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## Increasing the Understanding and Characterisation of Natural Hazard Interactions

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# **Increasing the Understanding and Characterisation of Natural Hazard Interactions**

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Thesis submitted for the degree of Doctor of Philosophy (PhD)  
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# Abstract

This thesis develops global and regional interaction frameworks to enhance understanding, characterisation, and visualisation of natural hazard interactions. This aims to support the international development of multi-hazard methodologies. **Chapter 2** presents a comprehensive characterisation and visualisation of the interactions between 21 natural hazards. We critically review 209 references to populate a global interaction matrix with 90 natural hazard interactions, noting case studies for 74 (82%) of these. **Chapter 3** develops a multi-hazard framework integrating natural hazards, anthropogenic processes and technological hazards/disasters. Variation in spatial and temporal extent, frequency and impact are examined in the context of four case studies of networks of hazard interactions (cascades). **Chapter 4** presents a systematic classification of 18 anthropogenic processes, describing their influence on 21 natural hazards. We critically review 121 references to construct a database of 57 examples of anthropogenic processes triggering natural hazards, with case studies identified for 52 (91%) of these. **Chapter 5** uses existing regional interaction frameworks to identify seven challenges when developing regional interaction frameworks: spatial extent, temporal extent, likelihood-magnitude relationships, hazard selection/classification, consensus, visual style, and limitations/uncertainty. We reflect on these challenges using 19 semi-structured interviews and a 3-hour workshop with hazard and civil protection professionals in Guatemala. **Chapter 6** develops regional (national/sub-national) interaction frameworks for Guatemala. We use peer- and grey-literature, field observations, interviews and a workshop to construct two hazard interaction matrices: (i) 21×21 national matrix, 49 interactions found; (ii) 33×33 sub-national (Southern Highlands) matrix, 112 interactions found. Using Matthews' Correlation Coefficient (*MCC*) the national matrix is contrasted with Guatemalan stakeholders' individual ( $0.21 \leq MCC \leq 0.45$ ) and collective ( $MCC=0.51$ ) knowledge. This thesis gives a series of generalised globally relevant and location-specific characterisations of interactions, presented using a range of accessible visualisation formats. These interaction frameworks can contribute to improved theoretical and practical understanding of hazards and disaster risk reduction.

**Note to Reader.** Chapters 5 and 6, and associated Appendices, have been omitted from the e-thesis due to inclusion of third party copyright material for which permissions could not be granted. Chapter summaries are included, together with a chapter breakdown within the Table of Contents. Page numbering throughout has not been changed from the published thesis. Please contact the author for further information on any material within this thesis.

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*For Stephanie, my rock.*  
*In te Domine spes nostra.*

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# Chapter 1. Introduction

## 1.1 Examples of Hazard Interactions

Forty-five years ago, Hewitt and Burton (1971, p. 5) advocated an "*all-hazards-at-a-place*" framework, encouraging a '*cross-hazard approach*' to understand the '*hazardousness*' of a given location. In this work, Hewitt and Burton (1971) note that most research on natural hazards takes a single hazard approach, but that a greater emphasis on systematic cross-hazard approaches is required. Hewitt and Burton (1971, p. 30) also characterised disasters as frequently involving multiple agents (i.e., hazards), with these either occurring in a compound manner (e.g., wind, rain and lightning all occurring simultaneously during a storm) or occurring in succession (e.g., a hurricane can trigger a landslide and/or flooding). This thesis is comprised of research to do with such interactions between natural hazards. We first give two detailed examples from Guatemala of hazard interactions, and then introduce briefly 18 other examples of hazard interactions.

On the 29<sup>th</sup> May 2010, Tropical Storm Agatha hit the Pacific Coast of Guatemala, bringing strong winds and torrential rains (Stewart, 2011; Stewart and Cangialosi, 2012). This heavy rain triggered mass movements, flooding, and contributed to a ground collapse event in Guatemala City (Stewart, 2011; Wardman *et al.*, 2012). The effects of Tropical Storm Agatha were exacerbated by the near-simultaneous eruption of Pacaya, a complex basaltic volcano located 30 km south west of Guatemala City. Pacaya, shown in [Figure 1.1](#), erupted two days prior to the onset of Tropical Storm Agatha on 27 May 2010 (Wardman *et al.*, 2012).



**Figure 1.1. Pacaya, Guatemala (2014).** A complex basaltic volcano, with summit elevation of 2552 m above sea-level (Global Volcanism Program, 2013a). Author's photo, taken in February 2014.

Ash and debris, ejected from Pacaya on 27 May 2010, covered much of Guatemala City. Reports suggested that this ash blocked 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 (Daniell, 2011; Wardman *et al.*, 2012).

Approximately 110 km north west of Pacaya, is the volcanic dome complex of Santiaguito, which has seen unsteady, extrusive activity since 1922 (Bluth and Rose, 2004). Ash and tephra deposits from the flanks of Santiaguito are mobilised by rainfall, resulting in lahars. These lahars subsequently trigger floods through increased sedimentation, the addition of large amounts of tephra material to the hydrological system (Harris *et al.*, 2006). This network of hazard interactions (cascades), illustrated in **Figure 1.2**, can be observed on an approximately annual basis during the rainy season, while Santiaguito is active.



**Figure 1.2. Hazard interactions associated with Santiaguito, Guatemala (2014).** (top left) Frequent eruptions of the Santiaguito Dome, with summit elevation 2500 m, produce large amounts of ash and tephra deposits (Global Volcanism Program, 2013b). (top right, bottom right) Rainfall mobilises ash and tephra deposits to create lahars with high erosive capacity. (bottom left) Ash, tephra and eroded material moves through the hydrological system and can trigger flooding in locations away from the volcanic dome (Harris *et al.*, 2006). Author's photos, taken in February 2014.

