative approaches to constrain and visualize hazard interactions:

1. *Qualitative descriptions and classifications* [*Han et al*., 2007].
2. *Hazard matrices and diagrams* [*Tarvainen et al*., 2006; *De Pippo et al*., 2008; *Kappes et al*., 2010; *van Westen et al*., 2014].
3. *Probability/scenario trees* [*Neri et al*., 2008; *Marzocchi et al*., 2009; *Neri et al*., 2013].

We now explore each of these three types of qualitative and quantitative approaches.

2.3.1. Qualitative Descriptions and Classifications

Han et al. [2007] defined and classified different hazard chains by grouping them into a number of categories. These categories included the following:

1. *Spatial and/or temporal chains* (a series of events that are triggered by the same stimuli or located in the same geographical or geotectonic setting).
2. *Endogenic processes* (with stimuli from below the surface of the Earth).
3. *Exogenic processes* (with stimuli from above the surface of the Earth).
4. *Human-induced chains*.
5. *Spatial/temporal coincidence of independent hazards*.

The authors then examined examples of each of these hazard chains in China, limiting their analysis to four hazard stimuli (or primary hazards): earthquakes, rainstorms, rapid snowmelt, and human activity. Their analysis of triggered (or secondary hazards) was limited to three hazards: landslides (which includes debris flows), flooding, and ground failure. Examples of the classifications (1 to 5) described above were then discussed (e.g., an endogenic process would be an earthquake-triggered landslide, an exogenic process would be a rainfall-triggered landslide).

Table 1. Approaches for Assessing Natural Hazard Interactions[a]

Type	Authors	Location	Hazards/Processes Considered	Interaction Classifications	Further Notes
Qualitative descriptions and classifications	*Han et al.* [2007]	General (case studies from China)	PRIMARY: Earthquake, rainstorm, rapid snowmelt, human activity SECONDARY: Landslides, debris flow activity, flooding, ground failure	(1) Spatial and/or temporal chains (2) Endogenic processes (3) Exogenic processes (4) Human-induced chains (5) Spatial/temporal coincidence of independent hazards	
Matrices and diagrams	*Tarvainen et al.* [2006]	Europe	NATURAL: Avalanche, drought, earthquake, extreme temperature, flood, forest fire, landslide, storm surge, tsunami, volcanic eruption, winter storm TECHNOLOGICAL: Air traffic accident, chemical plant, nuclear power plant, oil processing/ transport/storage	One hazard influencing another hazard, based on real physical processes from casual correlation	Binary matrix examining interactions
	De Pippo et al. [2008]	Northern Campania, Italy	Shoreline erosion, riverine flooding, surge, landslide, seismicity and volcanism, man-made structures	One hazard influencing another hazard	Descriptive matrix to describe interactions
	Kappes et al. [2010]	Barcelonnette, Southern French Alps	Avalanche, debris flow, rock fall, landslide, flood, heavy rainfall, earthquake	(1) Triggering relationships (2) One hazard changing the disposition or general setting that favors a specific hazard process	Binary matrix and descriptive matrix examining interactions
	van Westen et al. [2014]	European Mountainous Environments	TRIGGERING FACTORS: Earthquake, meteorological extremes SECONDARY HAZARDS: Mass movement, snow avalanche, forest fire, land degradation, flooding, seiche, technological hazard	(1) Hazards triggered simultaneously (coupled) (2) Hazards causing another hazard	Possible interactions visualized in network diagram form
Probability/ scenario trees	*Neri et al.* [2008]	Vesuvius, Italy	Volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, landslide, lahar, mudslide, heavy rain	*Not Stated*	Probability tree for a specific volcanic setting
	Marzocchi et al. [2009]	NA	Volcanic eruption, fire, contaminant migration	Triggering effects and/or cascade adverse events	Hypothetical example
	Neri et al. [2013]	Kanlaon, Philippines	Volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, lahar/mudslide	*Not Stated*	Probability tree for a specific volcanic setting

[a]A range of approaches for assessing natural hazard interactions have been utilized, including qualitative descriptions and classifications, matrices, and diagrams, and probability/scenario trees (NA = Not applicable).

Other examples of a discursive methodology or review can be found within the case studies outlined in sections 2.1 and 3.3. These examples of specific interaction events, where one hazard has triggered or increased the probability of another hazard, use a discursive methodology to describe the relationship between primary and secondary hazards.

2.3.2. Hazard Matrices and Diagrams

A hazard matrix approach examines a range of spatially relevant hazards and then determines which of these hazards could trigger or increase the probability of other hazards. It offers a semi-quantitative and structured approach to examine and visualize hazard interactions. Three major studies considering such an approach are as follows:

1. *Tarvainen et al*. [2006] set out a binary matrix of 11 natural and four technological hazards that they deemed to be spatially relevant to areas within Europe.
2. *De Pippo et al*. [2008] used a descriptive matrix of six hazard types identified to be spatially relevant in the Northern Campanian coastal zone of Italy.
3. *Kappes et al*. [2010] proposed a matrix with a small-scale study of seven hazards relevant within an Alpine region.

Each author examined and visualized hazard interactions in a different way. Both binary approaches [*Tarvainen et al*., 2006; *Kappes et al*., 2010] and descriptive approaches [*De Pippo et al*., 2008; *Kappes et al*., 2010] were used to outline the influence of one hazard upon another. Both *Tarvainen et al*. [2006] and *De Pippo et al*. [2008] include all relationships (where one hazard is shown to have an influence over another) in the same matrix. However, *Kappes et al*. [2010] propose two matrices: a binary matrix for triggering relationships and a descriptive matrix to outline how a hazard may change the disposition or general setting that favors a specific hazard process. This descriptive matrix can be thought of as the identification of changes to the physical environment by one hazard, which may increase the probability of a secondary hazard.

In addition to matrices, hazard diagrams have been used. For example, in the work of *van Westen et al*. [2014], alpine mountainous environment hazards were grouped by (i) triggering factors (earthquakes, meteorological extremes, and "contributing factors") and (ii) possible secondary hazards. A distinction is made between hazards triggered simultaneously (termed *coupled* hazards) and hazards causing another hazard.

2.3.3. Probability/Scenario Trees

The development of more quantitative approaches to assessing hazard interactions includes the use of probability or scenario trees. *Neri et al*. [2008] compiled a probability tree for possible future scenarios at the volcano Vesuvius. This probability tree included possible eruption styles and the secondary hazards associated with them. The authors used both quantitative processes and expert elicitation to calculate a range of conditional probabilities. In another study, *Marzocchi et al*. [2009] also describe the identification of different scenarios and the quantification of these scenarios using probability trees. While they did not develop this quantitative approach for a range of hazard combinations found within a town or city, they demonstrated a methodology that could be used if sufficient information was available to quantify key parameters. In a third study, *Neri et al*. [2013] used a probability/scenario tree for the Kanlaon volcano (Philippines), showing the types of hazardous events in this location and estimates of their frequencies. It is worth noting that all three of these examples are for volcanic areas and associated secondary hazards.

Quantifying the range of parameters of interest, together with all possible outcomes, is a complex process. It requires significant types and amounts of data. Assessing and quantifying the uncertainties associated with each parameter and possible outcomes is a difficult process. The example of *Neri et al*. [2008], however, demonstrates that this approach can be utilized, using expert elicitation to help constrain parameters where necessary.

Here we aim to build on the contributions discussed above through the development of a broad conceptual framework for the study of hazard interactions. While there have been a series of "bottom-up" reviews, a gap exists in terms of a general, "top-down" review and framework for the understanding of hazard interactions and their importance in the natural environment. This gap has a number of implications, including the absence of standard terminology. This is highlighted by *Kappes et al*. [2012], who found that while multiple papers referred to interactions between natural hazards, a diverse and extensive range of terminology is used (e.g., chains, cascades, domino effects, interconnections, interrelations, and triggering). An absence of a standard approach to considering multihazard interactions has also resulted in an emphasis on certain hazard types within local scale studies. A full range of hazard interactions is rarely being applied within case studies. Here we aim to fill partially this gap, proposing a conceptual framework that will assist in the progression of research into hazard interactions, with the overall aim that these interactions are more widely considered and integrated within hazard assessments.

2.4. Hazards and Hazard Types

In this study, we examine 21 different natural hazards (including many of those examined in Figure 1). Table 2 describes and defines each of these hazards and the processes associated with them. For example, a volcanic eruption includes a combination of processes, such as gas and aerosol emission, tephra and ash ejection, pyroclastic density currents and lava flows. These 21 hazards have been sorted into six hazard groups: geophysical, hydrological, shallow Earth processes, atmospheric, biophysical and space (or celestial). These groups are proposed based on the overriding physical nature of the hazard, but alternative groupings could also be considered (e.g., based on the type of damage they produce, the speed of onset, or the frequency).

Although this list of natural hazards presents 21 of the most common and important hazards, it is recognized not to be an exhaustive list. Additional hazards and broader systems could be included within future work, including additional natural and environmental hazards (e.g., disease and ground-based volcanic gases), anthropogenic hazards (e.g., over-abstraction of groundwater, desertification, deforestation, and mining subsidence), and technological hazards (e.g., nuclear meltdown, dam failure, power failure, and communications failure).

Most hazards within our study could also be divided into subcategories. For example, landslides could be subdivided into rockfalls, rotational and translational slides, debris flows, lahars and soil-creep; floods into flash floods, fluvial floods, rural ponding, urban flooding, and coastal flooding. For the purposes of this study, it was decided that the range of hazards set out in Table 2 would generate results applicable across multiple types of regimes (e.g., tectonic, climatic, and hydrologic). The further development and extension of this research, including the incorporation of additional hazards, is discussed in section 7.

2.5. Visualization of Information

As noted by *Kappes et al*. [2012], the effective visualization of large amounts of diverse information is a challenging task. It should collate information from multiple disciplines and represent this in an effective way that allows multiple stakeholders to interpret the information in a clear and easy manner. Examples of possible visualization methods can be seen in the studies reviewed in section 2.3, including matrices and scenario trees. A matrix [e.g., *Tarvainen et al*., 2006; *De Pippo et al*., 2008; *Kappes et al*., 2010] is a simple way of representing information about multiple different hazards, with either symbols or text used to outline the existence of interaction relationships. There are advantages and disadvantages to both symbols and text, with the former giving ease and speed of access to basic information by multiple stakeholders and the latter giving greater depth to the available information at the potential loss of lucidity. A scenario tree [e.g., *Marzocchi et al*., 2009] can be used to demonstrate possible interactions and networks of interactions in an effective manner. Scenario trees are useful in representing multiple hierarchies of information and situations where secondary hazards trigger tertiary hazards, although they can rapidly become complicated, making it difficult to extract the required information.

Effective visualization within the context of the study presented here means the successful communication of complex information to multiple stakeholders, from multiple disciplinary backgrounds. While information can be successfully presented in text format, a carefully constructed figure can present large amounts of information in a simpler and more accessible manner, crossing disciplinary boundaries with greater ease [*Mol*, 2011]. Careful consideration of factors such as the type of figure, the color choices, the order in which information is presented, and the symbol choice have an important role in controlling how effectively information is communicated.

In this paper, we develop and present two key ways of visualizing hazard interaction relationships, utilizing both matrices and network diagrams. In the first form of visualization, a series of matrices are presented in sections 3–6, where each matrix examines and constrains interactions between the 21 natural hazards set out in Table 2. The matrices display each of these hazards as the primary hazard or stimuli (the initial hazard that triggers or increases the probability of another hazard occurring) on the vertical axis and as the secondary hazard or response (the triggered hazard or the hazard of which the probability of occurrence has been increased) on the horizontal axis. The second form of visualization (section 3.4), network diagrams, displays each of the 21 hazards as a node, using color and line pattern to display different relationships.

Table 2. Natural Hazards and Natural Hazard Groups Used in This Paper[a]

Hazard Group	Hazard	Code	Definition	Component Hazards (Where Applicable)
Geophysical	Earthquake	**EQ**	The sudden release of stored elastic energy in the Earth's lithosphere, caused by its abrupt movement or fracturing along zones of preexisting geological weakness, and resulting in the generation of seismic waves [*Smith and Petley*, 2009].	Ground shaking, ground rupture and liquefaction.
	Tsunami	**TS**	The displacement of a significant volume of water, generating a series of waves with large wavelengths and low amplitudes [*Alexander*, 1993]. As the waves approach shallow water, their amplitude increases through wave shoaling.	
	Volcanic eruption	**VO**	The subterranean movement of magma and its eruption and ejection from volcanic systems under the influence of its confining pressure and superheated steam and gases [*Alexander*, 1993], together with associated tephra, ash, and gas.	Gas and aerosol emission, ash and tephra ejection, pyroclastic and lava flows.
	Landslide	**LA**	The downslope displacement of surface materials (predominantly rock and soil) under gravitational forces [*Smith and Petley*, 2009].	Rockfall, rotational and translational slide, debris flow, lahar and soil creep.
	Snow avalanche	**AV**	The downslope displacement of surface materials (predominantly ice and snow) under gravitational forces [*Smith and Petley*, 2009].	
Hydrological	Flood	**FL**	The inundation of typically dry land with water.	Flash flood, fluvial flood, rural ponding, urban flood, coastal flooding, storm surge, jökulhlaups, glacial lake bursts.
	Drought	**DR**	A prolonged period with lower than expected precipitation [*Smith and Petley*, 2009] resulting in a serious hydrological imbalance [*Alexander*, 1993] or the removal of once existent and persistent water through poor agricultural practice or water diversion.	Meteorological drought, agricultural drought, hydrological drought.
Shallow Earth processes [adapted from *Hunt*, 2005]	Regional subsidence	**RS**	The sudden or gradual, downward vertical movement of the ground surface over a regional spatial extent.	Tectonic subsidence.
	Ground collapse	**GC**	The rapid, downward vertical movement of the ground surface into a void.	Karst and evaporite collapse, piping, metastable soils.
	Soil (local) subsidence	**SS**	The gradual, downward vertical movement of the ground surface over a localized spatial extent.	Soil shrinkage, natural consolidation and settlement.
	Ground heave	**GH**	The sudden or gradual, upward vertical movement of the ground surface.	Tectonic uplift, expansion (swelling) of soils and rocks.
Atmospheric	Storm	**ST**	A significant perturbation of the atmospheric system, often involving heavy precipitation and violent winds.	Tropical cyclone, hurricane, typhoon, midlatitude storm.
	Tornado	**TO**	A violently rotating column of air pendant (normally) from a cumulonimbus cloud and in contact with the surface of the Earth [*Alexander*, 1993].	
	Hailstorm	**HA**	A significant perturbation of the atmospheric system, in which strong updraughts occur within convective storms where there is an ample supply of supercooled water droplets, resulting in heavy precipitation of hailstones when they have sufficient mass to leave the atmospheric system [*Alexander*, 1993].	
	Snowstorm	**SN**	A significant perturbation of the atmospheric system, with heavy precipitation of snow.	
	Lightning	**LN**	The atmospheric discharge of static electricity, caused when the resistance of the intervening	

Table 2. (continued)

Hazard Group	Hazard	Code	Definition	Component Hazards (Where Applicable)
			air between areas of positive and negative charge is overcome [*Alexander*, 1993].	
	Extreme temperatures (Heat)	**ET (H)**	A prolonged period of temperatures above the normal average for that period of time (either short or long term, local, regional, or global).	Heat waves, climatic change.
	Extreme temperatures (Cold)	**ET (C)**	A prolonged period of temperatures below the normal average for that period of time (either short or long term, local, regional, or global).	Cold waves, climatic change.
Biophysical	Wildfires	**WF**	An uncontrolled fire fuelled by natural vegetation [*Smith and Petley*, 2009].	
Space/Celestial	Geomagnetic storms	**GS**	A perturbation of the Earth's magnetosphere because of changes in space weather, i.e., the intensity of solar wind.	
	Impact events	**IM**	The impact of a celestial body with the Earth's surface.	Asteroid, meteorite.

[a]An outline of six hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical and space/celestial). These hazard groups contain 21 different natural hazards, with the codes used in this paper noted. Each natural hazard is defined, and the component hazards outlined.

Within each visualization, careful attention was paid to appropriate and constructive visualization [e.g., *Bostrom et al*., 2008], in order to maximize the range of end-users, improve their experience when using these visualizations and allow for straightforward interpretation of information [*Kappes et al*., 2012]. The use of complementary colors, symbols, and shapes has enabled a series of intuitive and simple-to-understand visualizations that synthesize information drawn from many scientific disciplines. It is anticipated that the matrices (sections 3–6) in particular offer relevant information to a variety of end users, including those working on hazard assessment, disaster risk reduction, and disaster management.

3. The Existence of Hazard Interactions

An extensive review of the available literature was undertaken in order to identify and constrain interaction relationships between the natural hazards outlined in Table 2. This section begins by outlining the review procedures adopted within this research (section 3.1), before setting out the results in a matrix form (section 3.2), discussing mechanisms and case studies (section 3.3) and analyzing hazard type linkages (section 3.4).

3.1. Review Procedures

Boaz et al. [2002] suggest seven necessary criteria to undertake a systematic review providing a guideline for establishing a wide-ranging, critical analysis and review of the literature. Table 3 describes each of these criteria and notes how the methodology we applied in this paper fulfilled them. Our review includes both those references cited at the end of this paper and over 200 references in Table S1 of the supporting information.

3.2. Hazard Interaction Matrix

Through our systematic review, for each of the 21 hazards chosen for this study we identified multiple hazard interactions. These are presented in a matrix form in Figure 2. This 21 × 21 matrix identifies 90 natural hazard interactions (out of a possible 441), including both triggered relationships and relationships where one hazard increases the probability of another. We have used a two-letter code for the 21 different natural hazards, as given in the legend, e.g., **EQ** = earthquake, **IM** = impact events. The vertical axis of the matrix in Figure 2 displays the primary hazards (rows 1 to 21, **EQ** to **IM**), i.e., the initial hazard that triggers or changes 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**), i.e., the triggered hazard, or the hazard for which the probability of occurrence has been increased. As mentioned, the 21 hazard types have been divided into six hazard groups, identifiable with different colors (geophysical = green, hydrological = blue, shallow Earth processes = orange, atmospheric = red, biophysical = purple, and space/celestial = grey) as indicated in the legend. 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 one

Table 3. Criteria for a Systematic Review[a]

Criteria [From *Boaz et al.*, 2002]	How Criteria Met Within Our Methodology
Protocols must be used to guide the process	Our procedure examined both discussion of interaction mechanisms and reported case studies (section 3.3) to determine whether an interaction event was included within our analysis. Special care was taken to assess evidence reliability where case studies were limited or recorded in research/reports more than 50 years old.
Focused on answering a specific question	Two very specific questions were posed within this study: (i) Does the primary hazard trigger the secondary hazard? and (ii) Does the primary hazard increase the probability of the secondary hazard?
Seeks to identify as much of the relevant research as possible	A wide literature base was used, including peer-reviewed literature, grey literature (technical and government reports), and media articles. Large literature databases were used to enable the identification of as much relevant research as possible.
Appraises the quality of the research included in the review	Quality approval was monitored through the cross referencing of case studies. Multiple case studies relating to a hazard interaction provided a stronger evidence base for the existence of the hazard interaction. Where very few case studies could be found, the reliability of these was scrutinized to see whether its inclusion could be justified. Controversial interactions were outlined in the matrix footnotes.
Synthesizes the research findings in the included studies	Findings were synthesized and presented in the matrix form, with care being taken to present the information in an accessible format, suitable for academics, policy makers, and practitioners, including both specialists and nonspecialists.
Aims to be as objective as possible about research to remove potential bias	Objectivity was promoted through the specific nature of the research questions and predetermined protocols. An assessment of potential sources of bias was undertaken and measures identified to reduce or eliminate these.
Updated in order to remain relevant	The results of this review can be regularly updated as new information becomes apparent.

[a]Key review criteria and a qualitative description of how we met these criteria in reviewing the range of hazard interactions within this study.

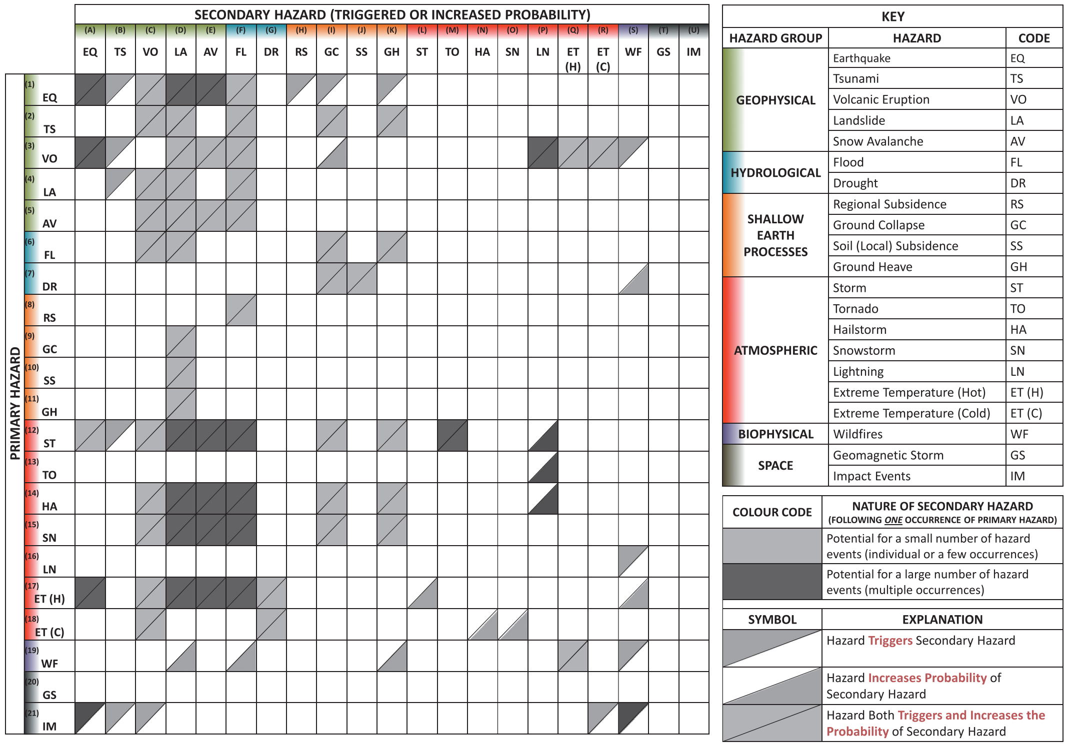
primary hazard-secondary hazard coupling. Of the 90 interactions identified in this 21 × 21 matrix, 63 (70%) are a situation where a primary hazard could trigger *and* increase the probability of a secondary hazard, 15 (17%) where a primary hazard could trigger (but does not increase the probability of) a secondary hazard, and 12 (13%) where a primary hazard could increase the probability of (but not trigger) a secondary hazard.

Light-grey shading indicates that the primary hazard has the potential to trigger just a small number (one or a few) occurrences of the secondary hazard. For example, just one tsunami might result from a landslide trigger, and just one episode of climatic change might result from a volcanic eruption. Dark-grey shading indicates that the primary hazard has the potential to trigger a large number of the secondary hazard (multiple occurrences). For example, an earthquake, severe storm, or snowmelt event could trigger thousands of individual landslides. We observe that 66 (73%) of the 90 interactions have the potential for a small number of hazard events (individual or a few occurrences) and 24 (27%) have the potential for a large number of hazard events (multiple occurrences).

Figure 2 does not distinguish between those relationships that are commonplace and those that are very rare. In situations where there is considerable debate about the nature of a hazard interaction (e.g., the triggering of a volcanic eruption by a storm), this is acknowledged in the figure footnotes, with footnotes corresponding to the intersection of a row (1 to 21) and column (A to U), e.g., 12C for row 12 (storms) and column C (volcanic eruptions). This footnote relates to the triggering of volcanic eruptions by storms. This primary hazard event could result in an increase to groundwater levels, conceivably triggering phreatic or phreatomagmatic eruptions. The unusual and low likelihood nature of this interaction means that a note of clarification in the footnotes aids the reader in understanding the inclusion of the interaction in the matrix.

A second limitation to the visualization used in Figure 2 is that it allows only for an analysis of situations where one primary hazard triggers one or more secondary hazards. The matrix has not been designed for situations where two primary hazards come together to trigger or increase the probability of a secondary hazard (e.g., drought and lightning coinciding to trigger or increase the probability of wildfires).

In addition to using Figure 2 to highlight possible natural hazard interaction relationships where one stimulus triggers one response, it can also be used to identify a possible network of hazard interactions



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 2. Identification of hazard interactions. A 21 × 21 matrix with primary 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 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.

(i.e., a cascade or domino effect). In such a network, a series of hazards are triggered one after another, or simultaneously, because of successive triggering processes. Using Figure 2, the row of the initial primary hazard can be traced across to reveal the potential secondary hazards. Each of these secondary hazards can then be thought of as the next primary hazard, having the potential to trigger further (tertiary) hazards. An example of such a hazard interaction network can be observed in Figure 3. In this example, a storm event (row 12, **ST**) may trigger flooding (column F, **FL**), which then (row 6, **FL**) triggers landslides (column D, **LA**). These landslides (row 4, **LA**) could then trigger or increase the probability of further flooding (column F, **FL**) through the blocking of a river or the addition of significant quantities of sediment into the fluvial system. This form of visualization could be used to represent the complex case studies presented in section 2.1 (e.g., Japan, 1792; USA, 1964) where a hazard triggered secondary hazards, which then triggered tertiary hazards. This analysis of possible cascade or domino effects may aid the implementation of a full and complete hazard assessment and the determination of possible mitigation strategies.

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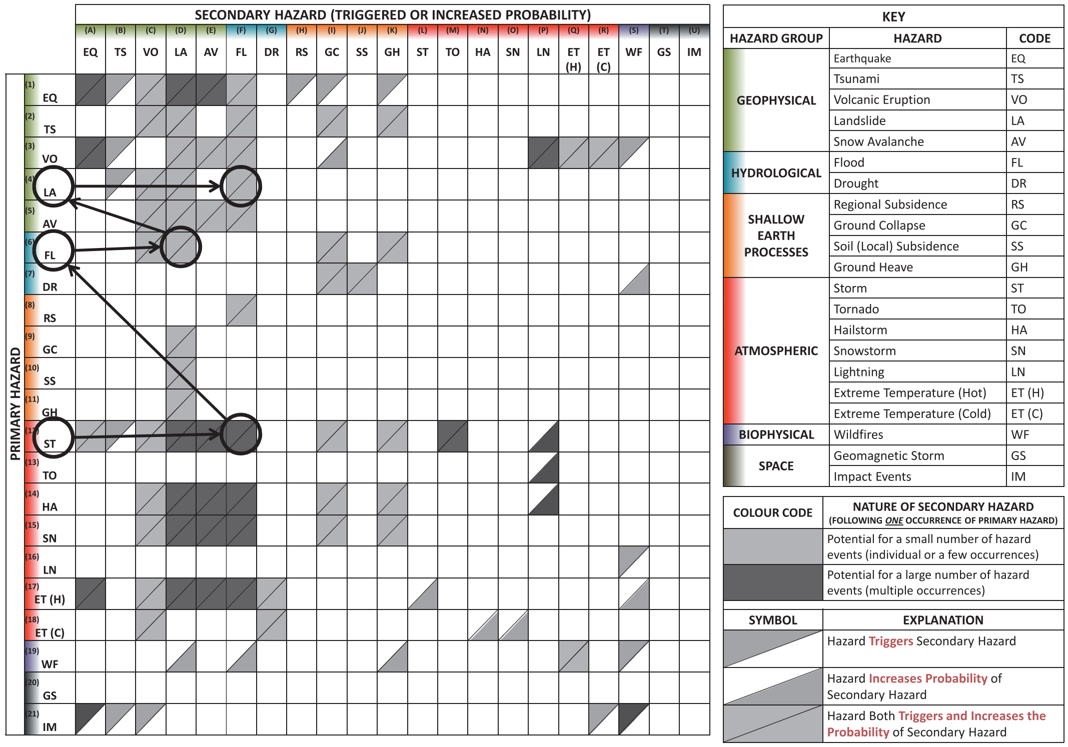


Footnotes
[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17A,D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large numbers of events, and are thus analysed in this way.
[1C] There is disagreement in the literature about the nature of this relationship .
[2,6,12,14,15C] 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 3. An example of a network of interacting hazards (a cascade system). A 21 × 21 matrix with primary natural hazards on the vertical axis and secondary hazards on the horizontal axis, the same as shown in Figure 2. These hazards are coded, as explained in the key. This matrix can be used to present an example of a hazard cascade system. 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.

The basic structure used for the visualization of the 21 hazard types described in this section and shown in Figure 2 will be used for the rest of this paper, when exploring other aspects of the hazards. In the first of these, we describe the hazard interaction mechanisms (section 3.3).

3.3. Hazard Interaction Mechanisms and Case Studies

As part of the construction of Figure 2, the identification and description of the physical process by which each primary hazard triggers or increases the probability of a secondary hazard was also undertaken. This information, together with examples of case studies, was used to compile Table S1 in the supporting information. As a primary hazard occurs, it brings about changes in environmental parameters within one or more components of the geosystem (i.e., the atmosphere, biosphere, lithosphere, and hydrosphere). A change in these environmental parameters (e.g., pore-water pressures, soil shear strength, surface water discharge, atmospheric aerosol concentration, confining pressures, and ground level above sea-level) can increase the likelihood of a particular secondary hazard or push it over a threshold and thus trigger it. This process of environmental change by the primary hazard is referred to here as the "mechanism" by which the secondary hazard is triggered or the probability increased. For example, returning to Figure 2, an earthquake (row 1, **EQ**) triggers a snow avalanche (column E, **AV**) through seismic shaking altering the shear stress and strength of the snow pack and results in the movement of snow and ice material under gravitational forces.

For 74 (out of 90) of the interaction relationships in Figure 2, we identified multiple key case studies in the academic or grey literature and noted these in Table S1. For example, the case study chosen to demonstrate an earthquake triggering landslides is taken from the 1994 Northridge (USA) earthquake. It is estimated that this $M_w = 6.7$ earthquake triggered more than 11,000 landslides [*Harp and Jibson*, 1995]. In another interaction relationship example, the case study chosen to demonstrate an earthquake triggering regional subsidence is taken from the 1964 Alaska earthquake, outlined in detail in section 2.1.2. More than 60 additional case studies, noted in Table S1, can also be used to highlight the importance of constraining hazard interaction relationships. Of the 16 interaction relationships for which no case study was identified, this could be due to them being low-frequency events or events where the interaction mechanism was difficult to determine (e.g., following a heavy storm, the triggering of a volcanic eruption through interaction with groundwater). Conceivable interaction relationships, with no noted case study, are still important as they were identified to be hypothetically possible (through an analysis of hazard interaction mechanisms) and thus should still be considered. There is also the possibility that existing case studies have not been reported widely in the literature and thus we missed them in our survey or that the interaction mechanism is not extensively discussed within appropriate case study analysis literature.

3.4. Hazard Type Linkages

The hazard interaction relationships identified and visualized in Figure 2 can also be represented in the form of a network diagram (Figure 4), which visualizes the significant interrelationships between the six hazard groups we have chosen. In Figure 4, each hazard group represents an edge of the six-sided polygon, with each of the 21 hazard types represented by a node. Hollow nodes (4 of the 21 hazards) are used for occasions where a given hazard type could trigger or increase the probability of further cases of that same hazard type (e.g., an earthquake triggering or increasing the probability of further earthquakes; a landslide triggering or increasing the probability of further landslides). Solid nodes (17 of the 21 hazards) suggest that a hazard triggering or increasing the probability of further hazard events of the same type does not occur (e.g., regional subsidence does not directly trigger or increase the probability of further regional subsidence; a tsunami does not directly trigger or increase the probability of further tsunamis). Lines are colored according to the hazard group of the primary hazard (e.g., if the primary hazard is atmospheric, the line is red). Line patterns are then used to represent three different interaction possibilities:

1. *Solid line*: 63 cases where both triggering and increased probability are possible.
2. *Dash-dotted line*: 15 cases where only a triggering relationship is possible.
3. *Dashed line*: 12 cases where only an increased probability relationship is possible.

For example, there is a red dash-dotted line between the lightning node and the wildfire node, as this is a direct triggering relationship, with the primary hazard being within the atmospheric hazard group. A purple dashed line goes from wildfires to landslides, as this is a relationship in which the probability of the secondary hazard is increased, with the primary hazard being within the biophysical hazard group.

From Figure 4 we can observe that there are significant interactions between different hazards and hazard groups. An assessment can be made of the relative severity of each of the 21 hazards. We use a network analysis procedure similar to *Tarvainen et al*. [2006], who analyzed the interactions between eleven natural and four technological hazards, ranking them according to how many times they influenced other hazards or were influenced by other hazards. *Tarvainen et al*. [2006] showed that the two highest-ranking primary natural hazards (in terms of having an influence over the greatest number of secondary hazards) were volcanic eruptions and earthquakes. They further showed that the two highest-ranking secondary natural hazards (in terms of being influenced by the most primary hazards) were forest fires and avalanches.