The examples given above, and illustrated in **Figures 1.1** and **1.2**, demonstrate the relevance of hazard interactions (e.g., one natural hazard triggering another natural hazard) in Guatemala. Hazard interactions can also be observed in many other locations around the world. In **Table 1.1**

we briefly characterise 18 diverse case studies involve hazard interactions. For each example we note a location and year associated with the event, recognising that some case studies extended over multiple territories and years. We also include an overview and references for each example. These 18 case studies demonstrate a range of different ways in which multiple hazards may occur simultaneously (e.g., two natural hazards coinciding spatially and temporally) or concurrently (e.g., one natural hazard triggering another natural hazard). Despite this prevalence of natural hazard interactions, many assessments continue to treat hazards as being independent phenomena (Kappes *et al.*, 2012). The assumption of independence is not always coherent with the observed reality, as demonstrated by the 18 case studies in **Table 1.1**. It can lead to a distortion of management priorities, an increased vulnerability to other spatially relevant hazards, or an underestimation of risk (Tobin and Montz, 1997; ARMONIA, 2007; Kappes *et al.*, 2010; Duncan *et al.*, 2016).

**Table 1.1. Hazard interactions case study examples.** Diverse case studies that demonstrate the prevalence of hazard interactions, with a location, year and overview stated for each of the 18 examples.

ID	Location	Year	Overview	Reference(s)
1	Unzen/ Mayuyama, Japan	1792	<ol style="list-style-type: none"> <li>1. Eruption of Mt. Unzen triggered the collapse of a volcanic flank on Mt. Mayuyama.</li> <li>2. Volcanic flank collapse (landslide) triggered a tsunami.</li> <li>3. Tsunami resulted in coastal flooding.</li> </ol>	Yoshida and Sugai (2007); Takarada and Melendez (2006)
2	Krakatoa, Indonesia	1883	<ol style="list-style-type: none"> <li>1. Volcanic eruption triggered a tsunami and large rock-falls.</li> <li>2. Rock falls triggered additional localised tsunamis</li> <li>3. Both types of tsunami triggered floods.</li> </ol>	Latter, 1981
3	Haiyuan, China	1920	<ol style="list-style-type: none"> <li>1. Earthquake triggered collapse of loess deposits, and ground subsidence.</li> <li>2. Loess deposits blocked rivers and triggered floods.</li> </ol>	Zhang and Wang (1995)
4	Merapi, Indonesia	1930– 31	<ol style="list-style-type: none"> <li>1. The infiltration of heavy rain may have destabilised the volcanic dome and triggered phreatomagmatic eruptions.</li> <li>2. Further heavy rain triggered lahars.</li> </ol>	Voight <i>et al.</i> (2000)
5	Huascarán, Peru	1970	<ol style="list-style-type: none"> <li>1. Earthquake triggered rock and ice fall.</li> <li>2. Rock and ice accumulated further material while travelling downslope, the ice/snow melted, and a mud-rich debris flow formed.</li> </ol>	Evans <i>et al.</i> (2009)
6	Alaska, USA	1981	<ol style="list-style-type: none"> <li>1. Earthquake triggered submarine and subaerial landslides, tsunami, and tectonic subsidence and uplift.</li> <li>2. Submarine landslides triggered further tsunami waves.</li> <li>3. Tsunami waves and initial tectonic subsidence resulted in coastal flooding.</li> </ol>	Eckel (1970); Suleimani <i>et al.</i> (2009)

ID	Location	Year	Overview	Reference(s)
7	Nevado del Ruiz, Columbia	1985	<ol style="list-style-type: none"> <li>1. Volcanic eruption triggered snow/ice melting.</li> <li>2. Snow and ice melt combined with debris to form lahars.</li> </ol>	Pierson <i>et al.</i> (1990)
8	Pinatubo, Philippines	1991	<ol style="list-style-type: none"> <li>1. Explosive volcanic eruption triggered earthquakes, and global cooling effects.</li> <li>2. Coincidence of volcanic eruption with Typhoon Yunya resulted in lahars and structural failures.</li> <li>3. Lahars blocked rivers, causing flooding.</li> </ol>	Self <i>et al.</i> (1996); White (1996); Harlow <i>et al.</i> (1996); Mori <i>et al.</i> (1996); Stenchikov <i>et al.</i> (1998); Scott <i>et al.</i> (1999) Robock (2000); Umbal and Rodolfo (1996); Self (2006); Chester (1993).
9	Mt Cook, New Zealand	1991	<ol style="list-style-type: none"> <li>1. Warm temperatures triggered snowmelt.</li> <li>2. Snowmelt triggered a large snow avalanche and landslide.</li> </ol>	Huggel <i>et al.</i> (2010)
10	Eastern USA	1992	<ol style="list-style-type: none"> <li>1. Hurricane Andrew triggered lightning, flooding and tornadoes.</li> </ol>	Molinari <i>et al.</i> (1994); NOAA (2013)
11	Northridge, USA	1994	<ol style="list-style-type: none"> <li>1. Earthquake triggered more than 11,000 landslides.</li> <li>2. Landslides blocked roads and hampered relief efforts.</li> </ol>	Harp & Jibson (1995)
12	Umbria, Italy	1996–97	<ol style="list-style-type: none"> <li>1. Rapid temperature increase triggered the melting of snow from a recent snowstorm.</li> <li>2. Snowmelt triggered many landslides.</li> </ol>	Cardinali <i>et al.</i> (2000)
13	Chi-Chi, Taiwan	1999	<ol style="list-style-type: none"> <li>1. Earthquake triggered 1000s of landslides, ground heave and large aftershocks.</li> </ol>	RMS (2000)
14	Wenchuan, China	2008	<ol style="list-style-type: none"> <li>1. Earthquake triggered more than 15,000 landslides, rock falls and debris flows.</li> <li>2. Some landslides blocked rivers and triggered floods.</li> </ol>	Yin <i>et al.</i> (2009)
15	Zhouqu, China	2010	<ol style="list-style-type: none"> <li>1. Heavy rain triggered a large debris flow.</li> <li>2. Debris flow blocked a river and triggered floods.</li> </ol>	Tang <i>et al.</i> (2011)
16	Maule, Chile	2010	<ol style="list-style-type: none"> <li>1. Earthquake triggered a tsunami and multiple aftershocks.</li> </ol>	Wilson <i>et al.</i> (2010)
17	Tohoku, Japan	2011	<ol style="list-style-type: none"> <li>1. Earthquake triggered tsunami, ground subsidence and landslides.</li> <li>2. Tsunami triggered floods.</li> </ol>	Mori <i>et al.</i> (2012)
18	Bududa, Uganda	2013	<ol style="list-style-type: none"> <li>1. Hailstorm triggered multiple mudslides and floods</li> </ol>	Wanzusi and Watala (2013)

The examples described in [Table 1.1](#) are taken from multiple continents. They include examples of interactions from as far back as 1792 (ID-1), and as recently as 2013 (ID-18). [Table 1.1](#) includes events that resulted in both high and low numbers of fatalities. For example, the 2011 Tohoku (Japan) earthquake and triggered hazards (ID- 17) resulted in more than 15,000 fatalities

(Mori *et al.*, 2012) and the 2013 Bududa (Uganda) landslide (ID-18) resulted in one fatality and 17 injured people (Wanzusi and Watala, 2013).

It is in this context that this research is placed, aiming to increase the understanding and characterisation of natural hazard interactions. This can help to facilitate the development of the improved ‘*cross-hazard*’ approaches described by Hewitt and Burton (1971). In this research we use a multi-method approach, that integrates the following three components:

- i. *Database development.* Critical reviews of large sets of diverse literature to create databases of relevant interactions.
- ii. *Accessible visualisations.* Development of accessible visualisations to communicate large amounts of multidisciplinary information, populated with information from the interaction databases.
- iii. *Field visits and stakeholder engagement.* Observations and discussion of hazard interactions in the multi-hazard environment of Guatemala, including 21 semi-structured interviews and one workshop with hazard and civil protection professionals.

Justification of these three components is included in individual research chapters. These components are combined to develop a set of comprehensive interaction frameworks (which we define to be *usable visualisations that aid the identification and characterisation of relevant interactions*) for both global and regional (Guatemala) contexts.

## 1.2 Rationale

While some progress towards systematic ‘*cross-hazard*’ approaches advocated by Hewitt and Burton (1971, p. 5) has been made, there is a continued focus by the natural hazards and disaster risk community on single hazard approaches to assess hazard potential. Such approaches often treat hazards as being independent phenomena. This is confirmed by both a rapid overview of the natural hazards literature and an examination of the structure of natural hazards sessions at international research conferences (e.g., the European Geoscience Union’s General Assembly).

Cross-hazard approaches can also be termed ‘*multi-hazard*’ approaches, and we use the latter through the rest of this thesis. Multi-hazard approaches are widely encouraged in key intergovernmental frameworks to facilitate disaster risk reduction (DRR). Examples include:

- i. Hyogo Framework for Action (2005–2015), requesting “*an integrated multi-hazard approach to DRR*” (UNISDR, 2005, p. 4).

- 
- ii. Sendai Framework for DRR (2015–2030), stating that “*DRR needs to be multi-hazard*” (UNISDR, 2015a, p. 10).

Despite the emphasis on multi-hazard approaches within these international agreements, neither the Hyogo or Sendai Frameworks define what multi-hazard approaches should include. At the time of writing, the term multi-hazard also does not appear in the most recent descriptions of terminology published by UNISDR (2009). Without a clear definition of multi-hazard, those implementing and monitoring progress against the Sendai Framework, for example, do not know what is necessary to fulfil its aim and guiding principles. ‘Multi-hazard’ is therefore used in different contexts by different members of the natural hazards and DRR community. Example types of uses include:

- Type 1. Independent analysis of multiple different hazards relevant to a given area (e.g., Granger *et al.*, 1999; Perry and Lindell, 2008).
- Type 2. Identification of areas of spatial overlap of different hazards, by superimposing hazard layers (e.g., Dilley *et al.*, 2005; Shi *et al.*, 2015).
- Type 3. Characterisation of both multiple hazards and possible interactions between these (e.g., Kappes *et al.*, 2010; Marzocchi *et al.*, 2012; Xu *et al.*, 2014).

While Types 1 and 2 both seek to understand the discrete risks due to multiple single natural hazards, Type 3 considers both multiple hazards and the interactions between them. Both improved single hazard approaches, and those approaches in Types 1 and 2 that are termed ‘multi-hazard’, are important steps in the development of the systematic cross-hazard approach described by Hewitt and Burton (1971). The identification and characterisation of interactions between hazards (Type 3), however, is important if we are to accurately reflect the dynamic environment in which hazards operate (Kappes *et al.*, 2012). The examples described in [Section 1.1](#) demonstrate these interaction relationships, and suggest that they are commonplace and important to consider in the context of understanding the ‘*hazardousness*’ of a region (Hewitt and Burton, 1971). While there are examples of multi-hazard studies that do incorporate interactions, these are limited in their scope (e.g., they focus on a small group of natural hazards, they do not include anthropogenic processes), and they are often specific to a case study region. In contrast, Kappes *et al.* (2010), encourages a top-down approach that progresses from coarse overviews of interactions to detailed, local studies. Such coarse overviews of global relevance are largely missing from the literature; however, they may be beneficial in the systematic assessment of relevant interactions in a given region.