Through a similar methodology, we examined the relative severity of each single hazard, by quantifying and ranking the extent to which individual hazards trigger other hazards or are triggered by other hazards. The number of hazard-type linkages was summated for each hazard in terms of the number of times a hazard triggers another hazard (primary hazard to secondary hazard links) and the number of times a hazard is triggered by other hazards (secondary hazard from primary hazard links). In this network analysis, relationships where one hazard increases the probability of another hazard are not included (i.e., only solid and dash-dotted lines from Figure 4 are used, with a total of 78 primary to triggered secondary hazard links). The 21 different hazards included within this study were then ranked based on this information and the information presented

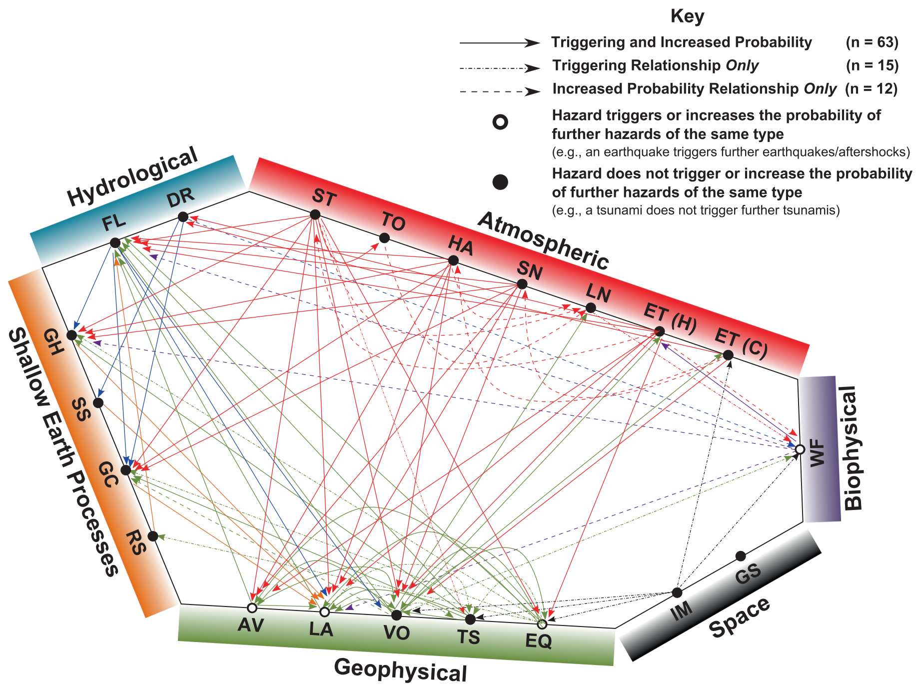


Figure 4. Hazard type linkages. A network diagram showing the potential hazard type linkages between 21 natural hazards: **EQ** = earthquake, **TS** = tsunami, **VO** = volcanic eruption, **LA** = landslide, **AV** = snow avalanche, **RS** = regional subsidence, **GC** = ground collapse, **SS** = soil (local) subsidence, **GH** = ground heave, **FL** = flood, **DR** = drought, **ST** = storm, **TO** = tornado, **HA** = hailstorm, **SN** = snowstorm, **LN** = lightning, **ET (H)** = extreme high temperatures, **ET (C)** = extreme cold temperatures, **WF** = wildfires, **GS** = geomagnetic storms, and **IM** = impact events. Hazards groups follow the same color coding as in Figure 2. Line patterns (see key) are used to represent cases where both triggering and increased probability are possible (solid), cases where only a triggering relationship is possible (dash-dotted), and cases where only an increased probability relationship is possible (dashed). Where a hazard may trigger or increase the probability of further hazards of the same type (e.g., earthquakes–**EQ**), the node is hollow to represent this relationship.

in Figure 5. This ranking shows that the hazards with the most primary hazard to secondary hazard links were volcanic eruptions (**VO**), earthquakes (**EQ**), and storms (**ST**) (each with nine primary to secondary links identified from Figure 4). Together these three primary hazards accounted for 27 (about a third) of the 78 total possible links where a primary hazard triggers a secondary hazard.

Hazards with the most secondary hazard from primary hazard links were found to be landslides (**LA**, 13 links), volcanic eruptions (**VO**, 11 links) and floods **(FL**, 10 links). These three secondary hazards accounted for 34 (almost half) of the 78 total possible triggered secondary from primary hazard links. These initial rankings (Figure 5) do not reflect the overall extent of *spatial overlap* and *temporal likelihood* of particular hazard interactions. A hazard that is ranked high on the list of triggered secondary hazard from primary hazard links may have received that ranking through the inclusion of many low *spatial overlap* and low *temporal likelihood* events. For example, volcanic eruptions (**VO**, 11 links) include both interactions with clear and well-documented case studies (e.g., a landslide, in the form of a flank collapse, triggering a volcanic eruption) and those that are conceivable but with few noted case studies (e.g., a flood, which could increase groundwater levels, triggering a phreatic/phreatomagmatic eruption). Other conceivable examples of the triggering of volcanic eruptions due to increased groundwater and surface water levels are as a result of storms, snowstorms, and hailstorms. Case studies for some of these interactions are included within Table S1 in the supporting information; however, for many of them, no case study was identified. The inclusion of these low *spatial overlap* and low *temporal likelihood* interactions results in higher than expected rankings. A method for including information about *spatial overlap* and *temporal likelihood* into the ranking of primary and secondary hazards is outlined in section 5.2.

Figure 5 can also be used to examine the total number of hazards within each of our six groups of hazards versus the summated number of triggering and triggered hazards in that group. Table 4 presents an analysis of each hazard grouping both before and after a normalization, based on the number of hazards within that hazard group, has been applied. In the upper half of Table 4, we present the non-normalized hazard group

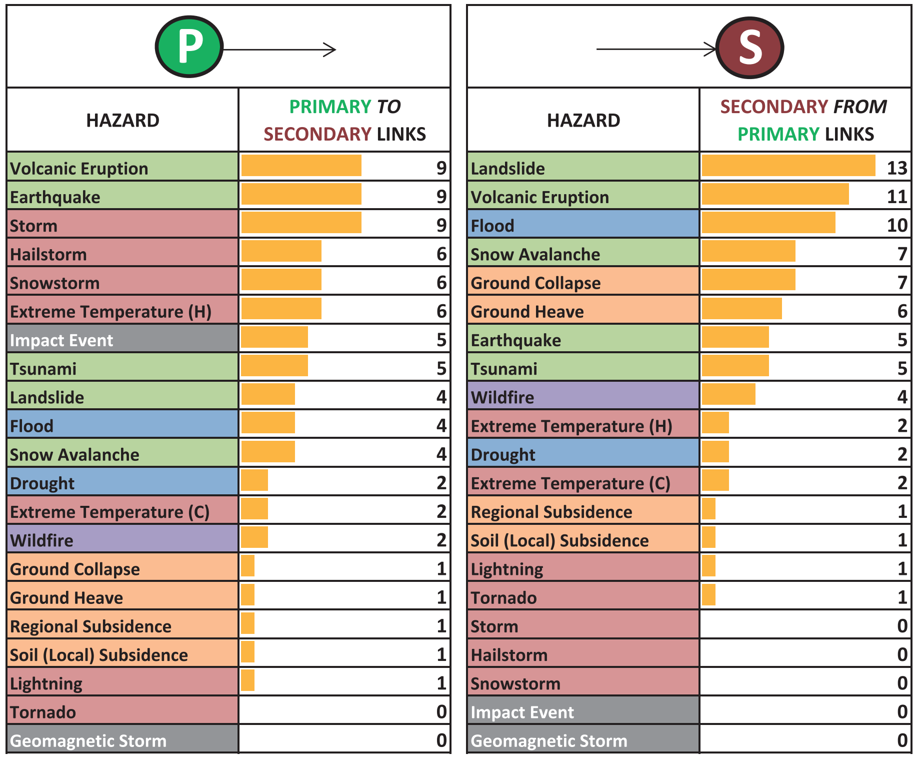


Figure 5. Ranking of individual hazards according to (left) the number of primary hazard to triggered secondary hazard links and (right) the number of triggered secondary hazard from primary hazard links**.** Using the hazard interaction matrix (Figure 2) and hazard type linkages (Figure 4) the number of primary hazard to triggered secondary hazard links is summated for each primary hazard within this study, and then ranked (Figure 5, left). This is repeated for each secondary hazard, summating and ranking triggered secondary hazard from primary hazard links (Figure 5, right).

ranking of primary hazard to secondary hazard links and secondary hazard from primary hazard links (the total number of times hazards within that group either trigger another hazard or are triggered by another hazard, respectively). In the lower half of the table, we present the same hazard groups but with the total number of linkages normalized by dividing them by the total number of hazards within the group. Again, these groups are ordered according to their ranking.

Table 4. Ranking of Hazard Groups in Terms of Number of Times Included Hazards Trigger and Are Triggered by Other Hazards (Non-Normalized and Normalized)[a]

Hazard Group (Ranked by Number of Primary to Secondary Links)	Number of Hazards Within Group (*n*)	Primary to Secondary Links	Hazard Group (Ranked by Number of Secondary from Primary Links)	Number of Hazards Within Group (*n*)	Secondary From Primary Links
			(A) Total (Non-Normalized)		
Geophysical	5	31	Geophysical	5	41
Atmospheric	7	30	Shallow Earth Processes	4	15
Hydrological	2	6	Hydrological	2	12
Space	2	5	Atmospheric	7	6
Shallow Earth processes	4	4	Biophysical	1	4
Biophysical	1	2	Space	2	0
			(B) Total (Normalized by Dividing by Number of Hazards Within Group, n)		
Geophysical	5	6.2	Geophysical	5	8.2
Atmospheric	7	4.3	Hydrological	2	6.0
Hydrological	2	3.0	Biophysical	1	4.0
Space	2	3.0	Shallow Earth Processes	4	3.8
Biophysical	1	2.0	Atmospheric	7	0.9
Shallow Earth processes	4	1.0	Space	2	0.0

[a]Ranking the selected hazard groups in terms of both the total number of primary hazard to triggered secondary hazard links and total number of triggered secondary hazard from primary hazard links. These results are normalized by dividing total values by the summated total of hazard types within the group (*n*).

We find (Table 4, upper half) that prior to normalization, *geophysical* and *atmospheric* hazards are identified as predominant triggers of other hazardous phenomena and *geophysical* and *shallow Earth processes* are identified as being the most triggered. After normalization (Table 4, lower half), we find that geophysical and atmospheric hazards are still the highest ranked triggers, whereas geophysical and hydrological hazards are now the groups that are triggered by the most other hazards. It is important to note that ranking by hazard groups is extremely sensitive to the number of hazards and particular hazards selected for inclusion within the study. Results from the analysis of hazard groups (Table 4) can be contrasted with the individual hazard rankings (Figure 5), in which the hazard group is visualized through the standard group colors used throughout this study.

It is proposed that by determining the single hazards with the most primary to secondary links and those with the most secondary from primary links, for specific countries or regions, this might supplement existing methods for deciding upon the allocation of resources for mitigation measures.

4. The Forecasting of Secondary Hazards

In addition to identifying the existence of hazard interactions, the extent to which each secondary hazard can be forecasted was also evaluated. In this context, the forecasting potential is defined as an ability to constrain each of the following three factors, noting that some interrelations may exist:

1. The *spatial location* (where the secondary hazard occurs).
2. The *timing* (when the secondary hazard occurs).
3. The *magnitude* of the secondary hazard (a function of the energy released during the hazard, itself a complex quantity, along with the hazard's spatial extent and temporal duration). For example, for a flood, this may include the area flooded, the duration of the flood, and the water velocity and depth.

Given information and data about a particular primary hazard event that has already occurred (including parameters such as the primary hazard's location, timing, and magnitude), an evaluation of the forecasting potential for possible secondary hazards can be made. Unlike the forecasting of many primary hazards, when attempting to forecast a secondary hazard there can already be substantial additional data and information available. In some cases, this additional information, gained from knowledge about the primary hazard, can be utilized within existing qualitative and quantitative hazard interaction relationships to constrain the spatial location, timing, and magnitude of possible secondary hazards. Returning to the case study from Alaska, USA (section 2.1.2) an evaluation of regions where subsidence had occurred would give us information about locations with an increased susceptibility to flooding. Similarly, if an earthquake epicenter and magnitude is known, estimates can be made of the likely travel path and speed of a tsunami, if generated.

An evaluation of our ability to constrain the location, timing, and magnitude of the secondary hazard (given appropriate information on the primary hazard) was estimated by reviewing existing information and empirical and probabilistic relationships. In situations where the secondary hazard is classified in Figure 2 as a large number of events, rather than an individual event, the analysis of spatial, temporal, and magnitude forecasting is for the hazard population rather than for a specific individual event. For example, where an earthquake triggers multiple landslides, information can be used about the location (including depth), timing, and magnitude of an earthquake, alongside existing relationships to forecast (with uncertainties) the spatial and temporal distribution of the cluster of landslides produced, but not to forecast specific location, timing, or volume for any individual landslide.

The *Government Office for Science* (UK) [2012] utilized a process of expert elicitation to determine the ability of the scientific community to produce reliable forecasts of natural hazards. The authors used a rating system (1 to 5), where 1 is a low ability and 5 is a high ability to produce reliable forecasts. This rating system was used to classify each of the following: spatial location, timing, and magnitude of single (primary) hazards. Hazards within their analyses included earthquakes, volcanic eruptions, landslides, tsunamis, storms, floods, and droughts. In our study, we adopt a similar method to the *Government Office for Science* (UK) [2012] to aid us in classifying the information we have collated.

The classifications we derive are based on existing relationships between the primary and secondary hazards, found from a systematic review of the available literature rather than an expert elicitation exercise. For each

Table 5. Scale for Classifying Ability to Characterize Secondary Hazards (in Terms of Location, Timing and Magnitude) Given Information From a Primary Hazard[a]

Forecasting Factor Ability	Description (Ability to Characterize Secondary Hazard Given Information From the Primary Hazard)	Numerical Value
None	There exists no knowledge to help constrain the particular forecasting factor.	0
Low	The knowledge to help constrain the forecasting factor is minimal or purely qualitative.	1
Medium	The forecasting factor can be partially constrained and expressed in a quantitative manner.	2
High	The forecasting factor can be very well constrained, and there are complete or significant quantitative relationships in existence that are widely accepted and used.	3

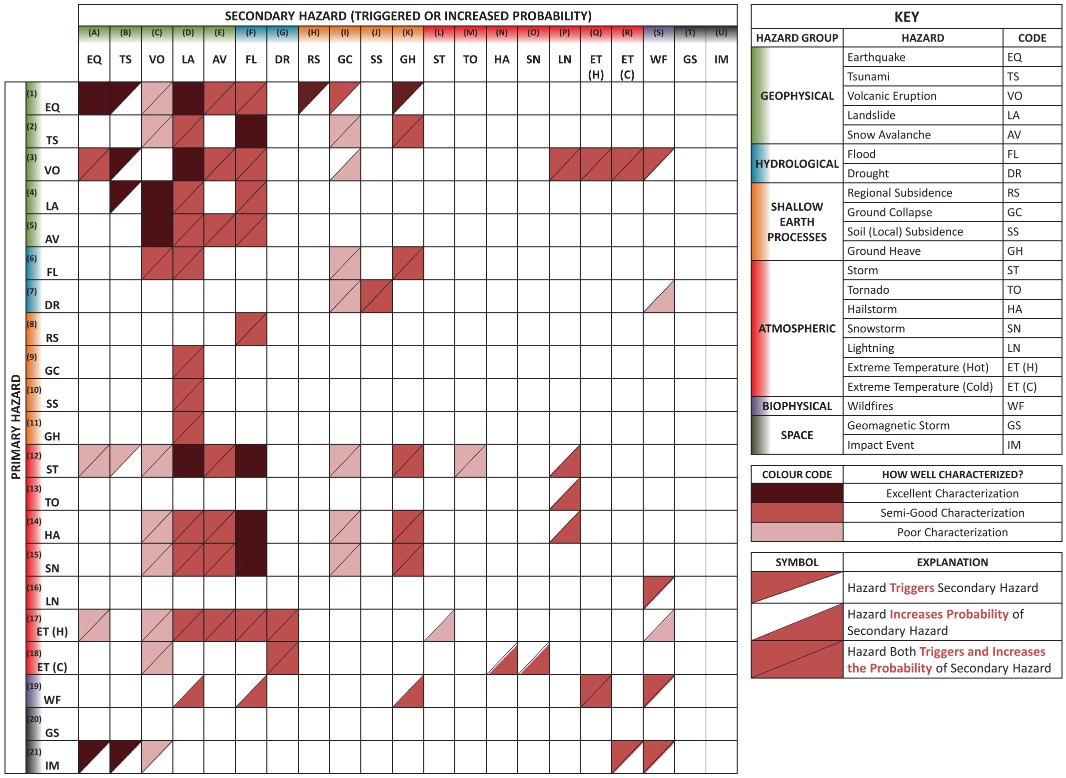
[a]This Likert-type scale is composed of a null category and a three-point bivalent scale, used to characterize each of the spatial location, timing, and magnitude of the secondary hazard, given information about the primary hazard. Specific information about all three factors, for each hazard interaction, is included in the supporting information (Table S2).

of the three forecasting factors (spatial location, timing, and magnitude), a classification system was derived as outlined in Table 5. The classification employed is an adaptation of a standard Likert scale, which typically has a bivalent scale of five points, but can have a different number (including even) of points [*Jamieson*, 2004]. In our classification, we adopt a four-point scale: a "null" category (where it is not possible to describe the forecasting factor, even in qualitative terms) and a three-point, bivalent Likert-type scale. Higher-point scales could be used but we believe they would be too fine a resolution based on the level of information available.

In Table 5, classifications of *None* (0), *Low* (1), *Medium* (2), and *High* (3) are broadly related to whether existing relationships are unable to be constrained (*None*), poorly constrained and/or purely qualitative (*Low*), partially constrained and semi-quantitative (*Medium*), or well constrained and quantitative (*High*). For each of the secondary hazards, a broad literature base was used to determine the appropriate classification for each of the three forecasting factors (spatial location, timing, and magnitude). Classifications on all three factors, for each triggered and increased probability secondary hazard, are included in the supporting information (Table S2). The summation of the three numerical values from each forecasting factor gives an overall rating 0–9. This enabled hazards to be categorized according to whether there was an excellent (overall rating 7–9), semi-good (overall rating 4–6), or poor (overall rating 0–3) ability to characterize the secondary hazard given information from the primary hazard. Each of these categories was color coded, with the results displayed in a matrix form (Figure 6), where the matrix has the same structure and layout as Figure 2 (see section 3.1 for a brief narrative). The matrix shown in Figure 6 uses different color saturations to show those relationships where there is a poor (pale red), semi-good (medium red), and excellent (dark red) ability to characterize secondary hazards.