From this discussion, we summarise in [Table 1.2](#) two observations regarding current multi-hazard approaches. We describe each observation, the problems that arise from these approaches, and examples of the benefits that would come from addressing these problems.

**Table 1.2. Observations regarding current multi-hazard approaches.** A description of two observations associated with current multi-hazard research, the problems that arise from these approaches, and examples of the benefits that would come from addressing these problems.

Observation Number	Description of Observation	Problem Arising from Observation	Benefit that Might Arise from Solving Problem
<b>Observation 1</b>	The term <i>multi-hazard</i> is frequently used but rarely defined, with different meanings depending on the study. For example, many studies that use the term <i>multi-hazard</i> do not consider relevant hazard interactions.	It is difficult to implement and monitor international DRR frameworks that call for <i>multi-hazard</i> approaches (e.g., the Sendai Framework for DRR 2015–30), without knowing what this entails.	A clear definition of <i>multi-hazard</i> , incorporating interactions, may encourage interactions between hazards to be systematically considered.
<b>Observation 2</b>	Some <i>multi-hazard</i> studies do include interactions, but these are commonly: (a) limited in terms of the hazards and processes included, and (b) created for location-specific case study examples. There is a lack of comprehensive, globally-relevant frameworks of interactions.	Those working on single-hazards are not able to place their work into its broader context. Those considering the relevance of interactions in a given region do not have globally-relevant databases of possible interactions to inform them.	Comprehensive globally-relevant interaction frameworks would help to raise awareness of what interactions could occur, and improve the systematic identification and incorporation of relevant interactions in multi-hazard approaches.

Recognising the issues outlined in [Table 1.2](#), the aim of this research is therefore to *increase the understanding and characterisation of natural hazard interactions and interaction networks at both global and regional scales*. We define networks of interactions to be linear and non-linear connections of multiple interactions, forming a hazard cascade, and define regional to be multi-national to sub-national depending on the context. Through this aim we seek to develop and improve multi-hazard assessments, by facilitating the integration of hazard interactions. Both global and regional approaches will be included as the purpose of the interaction framework, and therefore the potential approach required, will likely differ depending on the spatial scale of interest.

Global and regional interaction frameworks that we will develop through this thesis have the following characteristics:

- i. *Comprehensive and systematic.* Interaction frameworks will include a broad range of hazard/process types.
- ii. *Generally applicable.* Global interaction frameworks should facilitate an effective analysis of relevant interactions in many regions of the world. For example, while not every interaction in the global interaction framework will be relevant in every region, the categories of hazards included should help the framework to be used in diverse regions, extracting the relevant interactions. Regional interaction frameworks should also enable generally applicable insights into regional applications of interaction frameworks.
- iii. *Accessible synthesis.* Information will be drawn from many different scientific disciplines, and used by many different professions. Visualisation tools should therefore be clear and accessible, enabling an effective understanding of the information.

Through the interaction frameworks that we develop, and associated commentary on the underlying theoretical context of hazard interactions, we hope to support the development of improved multi-hazard methodologies for understanding natural hazards and disaster risk. Additional discussion of the challenges of existing multi-hazard approaches, and the integration of information on hazard interactions, is included in the following chapters.

### 1.3 Research Objectives and Questions

In addressing the research aim initially outlined in [Section 1.1](#), and further developed through [Section 1.2](#), we identify two principal research objectives (**O1** and **O2**).

- O1. [Global scale]** To undertake a comprehensive review, and develop broad based classifications, of interactions across a diverse range of hazard and process types. This will result in a global interaction framework.
- O2. [Regional Scales]** To adapt the global interaction frameworks (developed in ‘**O1**’) for use in regional settings (Guatemala); exploring, quantifying and contrasting hazard interaction networks developed from data and understandings populating contrasting knowledge worlds (specifically, the international scientific literature, and hazard/civil protection professionals operating in the region).

We address these objectives through a set of five cross-cutting research questions (**Q1** to **Q5**), with some sub-questions noted where appropriate. The chapters in which these questions are tackled are added in brackets, for example [\[Chapter 2\]](#).

- Q1.** What broad types of interaction can be identified in the literature, and how do these interactions join together to form networks of hazard interactions (cascades)? [**Chapters 2, 3 and 4**]
- Q2.** What examples of a hazard/process triggering a natural hazard can be identified in the literature? [**Chapters 2, 3 and 4**]

Example sub-questions include:

- a. What examples exist of natural hazards triggering other natural hazards, and can these interactions be further characterised, in terms of (i) relative forecasting ability; (ii) relative likelihood; and (iii) primary and secondary hazard intensity relationships?
  - b. What examples exist of anthropogenic processes and technological hazards triggering natural hazards?
- Q3.** What visualisations can be developed to better understand and communicate these interactions and networks of hazard interactions (cascades)? [**Chapters 2, 3, 4, 5 and 6**]
- Q4.** At a national spatial extent, and for one sub-national spatial extent in Guatemala, what potential hazard interactions can be identified, and how can we characterise them? [**Chapters 5 and 6**]

Example sub-questions include:

- a. What are the principal challenges in constructing regional interaction frameworks and populating them with interaction information?
  - b. What methods exist to address these challenges, or communicate the uncertainties associated with them in the regional interaction framework?
  - c. What interactions are relevant in different regions of Guatemala?
  - d. How do interactions documented in the literature contrast with the knowledge of hazard/civil protection professionals operating in the region?
- Q5.** What are the implications of our global and regional interaction frameworks for multi-hazard methodologies to support disaster risk reduction (DRR), management, and response? [**Chapters 2, 3, 4, 5 and 6**]

These questions are addressed through five research chapters, with a summary of each presented in the following section.

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## 1.4 Thesis Outline

To address research questions **Q1** to **Q5**, this thesis is organised into two parts:

- Part I.** Global interaction frameworks and multi-hazard methodologies [**Chapters 2, 3, 4**].
- Part II.** Adapting and applying global interaction frameworks for use in regional (multi-national, national, and sub-national) settings in Guatemala [**Chapters 5 and 6**].

Each chapter contains relevant background literature, motivation and methodology sections. Definitions of terms used are introduced in individual chapters where appropriate. Two of the chapters (**Chapters 2 and 3**) have been published in peer-review journals, with one further chapter (**Chapter 4**) currently in review. There is a small amount of repetition in chapters, partly as a result of the context needed in published chapters, with this also aiding consistency of thought and presentation. The chapters are organised as follows, with a summary given for each:

### **Part I - Global Interaction Frameworks and Multi-Hazard Methodologies**

**Chapter 2. Reviewing and Visualising the Interactions of Natural Hazards.** This primary research chapter presents a broad overview, characterisation and visualisation of the triggering and increased probability interaction relationships between 21 natural hazards, drawn from six diverse hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical and space hazards). A critical review and analysis of more than 200 references is used to construct a database (**Appendix A, Table A.1**) of 90 natural hazard interactions between the included 21 natural hazards. We develop two types of accessible visualisation to represent this information: interaction matrices and network linkage diagrams. Information from the database is used to populate interaction matrices and a network linkage visualisation. A suite of five interaction matrices is developed to characterise different aspects of the 90 natural hazard interactions. This chapter was published in *Reviews of Geophysics* (Vol. 52(4)) in 2014.

**Chapter 3. Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies.** This chapter combines research and commentary to develop an enhanced multi-hazard framework, integrating natural hazards, anthropogenic processes and technological hazards/disasters. This chapter (i) describes and defines three groups (natural hazards, anthropogenic processes and technological hazards/disasters) as relevant components of a multi-hazard environment; (ii) outlines three types of interaction relationship (triggering, increased probability, and catalysis/impedance); and (iii) assesses the importance of networks of interactions (cascades) through diverse case study examples. These case studies are examined to demonstrate the diversity and complexity of interaction networks (cascades) in

terms of spatial and temporal extent, frequency and impact. This chapter contributes to the underlying theoretical framework required as this emerging field of research develops. It reinforces the importance of integrating interactions and interaction networks (cascades) into multi-hazard methodologies. This chapter was published in *Earth System Dynamics* in 2016.

#### **Chapter 4. Anthropogenic Processes, Natural Hazards and Multi-Hazard Interactions.**

Humans play a key role in shaping the natural environment, which influences the triggering, catalysing and impeding of natural hazards. This chapter therefore presents a systematic classification and characterisation of 18 anthropogenic processes, describing their influence on 21 natural hazards. A review methodology is used to identify and review 121 references, and construct a database (**Appendix B, Table B.1**) of 57 examples of anthropogenic processes triggering natural hazards. Information from this database, is used to populate an interaction matrix, with case studies identified for 52 (91%) of these 57 triggering interactions. In addition, this chapter presents: (i) an overview of anthropogenic processes triggering other anthropogenic processes to occur, and (ii) a methodology for anthropogenic processes catalysing and/or impeding natural hazards, using the example of vegetation removal. This chapter has been written in the form of a research publication and will shortly be submitted for peer-review.

### **Part II - Adapting and Applying Global Interaction Frameworks for Use in Regional Settings (Guatemala)**

Resulting from **Chapters 2–4** is a series of generalised, globally relevant characterisations of interactions, presented using both interaction matrices and network linkage diagrams. The adaptation of these global interaction frameworks (**Part II** of this thesis) for application in regional settings, such as the multi-hazard environment of Guatemala, is important if interactions are to be given more consideration by scientists and practitioners.

#### **Chapter 5. From Global to Regional Perspectives on Natural Hazard Interactions: Challenges and Opportunities.**

This chapter uses a comparative synthesis of seven existing ‘regional interaction frameworks’, 19 semi-structured interviews and a 3-hour workshop with hazard and civil protection professionals in Guatemala to identify and address challenges when developing regional interaction frameworks. Our comparative synthesis aids the identification of seven challenges when constructing regional interaction frameworks and populating them with relevant information. These seven challenges are: spatial extent, temporal extent, likelihood-magnitude relationships, selection and classification of hazards/processes, consensus on interactions, visual style and user requirements, and limitations and uncertainty. A multi-method approach is used to explore these seven challenges and consider ways to

address them. Perspectives from existing regional interaction frameworks and other literature, are combined with stakeholder engagement in Guatemala, including 19 semi-structured interviews and a 3-hour workshop. This multi-method approach facilitates the development of suggestions as to how to address challenges when constructing regional interaction frameworks and populating them with relevant information on hazard interactions.

**Chapter 6. Regional Perspectives on Natural Hazard Interaction Frameworks (Application to Guatemala).** This final research chapter uses the results of **Chapters 2 to 5** to inform the development of regional interaction frameworks for use in Guatemala. Interaction frameworks are developed for a national spatial extent and a sub-national spatial extent (Southern Highlands) for Guatemala. These frameworks are populated using information from five evidence sources, including both internationally- and locally-accessible sources. Evidence sources used are: (i) a comprehensive synthesis of 93 peer-review and 76 grey- literature sources describing natural hazards and natural hazard interactions in Guatemala; (ii) locally-accessible government issued civil protection bulletins; (iii) field reconnaissance observations; and (iv) 19 semi structured interviews with stakeholders in Guatemala; and (v) a 3-hour workshop with stakeholders in Guatemala. Evidence sources are then integrated and used to do to three tasks.