The classification presented in Figure 6 is designed to allow a rapid, coarse-resolution overview of the differential capabilities to characterize (given information from the primary hazard) the secondary hazards examined within this study. This figure demonstrates that out of 90 relationships, there are 17 (19%) which have an excellent ability to be characterized (e.g., earthquake triggering or increasing the probability of landslides, storm triggering or increasing the probability of flooding, or tsunami triggering or increasing the probability of flooding), 51 (57%) with a semi-good ability to be characterized, and 22 (24%) which have a poor ability to forecast (e.g., drought triggering or increasing the probability of ground collapse, storms triggering or increasing the probability of volcanism).

In the case of the example where earthquakes trigger or increase the probability of further earthquakes (aftershocks), there are several existing relationships that can be used to forecast (with uncertainties) the frequency-size distribution of the aftershock magnitudes and the spatial location and timing of the aftershocks. Relationships such as Båth's Law [*Båth*, 1965], the Gutenberg–Richter relationship [*Gutenberg and Richter*, 1944], and their modifications, can be applied to give an indication of the frequency-size distribution of aftershock magnitudes. Relationships also exist that can constrain the spatial location of earthquake aftershocks using the ruptured fault characteristics [e.g., *Felzer and Brodsky*, 2006] and the overall decay of aftershock magnitudes with time after the primary earthquake [*Omori*, 1894; *Utsu*, 1961]. These relationships allow, in our Figure 6, for an "excellent" forecasting ability for the total group (or population) of aftershocks. Following a large earthquake, such as that in Alaska in 1964 (section 2.1.2), one can forecast, with uncertainties, the likely location, timing, and magnitude distribution of the cluster of aftershocks. Forecasting for each individual aftershock, however, is still a significant challenge.



Footnotes

[1A,D,E; 3A,P; 12D-F,M,P; 13P; 14D-F,P; 15D-F; 17D-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 6. Ability to characterize triggered and increased probability secondary hazards given information from the primary hazard. A 21×21 matrix with primary natural hazards on the vertical axis and secondary hazards on the horizontal axis, as introduced in Figure 2. These hazards are coded, as explained in the key. This matrix outlines current ability to characterize each secondary hazard, given information about the primary hazard. This was constructed by reviewing the ability to forecast the spatial location (where the secondary hazard occurs), the timing (when the secondary hazard occurs), and the magnitude (incorporating spatial extent, duration, and intensity). Based on the literature, each of the three factors (location, timing, and magnitude) is given a forecasting ability value of 0–3 (Table 5). These three values are then summated to give an overall forecasting ability score of 0–9, which are classified in terms of excellent (overall rating 7–9, dark shading), semi-good (overall rating 4–6, medium shading) or poor (overall rating 0–3, light shading). Footnotes give further information about some of the relationships.

In contrast, given precise details of the location, timing, and magnitude of a drought (primary hazard), it is difficult to forecast incidences of drought triggering or increasing the probability of ground collapse (secondary hazard). Drought can result in the removal of hydraulic support from fracture systems, increasing the probability of or resulting in rapid ground collapse. For this interaction, it is difficult to use information or data from the drought to forecast specific locations that may be vulnerable to ground collapse (e.g., regions of karst) due to the difference in spatial scales upon which these hazards act (see Figure 1). The slow-onset nature of drought, compared to the rapid onset nature of ground collapse, means that it is difficult to forecast the timing and magnitude of possible collapses based on information from the drought, and we therefore give the characterization of drought to ground collapse a “poor” in Figure 6.

While the visualization used in Figure 6 provides a rapid, coarse resolution summary of how well we are able to characterize potential secondary hazards in terms of their location, timing, and magnitude, this approach does not make available the specific and quantitative information that could be used to assist in

Table 6. Parameters Selected to Assess the *Spatial Overlap* and *Temporal Likelihood* of Each Triggering Relationship[a]

Parameter	Description	Assessment Methodology	Assessment Criteria and Classification
Spatial overlap	In all the locations where the primary hazard is present, what proportion of these could occurrences of the secondary hazard also occur?	Determined by collating a catalog of simple global hazard distribution maps. Simple spatial overlay techniques were then used to determine a first-order approximation of *spatial overlap*.	Classifications were approximately based on the following overlap percentages, derived by visual inspection: **Large** (~70–100%): Secondary hazard occurs in most places that are affected by primary hazard. **Medium** (~30–70%): Secondary hazard occurs in some places that are affected by primary hazard. **Limited** (~0–30%): Secondary hazard occurs in a small percentage of places affected by primary hazard.
Temporal likelihood (of all necessary environmental conditions coinciding for the secondary hazard to occur)	For a hazard to occur, a number of conditions should be met or a series of environmental factors coincide spatially and/or temporally. This can include a minimum value (threshold) for the primary hazard intensity. This parameter is analogous to the Cumulative Act Effect Model [*Reason*, 1990] otherwise known as the "Swiss Cheese Model." This suggests that failure occurs when individual weaknesses within levels of a system momentarily align to create a "trajectory of accident opportunity."	Qualitative analysis of reviewed literature, which enabled an understanding of the relative occurrence of secondary hazards after primary cases of a primary hazard. A more mechanistic approach, using a form of engineering judgment, complemented this review of case studies. The number of environmental parameters that have to coincide for the secondary hazard to be triggered was examined. These approaches could be further constrained by using an expert elicitation methodology to get a general consensus on the *temporal likelihood* of a range of hazard interactions.	Classifications were approximately based on the prevalence of case studies in the literature: **High**: Widespread case studies or examples of the primary hazard triggering the secondary hazard. **Medium**: Some case studies or examples of the primary hazard triggering the secondary hazard. **Low**: Occurrences in the literature of the primary hazard triggering the secondary hazard are either rare or non-existent but believed to be hypothetically possible.

[a]A description of both parameters (*spatial overlap* and *temporal likelihood*) chosen to assess globally the *Overlap–Likelihood* Factor (section 5.2) of a triggered secondary hazard occurring after a primary hazard has already occurred, the assessment methodology for each and the criteria used for classifying each parameter.

forecasting. The resolution of the classification employed could also lead to the loss of information that distinguishes the different hazard interactions being studied. Options to overcome these limitations are discussed in section 7.

5. The *Spatial Overlap* and *Temporal Likelihood* of Secondary Hazards Occurring

We now evaluate globally the *spatial overlap* and *temporal likelihood* of each situation where a primary hazard was identified as having the capability of triggering (but not increasing the probability of) a specific type of secondary hazard. These evaluations are based on the assumption that the primary hazard has already occurred and therefore do not take into account the relative likelihood of the primary hazard. The classifications we present in this section are concerned with whether the secondary hazard does or does not occur after a given primary hazard event and the relative *spatial overlap* and *temporal likelihoods* between different interactions taking place. This section begins by first examining the review procedures used to assess relative *spatial overlap* and *temporal likelihood* (section 5.1) and then presents the results of this review for triggered hazard interactions in a matrix form (section 5.2).

5.1. Review Procedures

This evaluation globally of *spatial overlap* and *temporal likelihood* of secondary hazards occurring was conducted based on an analysis of two parameters (described more fully in Table 6):

1. The *spatial overlap* of each hazard combination.
2. The *temporal likelihood* (in those regions where *spatial overlap* occurs) of all necessary environmental conditions coinciding for the secondary hazard to occur. This involved the identification of any relevant thresholds or tipping points.

Together, these two parameters (*spatial overlap* and *temporal likelihood*; see Table 6) give an indication of the *Overlap-Likelihood* Factor (section 5.2) of any particular triggered secondary hazard occurring after a primary hazard. For a primary hazard to trigger a secondary hazard, their spatial distribution should overlap. A large *spatial overlap* will often result in a greater likelihood of interactions than a limited *spatial overlap*. For example, it is more likely that an earthquake will trigger landslides than snow avalanches due to the difference in the global hazard distribution of landslides and snow avalanches. The *spatial overlap* alone, however, does not guarantee that a hazard will be triggered. It is also important to consider *temporal likelihood* of any particular secondary hazard being triggered in regions where there is *spatial overlap*. In an analogy to the Cumulative Act Effect Model [*Reason*, 1990], a secondary hazard is less likely when there are more environmental conditions that must coincide. This can also mean that there are more thresholds to overcome. We will take here the *temporal likelihood* as the likelihood of environmental conditions coinciding such that given an occurrence of the primary hazard, the secondary hazard occurs.

The assessment of each of these two parameters was undertaken using a mixture of assessment methodologies and criteria, also outlined in Table 6. The determination of *spatial overlap* (large, medium, and limited) was assessed at a coarse resolution using a selection of global hazard distribution maps (Table S3 in the supporting information). The assessment of *temporal likelihood* (high, medium, and low) within regions where there is a *spatial overlap* was evaluated through a qualitative review of a wide range of literature sources, noted both in the references at the end of this paper and the supporting information. A qualitative analysis of the literature used within the review enabled an approximation of the relative occurrence of secondary hazards after a primary hazard. This was supplemented by a more mechanistic approach, using a form of engineering judgment and analyzing the conditions that must be met for a secondary hazard to be triggered. In further work, these methods could be constrained using an expert elicitation methodology to get a general consensus on the *spatial overlap* and *temporal likelihood* of a range of hazard interactions.

5.2. Triggered Hazard Interactions: *Spatial Overlap* and *Temporal Likelihood* Matrix

Results of our analyses of examining the *spatial overlap* and *temporal likelihood* of hazard-triggering interactions are displayed in a matrix form in Figure 7, using a similar layout and structure as previous matrices (Figures 2 and 6). The main difference between previous matrices and Figure 7 is that Figure 7 only visualizes interactions where a primary hazard triggers a secondary hazard, not those in which the probability of a secondary hazard is increased. Each grid square therefore represents only triggering relationships.

To construct Figure 7, we take the two parameters (each with three classes) described in Table 6 and give them colors and codes: *Spatial overlap* was color coded (yellow = limited, orange = medium, pink-red = large), and *temporal likelihood* was coded with the use of an L, M, H (where L = low, M = medium, and H = high). These two parameters combine to give nine possible classifications, ranging from events that have a limited *spatial overlap* and a low *temporal likelihood* (yellow, with the letter L), to events that have a large *spatial overlap* and a high *temporal likelihood* (pink-red, with the letter H). While it is recognized that the application of a three-point classification scheme for each of these parameters limits the differentiation of different hazards, it also allows for a simple comparison across multiple hazards and is an appropriate resolution for the amount of information that is often available.

We observe from Figure 7 that for the 78 triggering relationship cells noted, the *spatial overlap* is fairly evenly divided between large (33%), medium (36%), and limited (31%), and the *temporal likelihood* somewhat less evenly divided between high (29%), medium (44%), and low (27%). In addition, all nine combinations of *spatial overlaps* and *temporal likelihoods* are represented, ranging from a minimum of five cells (medium *spatial overlap* and high *temporal likelihood*) to a maximum of 17 cells (medium *spatial overlap* and medium *temporal likelihood*). The range of *spatial overlap* and *temporal likelihood* combinations is also demonstrated by the following examples:

1. Cell 12D (*Storms* triggering *landslides*). The relationship between storms (row 12, **ST**) and landslides (column D, **LA**) has been classified as being large (pink-red cell), in terms of *spatial overlap*, and having a high *temporal likelihood* (letter H) of all necessary environmental parameters coinciding. It is possible for landslides to occur in many of the places affected by storms (note the landslide hazard includes both subaerial and submarine landslides). If a storm does occur in one of these areas of *spatial overlap*, it will increase groundwater levels and reduce effective stress. There is, therefore, a high *temporal likelihood* of slope failure. There are many examples of this interaction, including the triggering of >11,500 landslides by Hurricane Mitch in Guatemala [*Bucknam et al*., 2001], the triggering of >100 landslides by a rainstorm in British Columbia [*Guthrie and Evans*, 2004], and the triggering of landslides during Tropical Storm Agatha in Guatemala (see section 2.1.4).

PRIMARY HAZARD ↓ / SECONDARY HAZARD (TRIGGERED) →	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH	(L) ST	(M) TO	(N) HA	(O) SN	(P) LN	(Q) ET (H)	(R) ET (C)	(S) WF	(T) GS	(U) IM
(1) EQ	H	M	L	H	H	L		M	M		M										
(2) TS			L	M		H			M		H										
(3) VO	H	L		M	M	M										M	L	L	M		
(4) LA		M	L	M		L															
(5) AV			L	L	M	L															
(6) FL			L	M					M		H										
(7) DR									M	H											
(8) RS						M															
(9) GC				M																	
(10) SS				M																	
(11) GH				M																	
(12) ST	L	L	L	H	H	H			M		H		L								
(13) TO																					
(14) HA			L	M	M	M			L		M										
(15) SN			L	M	M	M			L		H										
(16) LN																			H		
(17) ET (H)	M		M	M	H	H	H														
(18) ET (C)			M				H														
(19) WF																	L		H		
(20) GS																					
(21) IM	H	H	M															H	H		

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 Event	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	AS

SYMBOL	EXPLANATION
(yellow / orange / pink-red)	**Triggering Relationship** Exists – See key below for details.

SPATIAL OVERLAP / TEMPORAL LIKELIHOOD	LOW (will rarely occur)	MEDIUM (will occur somewhat)	HIGH (very common to occur)
LARGE (Secondary hazard occurs in most places that are affected by the primary hazard)	L	M	H
MEDIUM (Secondary hazard occurs in some places that are affected by the primary hazard)	L	M	H
LIMITED (Secondary hazard occurs in small % of places affected by primary hazard)	L	M	H

Footnotes

[1A,D,E; 3A,P; 12D-F; 14D-F; 15D-F; 17D-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.
[1B] Generally only applicable if earthquake has moment magnitude $M_w > 7$.
[1C] Generally only applicable if earthquake has moment magnitude $M_w > 8$.
[2,6,12,14,15C] Water input triggers a phreatic/phreatomagmatic eruption.
[3Q,R] Generally only applicable if height of eruption column is > 10 km.
[12A] Low pressure systems have been shown to trigger slow earthquakes on faults that are already close to failure (Liu *et al.*, 2009).
[17C-F] Secondary hazards triggered 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.
[21A,B,C,S] Generally only applicable if asteroid impact has energy > 10 Mt.
[21Q,R] Generally only applicable if asteroid impact has energy > 10^5 Mt.

Figure 7. *Spatial overlap* and *temporal likelihood* of triggering relationships occurring. A 21 × 21 matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis, as introduced in Figure 2. These hazards are coded, as explained in the key. This matrix outlines the *spatial overlap* and *temporal likelihood* of each triggering relationship (described in detail in Table 6), given that the primary hazard has already occurred. This matrix does not show relationships where a primary hazard increases the probability of a secondary hazard. The *spatial overlap* and *temporal likelihood* were determined globally as a function of (i) the *spatial overlap* (yellow = limited, orange = medium, pink-red = large), and (ii) the *temporal likelihood* of all necessary environmental conditions (where there is *spatial overlap*) for the secondary hazard to occur (L = low, M = medium, H = high) and any specific thresholds that must be overcome (shown in the footnotes). Footnotes give further information about some of the relationships.

2. Cell 12 K (*Storms* triggering *ground heave*). The relationship between storms (row 12, **ST**) and ground heave (column K, **GH**) has been classified as having a medium *spatial overlap* (orange cell) and high *temporal likelihood* (letter H) of all necessary environmental parameters coinciding. Expansive rocks and soils are found in some places affected by storms. If a storm does occur in one of these areas of *spatial overlap*, there is a high *temporal likelihood* of ground heave as the water interacts with clay minerals. An example of this interaction is cited by *Noe* [1997] and taken from Colorado, USA. Following large summer thunderstorms in the 1990s, differential movement of 80 mm was noted to have occurred in the space of 24 h [*Noe*, 1997].
3. Cell 4C (*Landslides* triggering *volcanic eruptions*). The relationship between landslides (row 4, **LA**) and volcanic eruptions (column C, **VO**) has been classified as having a limited *spatial overlap* (yellow cell) and a low *temporal likelihood* (letter L) of all necessary environmental parameters coinciding. The vast majority of landslides do not occur on the flanks of volcanoes and thus would not trigger a volcanic eruption. If a landslide did occur on the slope of a volcano, it would be unlikely to trigger an eruption. The landslide would have to be of a significant volume and the volcanic system would have to be close to an eruptive state already. An example of an occasion when this interaction did occur is noted by *Lipman et al.* [1990] when discussing depressurization of magma chambers on Hawaii and a possible phreatomagmatic eruption triggered by a flank collapse.

The two parameters (*spatial overlap* and *temporal likelihood*) utilized in Figure 7 (see legend) can also be integrated into the assessment and ranking of hazard linkages. Initial rankings of triggered secondary hazards from primary hazard links (section 3.4, Figure 5) do not necessarily reflect the differential *spatial overlap* and *temporal likelihood* of particular hazard interactions. For example, as previously mentioned, a hazard that has a high ranking in Figure 5 may have received that position through the inclusion of many low *spatial overlap* and low *temporal likelihood* events.

In order to integrate both *spatial overlap* and *temporal likelihood* information from Figure 7 into the assessment of hazard linkages, each of the three classes within both of these parameters were given a numerical value of 1 to 3 (*spatial overlap*: 1 = limited, 2 = medium, 3 = large; *temporal likelihood*: 1 = low, 2 = medium, 3 = high). The two numbers allocated to each interaction were then multiplied to give six possible overlap-likelihood numbers (1, 2, 3, 4, 6, and 9), which we present using the *Overlap-Likelihood* Factor (OLF) notation (I, II, III, IV, V, and VI, respectively). For example, in Figure 7 a landslide triggering a tsunami was noted to have a medium *spatial overlap* (numerical value 2) and a medium *temporal likelihood* (numerical value 2). The multiplication of these two values gives us 4, and this therefore correlates to an *Overlap-Likelihood* Factor of OLF = IV. In another example, an earthquake triggering landslides would have a high *spatial overlap* (3) and a high *temporal likelihood* (3), which when multiplied give 9, corresponding to OLF = VI. These *Overlap-Likelihood* Factors (ranging from I to VI) can then be used to revise the analysis of hazard linkages set out in section 3.4.

Figure 8 shows a series of stacked histograms, one for each possible triggered secondary hazard. On the *x* axis there are six possible *Overlap-Likelihood* Factors (OLF), ranging from those with a limited *spatial overlap* and low *temporal likelihood* (I) to those that have a large *spatial overlap* and a high *temporal likelihood* (VI). On the *y*-axis is the frequency (*f*) or number of times the hazard interaction (with the specified secondary hazard) was allocated that *Overlap-Likelihood* Factor. For example, Figure 8d visualizes situations where wildfire is the secondary hazard. From Figure 7 (which examines only triggered hazards), wildfire is a triggered, secondary hazard associated with $n = 4$ primary hazards: volcanic eruptions, lightning, other wildfires, and impact events. For these interactions, the respective *spatial overlap* × *temporal likelihood* and corresponding *Overlap-Likelihood* Factor (OLF) are as follows:

1. volcanic eruption triggering wildfire: 3 (large overlap) × 2 (medium likelihood) = 6; OLF = V
2. lightning triggering wildfire: 3 (large overlap) × 3 (high likelihood) = 9; OLF = VI
3. wildfire triggering further wildfire: 3 (large overlap) × 3 (high likelihood) = 9; OLF = VI
4. impact event triggering wildfire: 2 (medium overlap) × 3 (high likelihood) = 6; OLF = V

In other words, two values ($f = 2$) of OLF = V and two ($f = 2$) of OLF = VI, which are then visualized as a histogram in Figure 8d. This same procedure is carried out for the other 15 triggered secondary hazard types that have at least one primary hazard triggering it, and each is given as a histogram in Figure 8.

Through examining the series of *Overlap-Likelihood* Factor (OLF) histograms in Figure 8, we can observe cases where there is a strong skew toward low OLF (e.g., (i) volcanic eruptions) and those with a strong skew toward high OLF (e.g., (c) earthquake, (d) wildfire and (j) drought). We can also observe cases with a broad range of OLF (e.g., (a) landslides, (b) floods, and (e) ground heave). Furthermore, this graphical analysis of OLF can be used to calculate OLF_T (total OLF) and $\overline{\mathrm{OLF}}$ (average OLF) for each triggered secondary hazard:

$$\mathrm{OLF}_T = \sum_{\mathrm{OLF}=\mathrm{I}}^{\mathrm{VI}} (f_{\mathrm{OLF}} \times \mathrm{OLF}) \tag{1}$$

$$\overline{\mathrm{OLF}} = \mathrm{OLF}_T / n \tag{2}$$

where in equation (1), f_{OLF} is the frequency for each OLF from I to VI, and in equation (2), n = number of triggered secondary from primary links. For the example given above, where wildfire is the secondary hazard, with $n = 4$ primary to secondary links, the total *Overlap-Likelihood* Factor $\mathrm{OLF}_T = (2 \times \mathrm{V}) + (2 \times \mathrm{VI}) = 22$, and the average *Overlap-Likelihood* Factor $\overline{\mathrm{OLF}} = 22/4 = 5.5$.

In Figure 9 we give, for each triggered secondary hazard, the ranking now based on OLF_T, the total Overlap-Likelihood Factor. We also give the corresponding number of primary to secondary hazard links (n) and the average *Overlap–Likelihood* Factor ($\overline{\mathrm{OLF}}$). Notable differences and some similarities can be observed between the new adjusted rankings presented in Figure 9 and those discussed in section 3.4

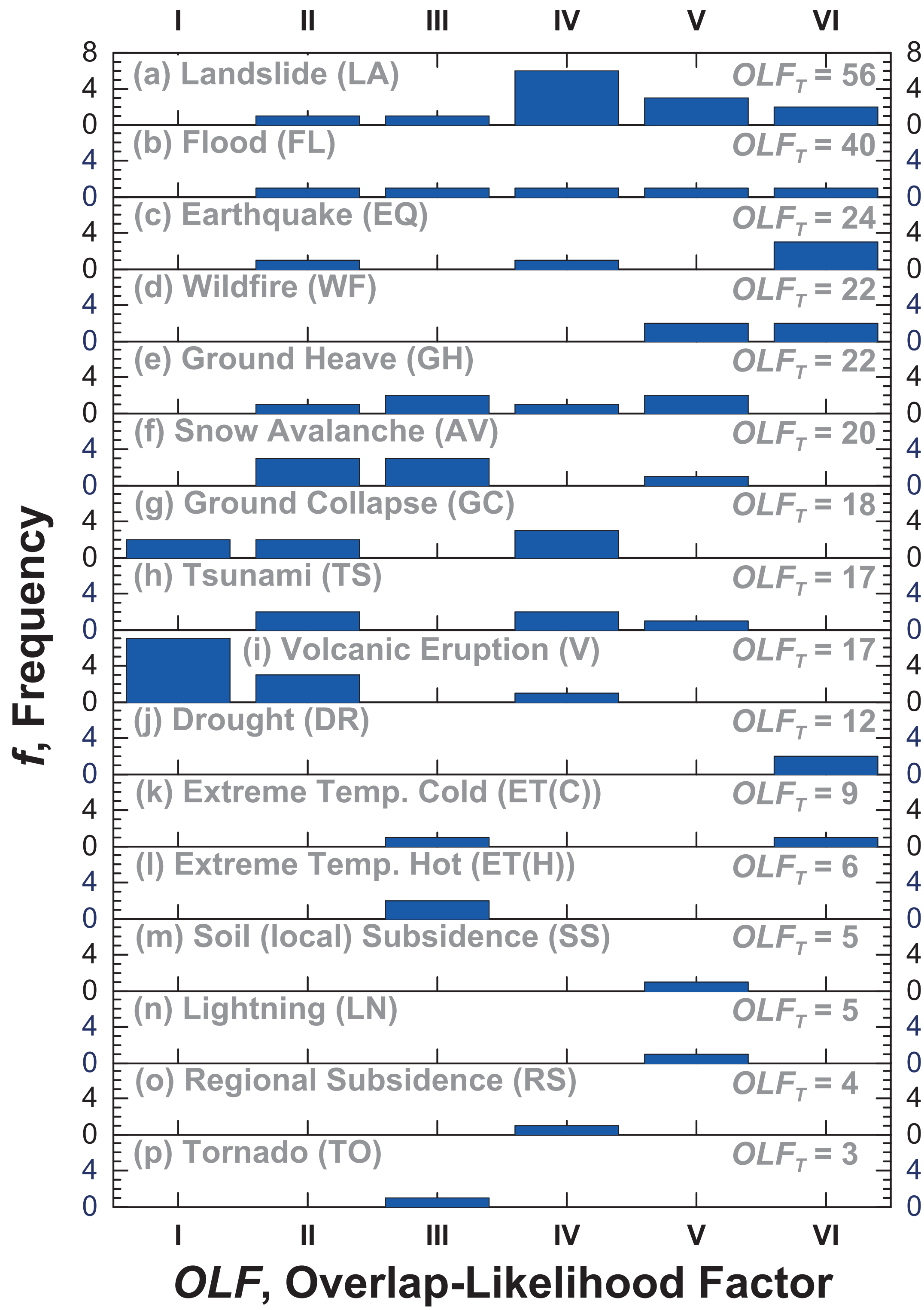


Figure 8. Graphical representations of the *Overlap-Likelihood* Factor (OLF) distribution for 16 triggered secondary hazards. The histograms give an indication of the frequency (*f*) distribution of the *Overlap-Likelihood* Factors (OLF), based on a global evaluation of the *spatial overlap* and overall *temporal likelihood* (see section 5 and Figure 7). On the *x*-axis there are six possible OLF (I–VI), ranging from I (limited *spatial overlap* and low *temporal likelihood*) to VI (large *spatial overlap* and high *temporal likelihood*). On the *y* axis is the frequency (*f*), i.e., the number of secondary hazards that have been allocated that OLF. Hazards have been ordered (a) to (p), based on OLF_T, the total OLF for that hazard (equation (1)), with OLF_T given in the upper right of each hazard's subpanel.

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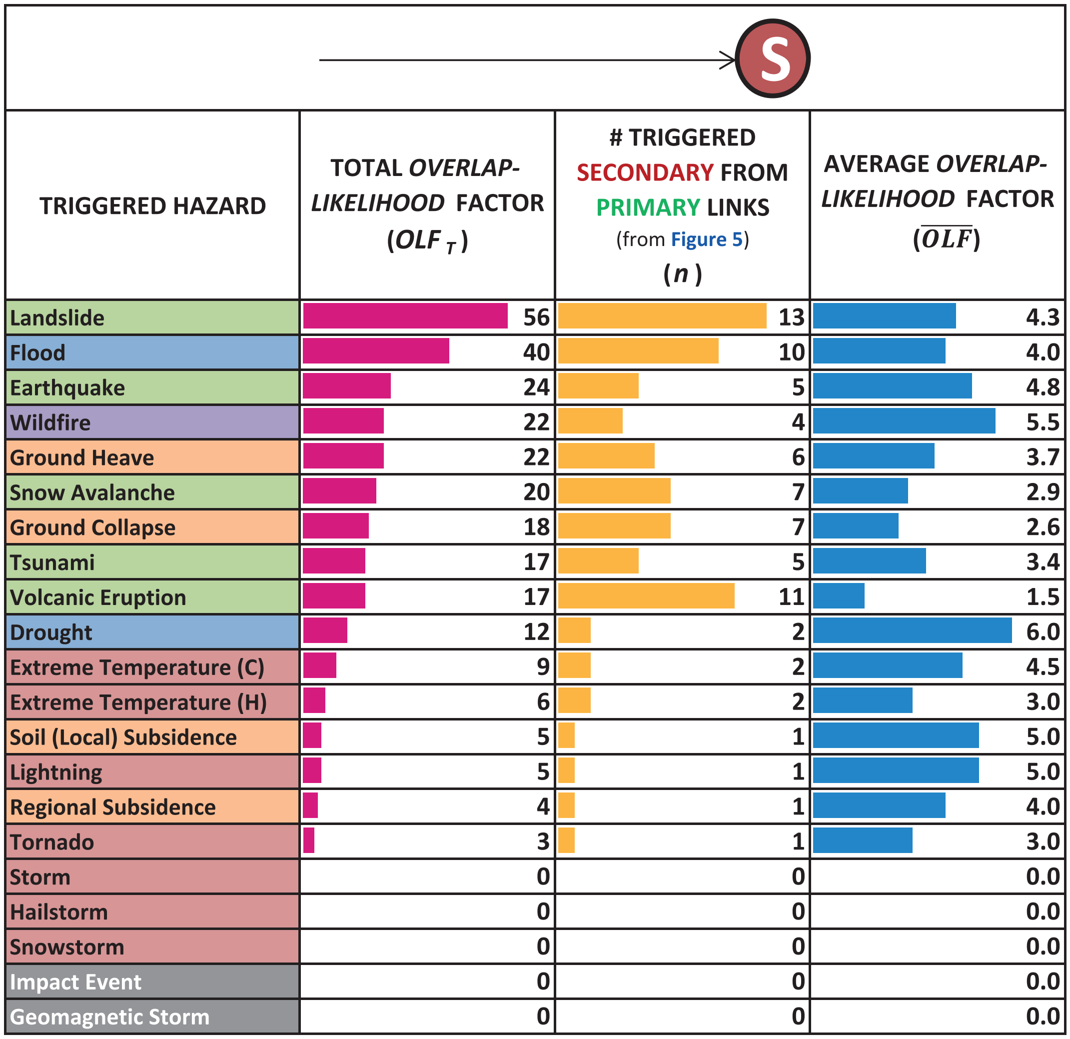


Figure 9. Ranking of individual triggered secondary hazards based on OLF_T, their total *Overlap-Likelihood* Factor. The first column gives the triggered secondary hazard. The second column gives OLF_T, the total *Overlap-Likelihood* Factor, based on equation (1) and as given in Figure 8. The third column gives the number of triggered secondary from primary hazard links, n, as given in Figure 5. The fourth column is the average *Overlap-Likelihood* Factor (equation (2)): $\overline{OLF} = OLF_T/n$.

and presented in Figure 5. We highlight three triggered secondary from primary hazard examples and their change in rankings from Figures 5–9:

1. *Volcanic Eruptions* (drop in rankings). An initial assessment of volcanic eruptions (Figure 5, right) ranked them second in terms of the number of triggered secondary from primary hazard linkages (triggered by 11 possible primary hazards). When the *spatial overlap* and *temporal likelihood* (Figure 7) of each of these 11 interactions is taken into account, we can construct a histogram (Figure 8i) that shows that 10 out of 11 of these interactions have OLF = I or II, resulting in $OLF_T = 17$ and $\overline{OLF} = 1.5$. Whereas in Figure 5, volcanic eruptions ranked second, based on OLF_T, in Figure 9, they ranked joint seventh.
2. *Wildfires* (rise in rankings). In Figure 5, wildfires ranked seventh, whereas in Figure 9 they ranked fourth with $OLF_T = 22$ (and corresponding $\overline{OLF} = 5.5$).
3. *Landslides* (same ranking). In contrast to the above two examples, landslides were ranked first in Figure 5 and first in Figure 9, with $OLF_T = 56$, $\overline{OLF} = 4.3$ and the highest frequency of triggered secondary hazard from primary hazard links ($n = 13$). This result highlights the global importance and widespread prevalence of landslides (which includes translational and rotational slides, debris flows, and rockfalls) and their potential to be triggered by multiple primary hazards.

In addition to an adjustment by using both *spatial overlap* and *temporal likelihood*, further refinements could be carried out (e.g., removing slow-onset triggered hazards such as drought).

6. Intensity Relationships

A further aspect of hazard interactions that can be constrained is the relationship between primary hazard intensity and secondary hazard intensity. In this context, we define intensity as being the severity of an event in terms of its impact (or potential impact) on the natural environment. This definition of intensity that we take for the purpose of this section excludes the impacts on human populations and the built environment and solely focuses on the relationships between different natural hazards and the natural environment. For example, in this study the intensity of a landslide may be considered to be the total volume of material displaced (natural environment) but not the total number of houses destroyed (human/built environment).

Given an understanding of the physical process by which one hazard triggers (section 6.1) or increases the probability (section 6.2) of a secondary hazard, it is possible to consider the likely impact of an increase or decrease in intensity of the primary hazard on the intensity of a particular secondary hazard. Descriptions of these physical processes are noted under the subheading "generic mechanism description" in Table S1 in the supporting information. Classifications derived below were determined by considering and utilizing the Table S1 descriptions of the generic mechanisms or physical processes by which one hazard triggers or increases the probability of a secondary hazard.

6.1. Intensity Relationships for Triggered Hazards

In this section, we examine those relationships where a secondary hazard has been triggered by a primary hazard and visualize the possible intensity relationships between the primary and triggered secondary hazard. In Table 7, we outline six possible relationships between the primary and triggered secondary hazard intensities. These relationships are hypothetical ones that we believe represent the majority of case studies that we have examined in this paper and can also be derived from an examination of the interaction mechanisms discussed in section 3.3. However, we also recognize that other relationships might exist. Five of the relationships in Table 7 are visualized graphically in Figure 10, with the intensity of the primary hazard on the *x* axis in arbitrary units and the intensity of the secondary hazard on the *y* axis (arbitrary units): (a) threshold "alone," (b) continuous "alone," (c) threshold + continuous, (d) continuous + cutoff, and (e) threshold + continuous + cutoff. The sixth category in Table 7 is labeled "complex," where a high level of dependency on a specific location means that it is difficult to represent this graphically. The five relationships shown in Figure 10 include various permutations of three key factors:

1. *Threshold*. A minimum amount of energy is needed from the primary hazard in order to initiate the secondary hazard.
2. *Continuous relationship*. The intensity of the secondary hazard will increase as the intensity of the secondary hazard also increases.
3. *Cutoff value*. The existence of one or more limiting factors means that even if the primary hazard intensity increases, the secondary hazard intensity would remain constant.