- Task 1. Develop an appropriate classification scheme for 21 natural hazard types and 37 sub-types that are relevant in Guatemala.
- Task 2. Construct a 21×21 hazard interaction matrix for a national spatial extent in Guatemala.
- Task 3. Construct a 33×33 hazard interaction matrix for a sub-national spatial extent (Southern Highlands) in Guatemala, and consider possible networks of hazard interactions (cascades) and the influence of anthropogenic processes in the Southern Highlands of Guatemala.

Interaction frameworks developed using these diverse strands of evidence are then contrasted with the individual and collective knowledge of hazard/civil protection professionals operating in Guatemala. We quantify the congruence between these two frameworks using Matthews' Correlation Coefficient (Matthews, 1975), and discuss these results in the context of disaster risk communication and multi-hazard understanding. We conclude by considering the role of regional interactions frameworks in increasing the understanding and characterisation of interactions and networks of interactions (cascades), to support multi-hazard methodologies.

Through **Chapters 2 to 6** we make an original contribution to the understanding of natural hazard interactions, and their integration into multi-hazard methodologies. This contribution is discussed

in full in **Chapter 7 (Summary and Conclusions)**, returning to our original research questions. **Chapter 7** also includes a discussion of research and knowledge transfer impact, including examples of future research directions.

## **1.5 Conclusion**

In this chapter we have given an overview of the context and rationale of the research presented in this thesis, defined two research objectives and five research questions, and presented an outline of each chapter. We return to the research objectives and questions that we have established in this chapter in the thesis conclusions and summary (**Chapter 7**).

# **Part I: Global Interaction Frameworks and Multi- Hazard Methodologies**

# Chapter 2. Reviewing and Visualising the Interactions of Natural Hazards\*

## Summary

This chapter presents a broad overview, characterisation and visualisation 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 chapter 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 characterise secondary hazards given information about the primary hazard. (iii) Determine the *spatial overlap* and *temporal likelihood* of the triggering relationships occurring. (iv) Examine the relationship between primary and secondary hazard intensities (*severity of an event in terms of its impact on the natural environment*) for each identified hazard interaction and group these into five possible categories. In this study we have synthesised, using accessible visualisation techniques, large amounts of information drawn from many scientific disciplines. We outline the importance of identifying and characterising hazard interactions, and reinforce the importance of a holistic (or multi-hazard) 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 disaster risk reduction (DRR) and management within both policy and practitioner communities.

\* **Published in *Reviews of Geophysics* in 2014.** Minor edits have been made to ensure consistency in reference style and language with the rest of the thesis. The substance of the chapter remains unchanged.

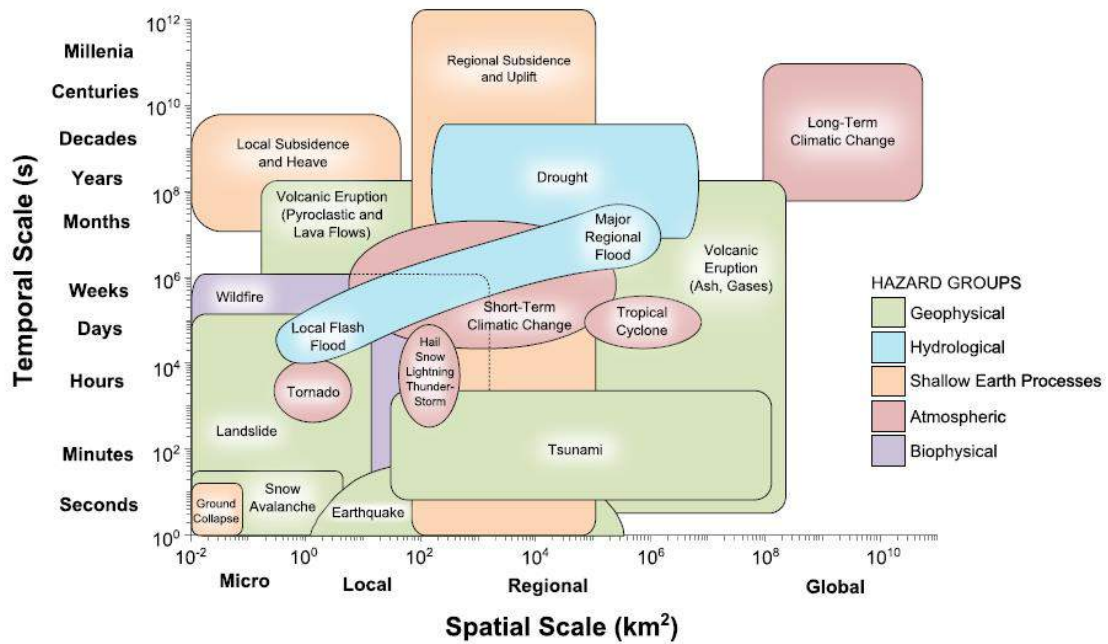
Gill, J. C., and Malamud, B. D. (2014) Reviewing and visualising the interactions of natural hazards, *Reviews of Geophysics*, 52(4), 680-722, doi:10.1002/2013RG000445.

## 2.1 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 chapter are to review the interactions between 21 different natural hazards, place these interactions into a visualisation framework, and reinforce the importance of incorporating natural hazard interactions into a multi-hazard approach. Here we use the term *hazard* as defined by UNISDR (2009) 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 *multi-hazards* to refer to all possible and relevant hazards, and their interactions, in a given spatial region and/or temporal period. The term *multi-hazard risk assessment*, including its history and various uses, will be discussed and described towards the end of this chapter ([Section 2.7](#)). 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 summarise the chapter’s organisation.