It is recognized that the hypothetical relationships described in Table 7 and visualized in Figure 10 are likely to be simplified representations, with local conditions also influencing the intensity relationship. The relationships described in this and the following sections are therefore simplified expectations rather than observed relationships.

As the definition of intensity is stated (section 6) to be "the severity of an event in terms of its impact (or potential impact) on the natural environment," it is feasible that the relationship can be described using more than one of the relationships outlined in Table 7 or Figure 10. A different classification may be used depending on the boundary conditions stated and which aspect of the natural environment is being examined. For example, whereas earthquake intensity would be measured by moment magnitude (a function of how much energy is released), landslide intensity could be measured by the total number of landslides or the total volume of material.

In Figure 11, we present a matrix highlighting these six intensity relationships for those hazard interactions where a primary hazard triggers a secondary hazard. This matrix has a similar structure and layout to previous matrices (Figures 2, 6, and 7). Each of the six relationships is represented using a different color code: threshold "alone" = green; continuous "alone" = purple; threshold + continuous = orange; continuous + cutoff = blue; threshold + continuous + cutoff = pink; complex/location-specific = grey. Where there are multiple relevant

Table 7. Possible Triggering Intensity Relationships[a]

Intensity Relationship	Relationship Description
Threshold “alone”	The secondary hazard will only occur if the intensity of the primary hazard is at or exceeds a minimum amount (a threshold). The intensity of the secondary hazard does not get greater if the intensity of the primary hazard gets greater.
Continuous “alone”	The intensity of the secondary hazard can be mapped in a proportional way to the intensity of the primary hazard (i.e., as the primary hazard intensity increases, so does the intensity of the secondary hazard).
Threshold + Continuous	The secondary hazard will only occur if the intensity of the primary hazard is at or exceeds a minimum amount (a threshold). After this exceedance value, the intensity of the secondary hazard will then increase in a proportional way to the intensity of the primary hazard.
Continuous + Cutoff	The intensity of the secondary hazard can be mapped in a proportional way to the intensity of the primary hazard (i.e., as the primary hazard intensity increases, so does the intensity of the secondary hazard). Beyond a certain primary hazard intensity, one or more limiting factors mean that the intensity of the secondary hazard will not increase any further.
Threshold + Continuous + Cutoff	The secondary hazard will only occur if the intensity of the primary hazard is at or exceeds a minimum amount (a threshold). After this exceedance value, the intensity of the secondary hazard will then increase in a proportional way to the intensity of the primary hazard. Beyond a certain primary hazard intensity, one or more limiting factors means the intensity of the secondary hazard will not increase any further.
Complex (location specific)	The intensity of the secondary hazard is very difficult to relate to the intensity of the primary hazard. This could be because of it being very specific to the particular location.

[a]Descriptions of possible relationships between the intensity of the primary hazard and the intensity of the secondary hazard for cases where one hazard triggers another hazard. Examples are given in Table 8.

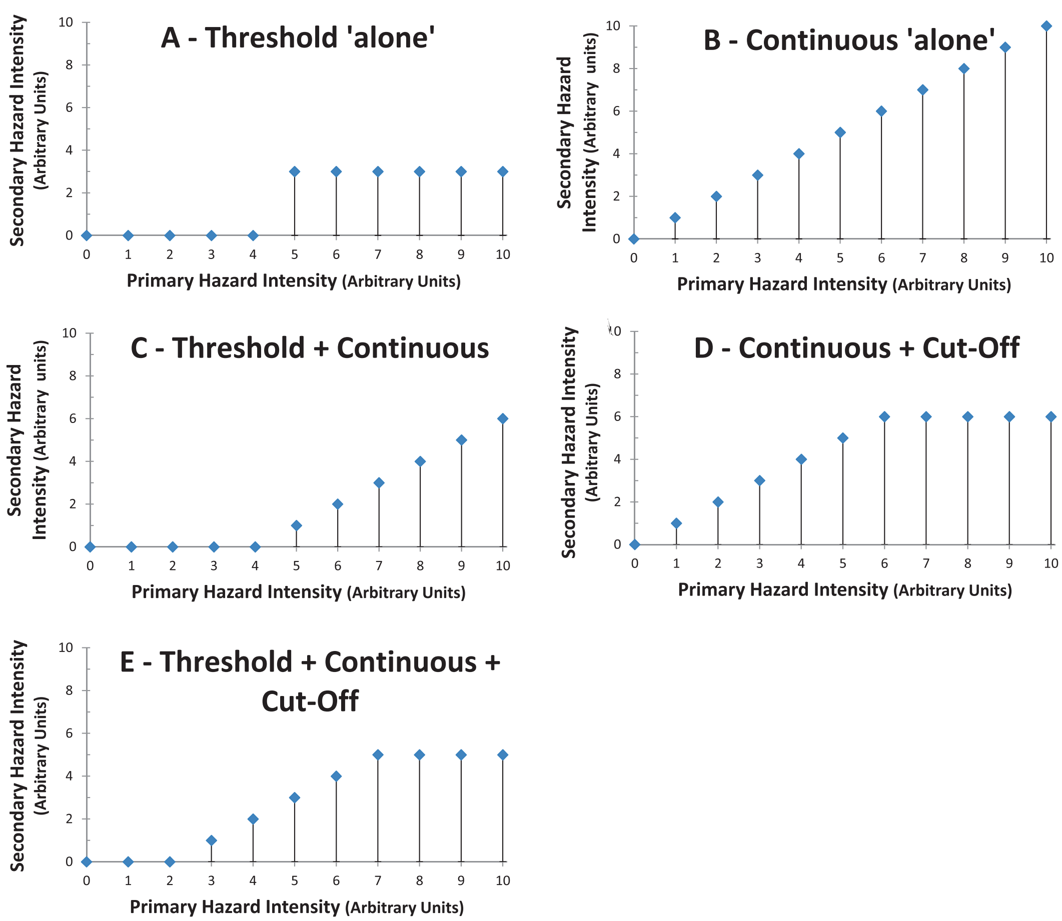
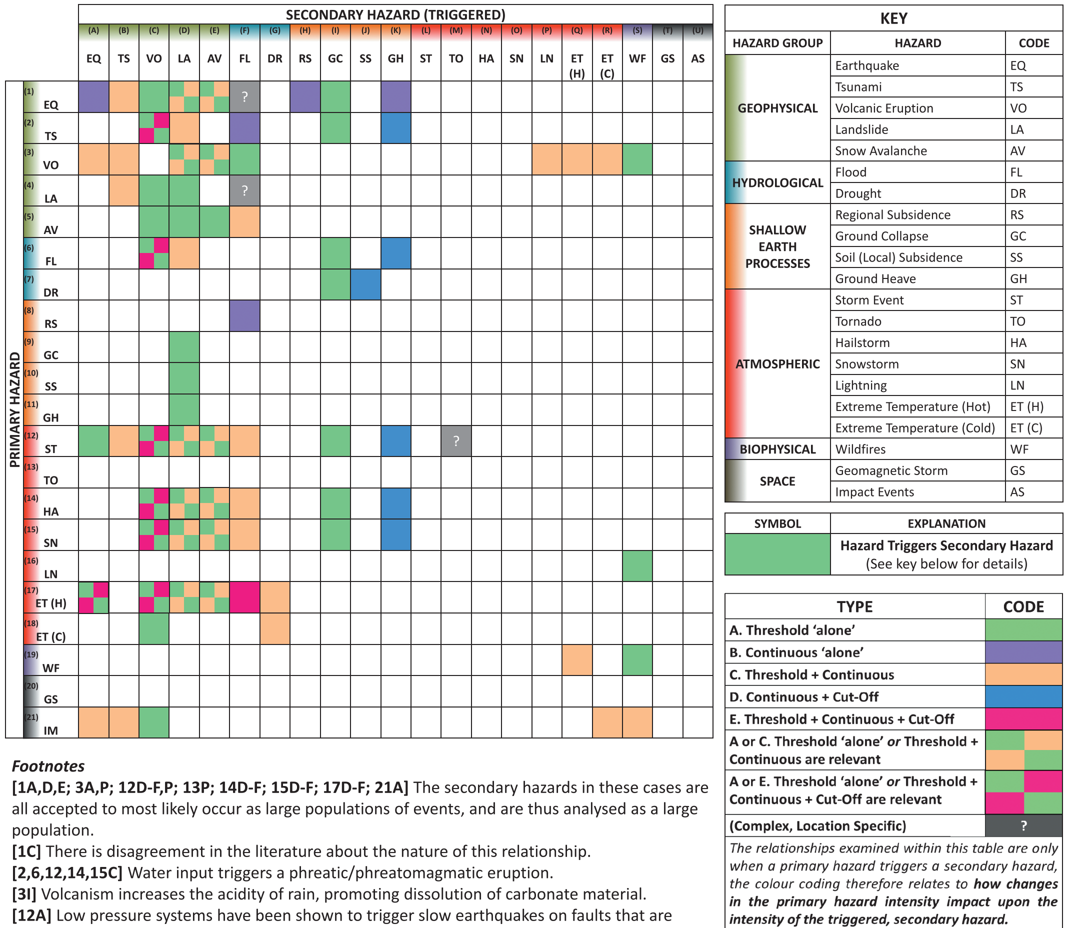


Figure 10. Possible triggering intensity relationships. Simplified cartoon graphs (using arbitrary units) of possible relationships between the intensity of the primary hazard and the intensity of the secondary hazard for cases where one hazard triggers another. Descriptions of each of these relationships can be found within Table 7.



Footnotes

[1A,D,E; 3A,P; 12D-F,P; 13P; 14D-F; 15D-F; 17D-F; 21A] The secondary hazards in these cases are all accepted to most likely occur as large populations of events, and are thus analysed as a large population.
[1C] There is disagreement in the literature about the nature of this relationship.
[2,6,12,14,15C] Water input triggers 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 slow earthquakes on faults that are already close to failure (Liu *et al.,* 2009).
[**12-15]** If these primary hazards stall then the primary hazard intensity will be spatially concentrated, and therefore the triggered hazard intensity is likely to increase.
[17C-F] Secondary hazards triggered 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 11. Triggering intensity relationships. A 21 × 21 matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded as explained in the key. This matrix outlines the different relationships between the intensity of the primary hazard and the intensity of the triggered secondary hazard. This matrix does not show relationships where a primary hazard increases the probability of a secondary hazard. The triggering intensity relationships, as introduced in Table 7, are one or a mixture of the following: threshold “alone” = green; continuous “alone” = purple; threshold + continuous = orange; continuous + cutoff = blue; threshold + continuous + cutoff = pink; complex/location-specific = grey.

relationships, both colors are assigned. Figure 11 shows 78 cells that have a triggering intensity relationship between primary and secondary hazards, with 23 cells (30%) showing a threshold “alone” (green), 21 cells (27%) showing a threshold + continuous (orange) relationship, and 12 cells (15%) showing a combination of these two (green + orange). The remaining 22 cells (28%) are distributed among the other triggering intensity types, with just one to seven cells per type. We also observe that when examining specific columns or rows, the range of different relationships can vary. For example, in columns that have landslides or snow avalanches as the triggered secondary hazard, the range of relationship types is small, but in rows that have earthquakes or storms as the primary hazard, the range of different relationship types is much greater.

In order to demonstrate how these triggering intensity relationships relate to the underlying physical mechanisms, Table 8 outlines an example of each intensity relationship using the classifications in Figure 11. These examples include seven different hazards drawn from across four of the six hazard groups used within this study and describe how a change in the primary hazard will influence the triggered secondary hazard.

Table 8. Examples of Each Triggering Intensity Relationships[a]

Intensity Relationship	Example	Example Description
Threshold "alone" (color code: green)	Landslides triggering volcanic eruptions	Assuming a volcano is in a close to eruptive state, a landslide on its flank will only trigger an eruption if it is at or above a specific intensity (in terms of the volume of material transported). Once this threshold is reached or crossed, the volcanic eruption will occur and its intensity is then determined by factors other ithan the intensity of the nitial landslide, the primary hazard.
Continuous "alone" (color code: purple)	Earthquakes triggering further earthquakes	Earthquakes cause changes in the lithospheric stress conditions. As the lithosphere responds to these changes in stress, this can lead to aftershocks. The likelihood of aftershocks with a greater intensity (in terms of the energy released) increases as the intensity of the primary hazard (main earthquake shock) increases.
Threshold + Continuous (color code: orange)	Landslides triggering tsunamis	The intensity of the landslide (in terms of the volume of material) must exceed a particular volume before a tsunami is generated. After this threshold has been crossed, there is a continuous relationship with bigger landslides triggering bigger tsunamis.
Continuous + Cut Off (color code: blue)	Storms triggering ground heave	Increased water results in the swelling of clay minerals, soil expansion, and ground heave. As storms increase in intensity, thus providing more water, the amount of uplift will increase. This will reach a cutoff value, however, when the clay is saturated and minerals have reached their full swelling capacity. After this point, if the primary hazard intensity continues to increase, the intensity of the secondary hazard will not be any greater.
Threshold + Continuous + Cut Off (color code: pink)	Storms triggering volcanic eruptions	Water from storms can trigger volcanic eruptions through its contact with magma and subsequent superheating. This mixture of steam, pyroclastic material, and magma can then be ejected to form a phreatomagmatic eruption. In this relationship, water would need to exceed a certain amount (or threshold) before an eruption was triggered. If this amount was exceeded, the intensity of the eruption will then be related in a continuous manner to the amount of water (i.e., the intensity of a storm), with water interacting with the magma supply to continuously drive an eruption. At the point where the magma supply is exhausted, it becomes a limiting factor and the system therefore reaches a cutoff value. The eruption will not increase in intensity as a result of increases in the primary hazard.
Complex (Location Specific) (color code: grey)	Earthquake triggered flooding	Earthquakes can trigger flooding if there is an intersection of faults and waterways. It is difficult to relate the intensity of this flooding with the intensity of the earthquake as it is very location specific.

[a]Examples and descriptions of possible relationships between the intensity of the primary hazard and the intensity of the secondary hazard, for cases where one hazard triggers another hazard. Intensity relationships are introduced in Table 7. Examples are taken from the classifications presented in Figure 11.

The relationships presented in Figure 11 have the potential to be used to improve our understanding and forecasting of the likely severity of secondary hazards. Given primary hazards of different intensities or a particular primary hazard changing intensities over time (e.g., the development of a small storm into a tropical storm), the intensity or expected behavior of triggered secondary hazards might be better understood. For example, primary hazards such as storms, snowstorms, or hailstorms could feasibly stall and stay in one particular location, thus increasing in intensity at that location. This stalling (or evolution) of a primary hazard could result in an increased intensity of a number of associated secondary hazards.

Two examples demonstrating how these visualizations could be used are now discussed. In 1969, a tropical depression stalled in Virginia, USA, depositing 780 mm of rainfall in 8 h and triggering approximately 3800 debris flows and widespread flooding [*Wieczorek and Morgan*, 2008]. In other words, a high intensity of rainfall (as the primary hazard) triggered a similarly "intense" set of debris flows and flooding (secondary hazards). The visualizations show how the secondary hazards may respond to an increase in intensity of the primary hazard. In another example, in Guatemala, during Tropical Storm Agatha (section 2.1.4) the

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Table 9. Intensity Relationships Where One Hazard Increases the Probability of Another Hazard[a]

Intensity Relationship	Relationship Description
Threshold "alone"	A primary hazard occurs and causes the threshold (point at which the secondary hazard occurs) to be approached but not exceeded.
Continuous "alone"	As the intensity of the primary hazard increases, the potential intensity of the secondary hazard will also increase. This could be in terms of the energy released within the event or the spatial extent it affects or a combination of both of these factors.
Complex, Location Specific	The intensity of the secondary hazard is very difficult to relate to the intensity of the primary hazard. This could be as a result of it being very specific to the particular location.

[a]Descriptions of possible relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard if it were to occur, for cases where one hazard increases the probability of another hazard. Examples are given in Table 10.

visualization could have been used to assess what impact an increase in storm intensity would have on the expected and observed secondary hazards (including flooding and landslides). By using the visualizations presented here, stakeholders might better visualize the possible evolution of secondary hazard intensities or use them to improve the understanding of and preparedness for secondary hazards.