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 2.1](#), the spatial vs. temporal scales over which 16 selected hazards act are presented, along with a summary of the literature consulted and synthesised to generate this figure. These hazards, many of which will be amongst the 21 natural hazards studied later in this chapter, are divided into five hazard groups:

- i. *Geophysical* (Earthquake, Tsunami, Volcanic Eruption, Landslide, Snow Avalanche)
- ii. *Hydrological* (Flood, Drought)
- iii. *Shallow Earth Processes* (Regional Subsidence and Uplift, Local Subsidence and Heave, Ground Collapse)
- iv. *Atmospheric* (Tropical Cyclone, Tornado, Hail, Snow, Lightning and Thunder Storm, Long-Term Climatic Change, Short-Term Climatic Change)
- v. *Biophysical* (Wildfire)



Group	Hazard	References
Geophysical	Earthquake	Dixon (1991); Ilk <i>et al.</i> (2005); Minster (2013)
	Tsunami	Chelton (2001); Ilk <i>et al.</i> (2005)
	Volcanic Eruption	Dixon (1991); Ilk <i>et al.</i> (2005)
	Landslide	Waugh (2000); Malamud <i>et al.</i> (2004); Winter <i>et al.</i> (2005)
	Snow Avalanche	Waugh (2000); Winter <i>et al.</i> (2005); Lemke <i>et al.</i> (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); Greci and Nese (2006); Laing and Evans (2011); Hirschboeck (1988)
	Tornado	Greci and Nese (2006); Laing and Evans (2011)
	Hail, Snow, Lightning, Thunder Storm	Edwards (1999); Greci and Nese (2006); Laing and Evans (2011); Hirschboeck (1988)
	Long-Term Climatic Change	Chelton (2001); Edwards (2008); Laing and Evans (2011)
	Short-Term Climatic Change	Chelton (2001); Laing and Evans (2011); Hirschboeck (1988)
Biophysical	Wildfire	Malamud <i>et al.</i> (1998); Hincks <i>et al.</i> (2013)

**Figure 2.1. 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 2.2.4](#).

In [Figure 2.1](#), lower bounds of  $10^{-2}$  km<sup>2</sup> (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 2.1**, it can be observed that natural hazards influence a range of spatial areas, from fractions of kilometres squared (what is termed here to be a micro scale) to hundreds of million kilometres 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<sup>2</sup> 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 2.1** 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 visualising hazard interactions between a broad range of natural hazards, this chapter is organised as follows: **Section 2.2** 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 2.3** presents the results of a systematic review to identify and visualise interactions between 21 different natural hazards. **Section 2.4** discusses our ability to characterise secondary hazards in terms of location, timing and magnitude, given information about the primary hazard. **Section 2.5** 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 2.6](#) 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 2.7](#), including the integration of hazard interactions into a multi-hazard framework. In addition, we provide extensive supplementary material in [Appendix A](#) which includes three additional tables expanding on the main text, and a list of over 200 references to support these additional tables, with many additional case studies to those noted in the main text.

## 2.2 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 2.2.1](#)), followed by a discussion of four types of hazard interaction ([Section 2.2.2](#)), an overview of previous research into hazard interactions ([Section 2.2.3](#)), a description of the six hazard groups and 21 individual hazards selected for this study ([Section 2.2.4](#)) and the importance of visualisation techniques for organising and presenting a wide array of complex information ([Section 2.2.5](#)).

### 2.2.1 Case Studies

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

- i. *Japan* (1792, volcanic eruption, earthquake, landslide, tsunami)
- ii. *USA* (1964, earthquake, landslides, tsunami, flooding)
- iii. *Philippines* (1991, volcanic eruption, typhoon, lahars)
- iv. *Guatemala* (2010, tropical storm, landslides, flooding, ground collapse, 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 2.3 to 2.6](#) and in the [Appendix A, Table A.1](#). 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.

### ***2.2.1a Mount Unzen and Mount Mayuyama, Japan, 1792***

In the first case study, the Japanese volcano Mount Unzen erupted in 1792. This volcanic eruption triggered 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).

### ***2.2.1b 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 sub-aerial 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).

### ***2.2.1c 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 the 15–16 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; Stenchikov *et al.*, 1998; Scott *et al.*, 1999). The volcanic eruption resulted in the ejection

of 17 megatons of sulphur 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 Mt. 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).

### **2.2.1d 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 two 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).

### 2.2.2 Hazard Interaction Types

Building on the four case studies just discussed ([Section 2.2.1](#)) and the wider literature, multiple hazard interactions can be identified, which we divide into four categories:

- i. *Interactions where a hazard is triggered,*
- ii. *Interactions where the probability of a hazard is increased,*
- iii. *Interactions where the probability of a hazard is decreased, and*
- iv. *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.

#### ***2.2.2a 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, rainfall event, snow-melt or erosion and undercutting of slopes during flooding, 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 2.2.1b](#)) a  $M_w = 9.2$  earthquake triggered multiple secondary hazards, which in turn triggered further hazards. The earthquake triggered regional subsidence and both sub-aerial 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 siltation. This siltation can trigger greater undercutting, thus developing a positive feedback or cyclic triggering.

### **2.2.2b 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 categorised as the primary hazard changing one or more environmental parameters so as to drive the system towards a specific threshold or ‘tipping’ point. In some situations, a primary hazard may not directly trigger a secondary natural hazard, instead it changes 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; Cannon *et al.*, 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 2.2.1b](#)), 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).

### **2.2.2c 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 sulphur 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 minimise 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 multi-hazard interactions, see [Section 2.7](#)), where a conservative approach would often be implemented.

#### ***2.2.2d Spatio-Temporal 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 recognise 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 impact the mitigation strategies followed by DRR practitioners.

Spatio-temporal 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 afterwards, 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 spatio-temporal 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 spatio-temporal coincidence of hazards can be seen in the case studies from the Philippines ([Section 2.2.1c](#)) and Guatemala ([Section 2.2.1d](#)). 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 spatio-temporal coincidence of the eruption of Volcano Pacaya and Tropical Storm Agatha also resulted in greater hazard potential.