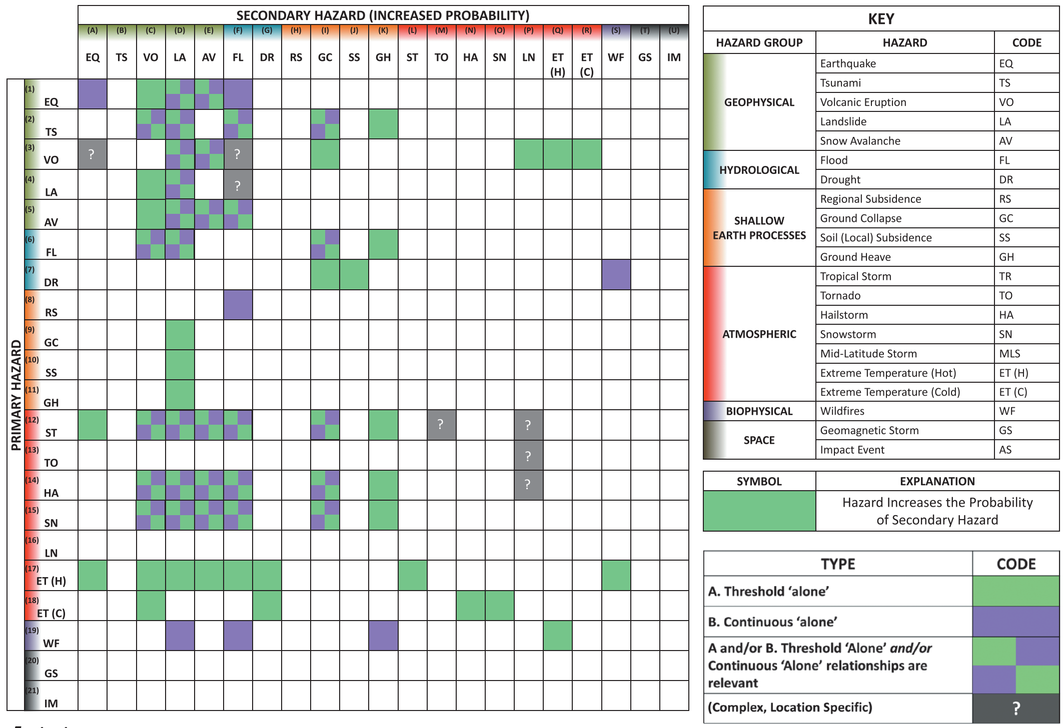
6.2. Intensity Relationships Where the Probability Has Been Increased

This section focuses on intensity relationships for those interactions where a primary hazard increases the probability of a secondary hazard occurring, as opposed to triggering, as considered in the previous section. In this case, the subject of interest is how changes in the intensity of a primary hazard impact upon the potential intensity of future secondary hazards. As these secondary hazards are not directly triggered by a primary hazard—only their probability increased—our examination is focused on how a change in the primary hazard intensity will impact upon the likelihood or potential intensity of the secondary hazard. That is, is there a relationship between the intensity of the primary hazard and the *potential* intensity of the secondary hazard (given another hazard event)? For example, in the event of a wildfire the amount of burnt area (or intensity) would contribute to the number of landslides (in the form of debris flows) that occur if there is a storm. This contrasts with case studies in section 6.1 where we examine how the intensity of a primary hazard directly relates to the actual intensity of a triggered secondary hazard.

In Table 9 we consider three increased probability relationship types between the primary and potential secondary hazard intensities: threshold "alone," continuous "alone," and complex (location specific). A threshold alone relationship is where the primary hazard changes the natural environment so as to change certain parameters that influence the occurrence of a secondary hazard, moving these parameters closer to the values required for a tipping point to be reached. A continuous alone relationship is one where as the intensity of a primary hazard increases, it changes the natural environment so as to increase the likely intensity (in terms of spatial extent affected, the temporal duration or the energy released) of any future occurrences of the secondary hazard. A complex (location specific) relationship is where there is a high level of dependency on a specific location, making it difficult to represent this graphically.

It is again acknowledged that these relationships are likely to be simplified representations, rather than observed relationships, and that certain local conditions may strongly influence the intensity relationship or nonlinearity may feature.

In Figure 12, we present a matrix highlighting the identified intensity relationships for hazard interactions where a primary hazard increases the probability of a secondary hazard. This matrix has a similar structure and layout to previous matrices (Figures 2, 6, 7, and 11). Each relationship is represented using a different color code (Threshold "alone" = green; continuous "alone" = purple; complex/location-specific = grey). Where there are multiple relevant relationships (i.e., the relationship could be both threshold and continuous) more than one color is assigned. Figure 12 shows 75 cells that have an increased probability intensity relationship between primary and secondary hazards, with 31 cells (41%) showing a threshold alone (green), 7 cells (9%) showing a continuous alone (purple) relationship, and 30 cells (40%) showing a combination of these two (green + purple). The remaining 7 cells (9%) are noted to be complex or highly dependent upon location. In contrast to the relationships described in section 6.1 (for triggering relationships), we observe that there is a much smaller range of possible relationships identified.



Footnotes
[1C] There is disagreement in the literature about the nature of this relationship
[1A,D,E; 3A,P; 12D-F,P; 13P; 14D-F,P; 15D-F; 17D-F] The secondary hazards in these cases are all accepted to most likely occur as large populations of events, and are thus analysed as a large population.
[2,6,12,14,15C] Water input 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 increase the probability of slow earthquakes on faults that are already close to failure (Liu *et al.,* 2009).
[12-15] If these primary hazards stall then the primary hazard intensity will be spatially concentrated, and therefore the hazard intensity is likely to increase.
[17C-F] Secondary hazard probability increased 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.

*The relationships examined within this table are only for when a primary hazard increases the probability of a secondary hazard occurring. The colour coding relates to **how changes in the intensity of the primary hazard impact upon the potential intensity of the secondary hazard, should it occur.***

Figure 12. Increased probability intensity relationships. 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, for relationships where one hazard increases the probability of secondary hazards, outlines the different relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard if it were to occur. This matrix does not show relationships where a primary hazard triggers a secondary hazard. The triggering intensity relationships, as introduced in Table 9, are one or a mixture of the following: threshold "alone" = green; continuous "alone" = purple; complex, location specific = grey.

In order to demonstrate how the intensity relationships visualized in Figure 12 relate to the underlying physical mechanisms, Table 10 outlines an example of each of them. These examples describe how a change in the primary hazard will affect the potential intensity of the secondary hazard. For example, the relationship between subsidence and flooding, observed in the 1964 Alaskan earthquake (section 2.1.2), can be characterized in this way. It would show a continuous "alone" relationship suggesting that the more subsidence there is (either in terms of spatial extent or vertical displacement) the greater the intensity of future flooding. The use of such intensity relationships supports stakeholders in the forecasting of secondary hazard behavior.

7. Discussion

Within this study, we have reviewed, classified, and visualized multiple natural hazard interactions and demonstrated the importance of constraining such interactions within the context of a holistic hazard assessment. We have developed a series of visualizations that support our understanding of four key aspects of work relating to natural hazard interactions:

Table 10. Examples of Each Increased Probability Intensity Relationship[a]

Intensity Relationship	Example	Example Description
Threshold "alone" (color code: green)	Volcanic eruption increasing the probability of climatic changes	A volcanic eruption can eject a significant amount of sulfur particles. The bigger the eruption, the more sulfur particles are ejected and the greater the likelihood of them entering the stratosphere, where they can then reside and contribute to climatic changes. As the volcanic eruption increases in intensity, this brings closer the threshold at which the secondary hazard (climatic change) will occur.
Continuous "alone" (color code: purple)	Wildfire increasing the probability of landslides	A wildfire increases the probability of landslides through removing vegetation (which acts as a water sink and provides anchorage, increasing shear strength). As the intensity of wildfires increase (i.e., they affect a bigger area), the potential intensity of the landslides also increases (i.e., a bigger area has an increased susceptibility to failure).
	Regional or local subsidence increasing the probability of flooding	Subsidence, as a result of either tectonic activity or clay shrinkage, increases the probability of a flood occurring through lowering the ground level and thus increasing its vulnerability to flooding. As the intensity of the subsidence increases (in terms of the extent of displacement both vertically and horizontally) the potential intensity of a flooding event will also increase.
Threshold "alone" and Continuous "alone" (color code: green + purple)	Earthquakes increasing the probability of landslides	An earthquake will change the stress conditions of slopes and in doing so may (i) trigger landslides or (ii) increase the probability of landslides. In the case of the latter, the shear stress may be increased, pushing the slope toward the point of failure but not passing this point (Threshold "alone"). An earthquake with a greater magnitude, however, will also impact a greater number of slopes and thus increase the probability of landslides across a wider area in the event of a further trigger (Continuous "alone").

[a]Examples and descriptions of possible relationships between the intensity of the primary hazard and the potential intensity of the secondary hazard if it were to occur, for cases where one hazard increases the probability of another hazard. Intensity relationships are introduced in Table 9. Examples are taken from the classifications presented in Figure 12.

1. An identification and review of hazard interactions where a primary hazard either triggers or increases the probability of a secondary hazard. This review includes the description of interaction mechanisms, the collation of relevant case studies, and the analysis of "primary hazard to triggered secondary hazard" links and "triggered secondary hazard from primary" hazard links (section 3).
2. An analysis of the forecasting potential for each secondary hazard (in terms of location, timing, and magnitude) that has been triggered or where the probability has been increased, given information about the primary hazard (section 4).
3. A determination of *spatial overlap* and *temporal likelihood* for each triggered secondary hazard, given that the primary hazard has already occurred (section 5).
4. An assessment of the simplified relationships between the intensity of a primary hazard and the intensity of a secondary hazard (section 6), where the secondary hazard is either triggered or the probability increased by the primary hazard.

Furthermore, throughout these earlier sections and in the supporting information (Table S1), we have presented multiple case studies that motivate this work. The supporting information also includes a discussion of generic mechanism descriptions (Table S1), a detailed breakdown of the classifications (spatial location, timing, and magnitude) used to assess our ability to characterize hazard interactions (Table S2), an outline of global hazard distribution maps (Table S3), and several high-resolution figures (Figures S1–S6).

In this section, we begin by discussing the limitations and uncertainties of the information generated within each aspect of this research (section 7.1). We then establish the importance of this research within the context of a multihazard framework (section 7.2), outlining a framework and presenting an overview of this discipline. We describe three potential users for the information and visualizations generated (section 7.3) and end by discussing four possible future research directions (section 7.4).

7.1. Limitations and Uncertainties

In this section we examine a number of limitations and factors that contribute to uncertainty within the analysis of hazard interactions. These include (1) knowledge bias, (2) exclusion and resolution of hazards, (3) use of older and grey literature, (4) the contrast between slow versus rapid onset secondary hazards, and (5) parameter uncertainty and hazard chains. These limitations impact upon both the accuracy and utility of the results. The wider issue of uncertainty analysis within this and similar research is also considered, including how we attempt to communicate and visualize this information within this work.

1. *Knowledge bias*. The nature of multihazard interaction research requires an awareness and understanding of multiple disciplines in order to avoid a bias toward certain hazards or hazard groups. The collation of >200 references (section 3.3) required to populate Table S1 in the supporting information and those primary-secondary hazard matrices derived from this information (including Figures 2, 6, 7, 11, and 12) implies a need to investigate knowledge from multiple disciplines. However, a knowledge bias may still arise. For example, a strong background in engineering geology is likely to involve a greater knowledge of case studies relating to landslides, ground subsidence, ground collapse, and ground heave. Somebody with a strong background in atmospheric dynamics or meteorology may have a greater knowledge of case studies related to severe storms or extreme temperatures. While it is possible to manage knowledge biases (e.g., by bringing in a diverse set of scientific backgrounds when investigating hazard interactions), they are very difficult to remove entirely.
2. *Exclusion and resolution of hazards*. A limitation, initially outlined in section 2.4, where we discussed hazards and hazard types, is the exclusion of certain hazards or hazard groups. In our study, a wide range of natural hazards were included (21 hazards within six groups; Table 2), however, other natural, anthropogenic, and technological hazards were excluded. This will result in the omission of certain hazard interactions from the literature review that forms our evidence base (section 3) and the hazard interaction matrix presented in Figure 2. This omission will then be carried through in subsequent sections and analyses. For example, in the case study from Guatemala, initially outlined in section 2.1.4, the secondary hazard of flooding was noted to be a result of heavy rain, blocked drainage, and poor maintenance. The latter two, like other anthropogenic processes, are not considered within the analyses of this study. In section 2.4, we also note that the resolution of hazard classifications within this study (e.g., using a more general classification of "landslides," rather than a more detailed classification of mud and debris flows, rotational slides, translational slides, and rockfalls) could impact upon the results and subsequent analysis. Clear definitions of hazards are required so that the reader can understand what processes are included within each hazard classification, as we attempt to do for each of the 21 hazards presented in Table 2. The selection and resolution of natural hazard classifications used within this study can be justified based on the global scale of interest adopted within this study, but we acknowledge that based on the particular biases and interests of the researcher(s) involved, different classifications could be chosen. The methodology we have presented could certainly be applied to alternative hazard selections and classifications, appropriate to more specific spatial or temporal scales of interest (see section 7.4).
3. *Use of older and grey literature*. Research presented within this paper required the overview of a wide literature base (discussed in section 3.1 and presented in Table S1 in the supporting information), utilizing both historical and recent case studies. The accuracy of historical recordings that document one hazard triggering or increasing the probability of another hazard is hard to determine, and therefore the selection of such examples was minimized where possible, with a preference given to more recent case studies. There are, however, instances where recent studies of historical examples provided useful information (e.g., studies of the multiple hazard events in Unzen and Mayoyama in 1792 as discussed in section 2.1.1 and the eruption of Krakatoa in 1883). The use of historical case studies as evidence is a source of uncertainty within the results of this research, due to the age of the event itself, lack of instrumental records, difficulties in verifying information and records, and the impact that possible differences in interpretation of the natural environment may have on descriptions. In addition to using literature describing historical and recent case studies, this research also used both peer-reviewed and grey literature (e.g., textbooks, government reports, and media reports). While this adds further uncertainty regarding the accuracy of utilized information, the inclusion was justified based on the following:

a. The requirements of a systematic review (Table 3) to use multiple sources of information.
b. The significant reporting of hazard events in nonacademic databases (e.g., media reports).
c. The importance of textbooks describing qualitative and quantitative methods used to quantify relationships between hazards [e.g., *Johnson and De Graff*, 1988; *Wyllie and Mah*, 2004; *Francis and Oppenheimer*, 2004; *Clague and Stead*, 2012].

Attempts were made to cross check sources of grey literature with sources of academic literature to reduce the reliance on grey literature alone. There were some instances, however, where grey literature was the most appropriate or only information available to assess whether a hazard interaction exists and should be included within those interactions given in Figure 2.

4. *Contrast between slow versus rapid onset secondary hazards*. A fourth uncertainty concerns the distinguishing of slow and rapid onset hazards. In many situations, the triggering and occurrence of a secondary hazard will appear to occur simultaneously with the primary hazard because of the rapid nature of onset (e.g., landslides, especially debris flows, triggered by and during a storm). This will limit the ability to utilize information about the primary hazard to determine the necessary forecasting parameters of the rapid onset secondary hazards (Figure 6) and reduce the usefulness of the information about hazard *spatial overlap* and *temporal likelihood* (Figure 7) within a disaster management context. The information presented in Figures 6 and 7 can still be utilized in a constructive manner for providing information in both of the following situations: (i) a slower onset of the secondary hazard(s) (e.g., increased ground heave after heavy rain), (ii) where a forecast can be made about a primary hazard and this information is carried forward to inform the forecasting of projected secondary hazards (e.g., using a storm forecast to derive information about the secondary hazards that may be associated with it). While this contrast between slow versus rapid onset hazards is a limitation to the utility of the information presented here, it does not impact upon the overall results.
5. *Parameter uncertainties and hazard chains*. The overall assessment of uncertainty and possible variations in the results due to a range of factors, including those outlined above, within hazard interaction research is challenging due to the propagation of uncertainties within hazard chains. Each parameter characterizing a primary hazard event (e.g., spatial location, timing, and magnitude) will have uncertainty associated with them. For example, in section 1 and Figure 1, we show the spatial and temporal scales upon which 16 selected natural hazards act. Both the spatial and temporal parameters have uncertainties associated with them. If using these (or other parameters) to try and characterize secondary hazards, these uncertainties will be carried through and thus increase the uncertainties associated with secondary hazard characterization. These uncertainties would then become even greater for tertiary hazards.

The sources of uncertainty outlined above can be classified according to whether they are epistemic (the true value does not vary, but there is uncertainty through lack of knowledge) or aleatoric (the true value varies, there is statistical uncertainty). *Rougier et al*. [2013] provide a nuanced discussion of uncertainty in the context of many different natural hazards, including both epistemic and aleatoric uncertainties. Factors (1) to (4) above are generally epistemic, where the overall uncertainty could be reduced if further research and improved classifications were to be undertaken. Factor (5), however, contains elements of both epistemic and aleatoric uncertainty where there exists elements of uncertainty that further research could help to constrain (epistemic uncertainty) but also statistical variation in parameters associated with the natural environment (aleatoric uncertainty). For example, when examining how a rock mass responds to earthquakes, if we assume that rock mass properties are uniform throughout the slope, then this is a form of epistemic uncertainty, as further mapping, modeling, and sampling would improve our understanding of the particular slope's behavior to seismic activity, therefore reducing uncertainty. In contrast, there is statistical variation (aleatoric uncertainty) in how the same part of a rock mass respond to the same earthquake parameters. Considering sources of uncertainty within the classification scheme given above (factors (1) to (5)) suggests that much of the uncertainties associated with the study of natural hazard interactions could be reduced, given sufficient resources.

In addition to acknowledging uncertainty in various discussions, both in previous sections and above, we have made some attempts to communicate and visualize uncertainty in figures and tables. Here we outline three examples of ways we have represented the relative degree of certainty that exists about the existence of hazard interactions:

1. *Where there are very few or no case studies for a given hazard interaction, this is noted*. In assessing possible uncertainty within our analysis of the existence of hazard interactions (section 3), we note that these results included 16 hazard interactions (out of 90) for which very few or no recorded case studies could be identified.

These were included based on the identification of a hypothetical interaction mechanism or discussion of the relationship within the literature and noted in Table S1 in the supporting information.

2. *Controversial interaction relationships noted in matrix footnotes*. There are relationships where significant debate is found in the literature as to their occurrence and likelihood (e.g., the triggering of a volcanic eruption by an earthquake). Relationships where controversy exists were included in matrix footnotes (see Figures 2, 6, 7, 11, and 12).
3. *Characterization of secondary hazard location*, *timing*, *and magnitude*. In section 4 and Figure 6, we discuss, review, and visualize our ability to characterize secondary hazards (in terms of spatial location, timing, and magnitude) given information about the primary hazard. The matrix presented in Figure 6 highlights where we have excellent (19% of all cases), semi-good (57% of all cases), and poor (24% of all cases) quantitative understanding of the secondary hazard based on information about the primary hazard. Although this characterization is not itself a direct measure of uncertainty, it gives a better understanding of uncertainty about the existence of secondary-primary hazard relationships. For example, when comparing Figure 2 (hazard interactions) with Figure 6 (characterization of the secondary hazard based on the primary hazard), we note that the majority of those relationships that are excellently characterized are relationships with a low degree of uncertainty about their existence (e.g., earthquakes triggering tsunamis and storms triggering flooding). In contrast, those relationships with a higher degree of uncertainty include more cases where our ability to characterize the secondary hazard is poor (e.g., earthquakes triggering volcanic eruptions and storms triggering earthquakes).

We recognize that the hazard interaction matrices and linkage statistics produced above have some limitations and uncertainties, but we believe that within the context of these limitations, the framework proposed in this paper can better integrate hazard interactions within a multihazard framework.

7.2. Hazard Interactions Within a Multihazard Framework

As outlined in section 1, hazard and risk assessments often take a "single hazard" approach to assessing hazard potential, in which hazards are treated as isolated, independent phenomena. The research presented in this paper supports the notion that a single hazard approach is not always adequate for understanding hazard potential within a region and that these assessments should be complemented by a better understanding of hazard interactions. In this section, we outline a framework for a "multihazard" approach, building on single hazard approaches, and discuss the contribution we believe this overview of hazard interactions can make to such a framework.

Multihazard approaches utilize a more holistic methodology to evaluate hazard potential and overall risk. Although multihazard approaches are widely encouraged [e.g., *UN*, 2002; *UN-ISDR*, 2005; *Government Office for Science* (UK), 2012] it is not common for the term multihazard to be defined or such approaches to be outlined. This has resulted in the term multihazard being used in many different ways, leading to some confusion within the natural hazards community. Some authors have used the term multihazard to describe the independent analysis of multiple different hazards [e.g., *Granger et al*., 1999; *Garcin et al*., 2008; *Perry and Lindell*, 2008]. Others use the term to refer to the superimposition of various hazard layers to identify areas of spatial overlap [e.g., *Dilley et al*., 2005; *Wipulanusat et al*., 2011; *Mahendra et al*., 2011]. Such approaches build on a concept proposed by *Hewitt and Burton* [1971], describing the "hazardousness" of a location and highlight the need for an "all-hazards-at-a-place" research design. While these examples emphasize an important aspect of multihazard research, the identification of all possible and spatially relevant hazards, there are other important factors within a multihazard approach to assessing hazard potential or risk. These factors include the integration of natural hazard interactions.

The approaches outlined above could be more helpfully described as "multilayer single hazard" approaches. This is in contrast with a multihazard approach to assessing hazard potential. In a "multilayer single hazard" approach, multiple different hazards are examined but these are still treated independently. In a multihazard approach, multiple different hazards are examined, and the interactions between these hazards are also recognized.

Kappes et al. [2012] notes two proposed frameworks for multihazard approaches that take into account the interactions of natural hazards. These are taken from (1) *Delmonaco et al*. [2006] and (2) *Kappes* [2011]:

1. *Delmonaco et al*. [2006] suggest that multihazard approaches should document the possible occurrences of multiple hazard types, by analyzing both the characteristics of single hazard events and their mutual

interactions and interrelations. This approach clearly communicates the importance of considering a full range of hazards in an area but not treating them as being independent.
2. *Kappes* [2011] outlines an approach that understands all possible hazards in a specific or defined region, constraining the totality of relevant hazards. Associated work [*Kappes et al*., 2010, 2012] also affirms the importance of hazard interactions within such an assessment.

In addition to these two approach descriptions, *Kappes et al*. [2012] describe key challenges associated with compiling a multihazard assessment. These include (1) allowing different hazards to be compared, (2) interrelationships between hazards to be noted, (3) physical vulnerability assessments to be validly contrasted, and (4) the synthesis, communication, and visualization of a broad array of information from multiple disciplines and methods. The description of approaches and challenges identified by *Delmonaco et al*. [2006]; *Kappes* [2011], and *Kappes et al*. [2012] offer a helpful introduction to outlining the notion of a multihazard approach. These will be built upon in order to encapsulate and communicate key components of a multihazard approach to assessing hazard potential and risk.

A multihazard methodology allows a comprehensive understanding of the holistic hazard potential or risk (if also taking into account vulnerability) to a specific geographical location. We propose four key factors that should be taken into account in order to fully understand and constrain the total risk when working with multihazards:

1. *Hazard identification and comparison*. The identification and valid comparison of all identified individual hazards relevant to a defined spatial area.
2. *Hazard interactions*. The identification and characterization of all possible interactions between identified hazards.
3. *Hazard coincidence*. An investigation into the impacts of hazards coinciding spatially and/or temporally, which may be different to the sum of their parts. Such an emergent system behaves differently than the component parts.
4. *Dynamic vulnerability*. The recognition that vulnerability is constantly changing as a result of changing societal dynamics (e.g., urbanization, population growth, and changes in social networks) and sudden shocks. This includes an understanding of how one, or a series of hazards, may also affect this vulnerability (e.g., large groups living in temporary shelters), thus changing the overall future risk to a location or community.

A working framework for an "ideal" multihazard risk assessment, incorporating these factors, could therefore be stated as follows: "A multihazard risk assessment should identify all possible and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses."

In Figure 13, this working framework is related to what has previously been defined as a "multilayer single hazard" approach. It is suggested that a spectrum exists between these two end members (multilayer single hazard approach and a full multihazard approach). Figure 13 recognizes that in order for a hazard assessment to make the transition from a multilayer single hazard risk assessment to a multihazard risk assessment, it is necessary to incorporate the four key factors outlined above.

The analysis of these four factors makes a thorough and complete multihazard assessment difficult and complex to undertake. The challenges of comparing very different phenomena, the inclusion of numerous possible interactions and sequences of interactions or cascade scenarios, and the inclusion of many possible scenarios relating to spatial/temporal coincidence add significant complexity to the construction of a multihazard risk assessment. We will also never know what all the hazards in a specific location are, or understand all parts of the system. Furthermore, the dynamic nature of vulnerability means that the risk a community is subject to is continually evolving, with the possibility of rapid vulnerability changes after a natural hazard or other event. A full multihazard approach assessing each of these factors would be time consuming, data and resource intensive and require the utilization and development of multiple methodologies that draw upon the expertise of multiple disciplines. For these reasons, single hazard approaches to assessing hazard potential and risk dominates research, policy making, and practice within the natural hazards community.

Most research that has examined multihazard approaches has focused on the development or application of methodologies for one or two of the main factors described in previous paragraphs. An overview of the

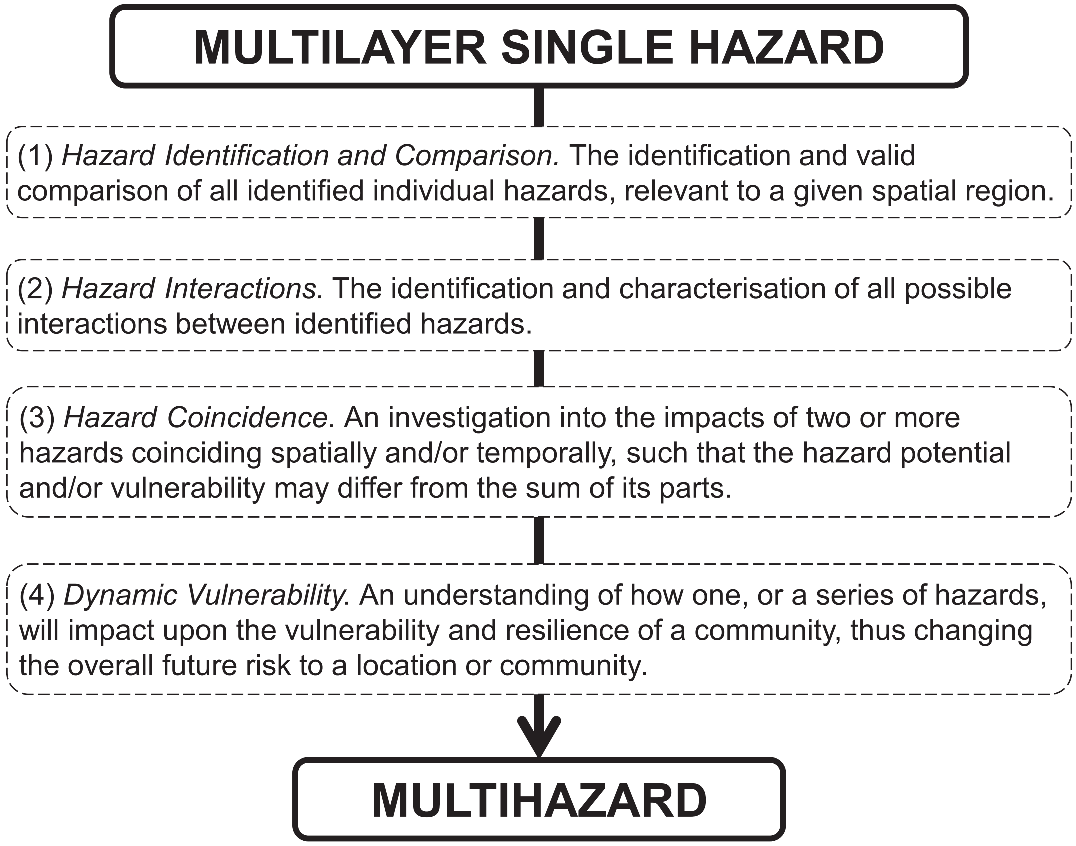


Figure 13. Multihazard framework. This figure represents the progression from a multilayer single hazard approach to a multihazard approach. This involves four key aspects, including (1) hazard identification and comparison, (2) hazard interactions, (3) hazard coincidence, and (4) dynamic vulnerability.

literature suggests that significantly more work has been done on the development of methods to allow the comparison of natural hazards [e.g., *Granger et al.*, 1999; *van Westen et al.*, 2002; *Greiving et al.*, 2006; *Grünthal et al.*, 2006; *Marzocchi et al.*, 2009] than on identifying and constraining hazard interactions [e.g., *Tarvainen et al.*, 2006; *Han et al.*, 2007; *De Pippo et al.*, 2008; *Kappes et al.*, 2010; *van Westen et al.*, 2014]. Hazard interaction relationships are commonly missing from many multihazard approaches, and yet these relationships are regularly observed in case studies, such as those from Japan, USA, Philippines, and Guatemala (section 2.1). Our review and analysis of hazard interactions contributes to the development of a holistic multihazard approach, aiding the identification and initial classification of hazard interactions required to strengthen such approaches.

7.3. Potential Users

Three user communities have been identified that may benefit from the overview, classification, and visualization of natural hazard interactions as presented within this study:

1. *Scientific community*. This research provides a potential mechanism to allow those within the scientific community researching any particular single hazard to place their research within the context of other natural hazards. As hazard interactions often involve more than one system (e.g., atmosphere, lithosphere, and hydrosphere), it is helpful for the scientific community to visualize and understand these interactions. We believe this will help to foster improved communication between hazard specialists and encourage a more interdisciplinary approach. The series of visualizations presented within this research may also aid the identification of future research directions (e.g., high/medium *Overlap–Likelihood* Factor interactions where our ability to characterize secondary hazards in terms of location, timing, and magnitude requires improvement) and collaborative partnerships.

2. *Disaster management/disaster risk reduction practitioners and policy makers*. This study simplifies a large amount of complex information to facilitate an effective analysis by those working on reducing and managing the risk from natural hazards within both the policy and practitioner sectors. The visualization schemes developed can help those within these sectors to understand the possible secondary hazards that could be triggered or have their probabilities increased by primary hazards. In particular, they would benefit from more site-specific information (discussed in section 7.4). The global approach and wide-ranging framework proposed within this study can be modified and utilized within a more local-scale study. Furthermore, it has been proposed that the improvement of approaches to assess multihazard risk would improve disaster risk reduction [*UN*, 2002; *UN-ISDR*, 2005; *Government Office for Science* (UK), 2012]. Constraining hazard interactions is an important component of such an approach, with the information presented here helping the process of identifying and understanding interactions. The qualitative classifications can also be used to inform the development of quantitative decision trees and scenario planning.
3. *Spatial planning*. This information, when combined with further information relating to the built environment could also inform spatial planning. An understanding of regions that are subject to multiple spatially coinciding hazards means that potential networks of interacting natural hazards (Figure 3) could be identified and development in these regions limited or subject to strict controls. As vulnerability dynamics are likely to change between each component of a hazard cascade scenario (often with vulnerability increasing), it is important to understand the potential implications of such scenarios on housing or infrastructure developments.

7.4. Future Research Directions

In this study we have completed a critical review, analysis, and visualization of natural hazard interactions. The limited amount of literature on this topic means that there are a number of useful opportunities for future research that could support the assessment and understanding of hazard interactions. Four possible ways to build upon the work within this study are outlined below:

1. *Incorporate additional hazards*, including further natural and environmental hazards (e.g., ground-based volcanic gases), anthropogenic hazards (e.g., deforestation), and technological hazards (e.g., dam failure). The interactions between these different categories of hazards (e.g., over-abstraction of groundwater leading to ground subsidence and deforestation increasing the probability of landslides) are important, and their review would help to constrain important components of hazard potential and risk. The resolution of hazard classifications could also be made finer, subdividing already included hazards further (e.g., landslides could be separated into debris flows, translational and rotational landslides, and rockfalls).
2. Examine hazard interactions within *specific regions or sites* and adapt the wide-ranging, top down, methodology outlined in this study to a more focused review. A series of "hazard interaction matrices" relevant to particular scales (regional, national, and local), particular tectonic regimes (extensional, compressional), or particular geological/geomorphological settings (quaternary deposits, fluvial, coastal, and arid environments) could be developed and utilized within both risk management and reduction.
3. Develop *improved alternative or expanded classifications* of our ability to characterize secondary hazards (section 4), *spatial overlap* and *temporal likelihood* (section 5), and intensity relationships (section 6). These could incorporate a greater number of classifications (thus improving resolution) or better quantify these relationships. A focus on more quantitative approaches would be highly desirable. The development of an expert elicitation exercise, such as that used by *Neri et al*. [2008] or *Government Office for Science* (UK) [2012], to constrain the interactions identified within this study and the existing ability to forecast them and assess their likelihood would be of great benefit.
4. Transpose this information into *rapid response tools* for assessing potential secondary hazards after a primary hazard has occurred. This could be through the development of an interactive database that relates the visualizations developed within this study to other information and data (key references, equations, case studies, and empirical relationships). Such a tool would allow interested parties from both practitioner and academic communities to access a wide range of information that helps them to better understand possible hazard interaction in the event of a major natural hazard or when planning mitigation strategies. The tool could either be run in an open format where expert communities have the ability to edit and update information relating to their field of expertise and specific hazard interactions or as a centrally managed and reviewed searchable database and tool.

8. Conclusion

In this study, we have presented a wide-ranging review of natural hazard interactions and discussed the importance of constraining such interactions within a multihazard framework. We have focused on interactions where one hazard triggers another or increases the probability of others occurring. This study has identified 90 possible interactions between 21 different natural hazards, with a range of *spatial overlaps* and *temporal likelihoods*. Given information about the primary hazard, many of these hazard interaction relationships can be forecasted to a greater or lesser extent (in terms of spatial location, timing, and magnitude). There are also many situations where the forecasting ability is poor, and further research is required. A broad visualization framework, utilizing matrices and hazard linkage analyses, has been developed in order to represent this information.

There are (see section 1), there are significant differences in terms of each hazard's spatiotemporal impacts, frequency and return periods, intensity, and the instrumentation and field techniques required for their study. This has resulted in the majority of hazard research being segregated, with each hazard type being treated in a distinct manner. While there are some notable exceptions (e.g., landslides triggered by storms or earthquakes and extreme temperatures triggered by volcanic eruptions), it is uncommon to find a research group studying the interconnected relations of multiple natural hazards. We have therefore developed a series of tools and a visualization framework that does the following: (1) supports the better understanding, integration, and quantification of natural hazard interactions; (2) reinforces the importance of a holistic approach to assessing hazard potential by visualizing the significant amount of possible interactions that exist within multiple natural hazard types, thus challenging the adequacy and appropriateness of solely using a single hazard approach; (3) allows those undertaking research into any particular single hazard to place their work within the context of other natural hazards, thus fostering communication between hazard specialists and encouraging a more interdisciplinary approach; and (4) simplifies a broad array of complex information to facilitate an effective analysis by those working on reducing and managing the risk from natural hazards within both the policy and practitioner sectors.

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