### ***2.2.2e Some Additional Points***

In [Sections 2.2.2a–2.2.2d](#) 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:

- i. *The importance of anthropogenic processes.* Our discussion of interaction types has focused on interactions between natural hazards, but we also recognise 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 chapter focuses on the interactions between natural hazards.

- ii. *Timescales*. It is important to consider timescales of interest when analysing 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.

### 2.2.3 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; Kappes *et al.*, 2012; Government Office for Science, 2012; Mignan *et al.*, 2014). There are, however, very few detailed reviews or broad characterisations 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 2.2.1](#)). There have also been a number of ‘bottom-up’ studies (summarised in [Table 2.1](#) and discussed in detail below) of interacting hazards, focusing on specific regions, landscapes or end-users.

The eight studies set out in [Table 2.1](#) suggest three broad qualitative and quantitative approaches to constrain and visualise hazard interactions:

- i. *Qualitative descriptions and classifications* (Han *et al.*, 2007).
- ii. *Hazard matrices and diagrams* (Tarvainen *et al.*, 2006; De Pippo *et al.*, 2008; Kappes *et al.*, 2010; van Westen *et al.*, 2014).
- iii. *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.

**Table 2.1. Approaches for assessing natural hazard interactions.** A range of approaches for assessing natural hazard interactions have been utilised, including qualitative descriptions and classifications, matrices and diagrams, and probability/scenario trees (NA = Not Applicable).

Type	Authors	Location	Hazards/ Processes Considered	Interaction Classifications	Further Notes
Qualitative Descriptions/ Classifications	Han <i>et al.</i> (2007)	General (case studies from China)	PRIMARY: Earthquake, rainstorm, rapid snowmelt, human activity SECONDARY: Landslides, debris flow activity, flooding, ground failure	(i) Spatial and/or temporal chains (ii) Endogenic processes (stimuli below the surface of the Earth) (iii) Exogenic processes (stimuli above the surface of the Earth) (iv) Human- induced chains (v) Spatial/temporal coincidence of independent hazards	
Matrices and Diagrams	Tarvainen <i>et al.</i> (2006)	Europe	NATURAL: Avalanche, drought, earthquake, extreme temperature, flood, forest fire, landslide, storm surge, tsunami, volcanic eruption, winter storm TECHNOLOGIC AL: Air traffic accident, chemical plant, nuclear power plant, oil processing/ transport/storage	One hazard influencing another hazard, based on real physical processes (causal correlation)	Binary matrix examining interactions
	De Pippo <i>et al.</i> (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

Type	Authors	Location	Hazards/ Processes Considered	Interaction Classifications	Further Notes
	Kappes <i>et al.</i> (2010)	Barcelonnette, Southern French Alps	Avalanche, debris flow, rock fall, landslide, flood, heavy rainfall, earthquake	(i) Triggering relationships (ii) One hazard changing the disposition or general setting that favours a specific hazard process	Binary matrix and descriptive matrix examining interactions
	van Westen <i>et al.</i> (2014)	European Mountainous Environments	TRIGGERING FACTORS: Earthquake, meteorological extremes. SECONDARY HAZARDS: Mass movement, snow avalanche, forest fire, land degradation, flooding, seiche, technological hazard	(i) Hazards triggered simultaneously (coupled) (ii) Hazards causing another hazard	Possible interactions visualised in network diagram form
Probability/ Scenario Trees	Neri <i>et al.</i> (2008)	Vesuvius, Italy	Volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, landslide, lahar, mudslide, heavy rain	<i>Not Stated</i>	Probability tree for a specific volcanic setting
	Marzocchi <i>et al.</i> (2009)	NA	Volcanic eruption, fire, contaminant migration	Triggering effects and/or cascade adverse events	Hypothetical example
	Neri <i>et al.</i> (2013)	Kanlaon, Philippines	Volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, lahar/mudslide	<i>Not Stated</i>	Probability tree for a specific volcanic setting

### 2.2.3a 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:

- i. *Spatial and/or temporal chains* (a series of events that are triggered by the same stimuli, or located in the same geographical or geo-tectonic setting)
- ii. *Endogenic processes* (with stimuli from below the surface of the Earth)
- iii. *Exogenic processes* (with stimuli from above the surface of the Earth)
- iv. *Human-induced chains*
- v. *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 (i to v) 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).

Other examples of a discursive methodology or review can be found within the case studies outlined in [Sections 2.2.1](#) or [2.3.3](#). 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.

### ***2.2.3b 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 visualise hazard interactions. Three major studies considering such an approach are as follows:

- i. Tarvainen *et al.* (2006) set out a binary matrix of eleven natural and four technological hazards that they deemed to be spatially relevant to areas within Europe.
- ii. 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.
- iii. Kappes *et al.* (2010) proposed a matrix with a small-scale study of seven hazards relevant within an Alpine region.

Each author examined and visualised 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 favours 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.

### 2.2.3c Probability/Scenario Trees

The development of more quantitative approaches to assess 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 utilised, 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, triggering). An absence of a standard approach to considering multi-hazard 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.

#### 2.2.4 Hazards and Hazard Types

In this study, we examine 21 different natural hazards (including many of those examined in [Figure 2.1](#)). [Table 2.2](#) 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).

**Table 2.2. Classification of natural hazards and natural hazard groups used in this chapter.** 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 chapter noted. Each natural hazard is defined, and the component hazards outlined.

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 pre-existing 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 water-waves with large wavelengths and low amplitudes (Alexander, 1993). As the waves approach shallow water, their amplitude increases through wave shoaling.	

Hazard Group	Hazard	Code	Definition	Component Hazards (where applicable)
	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 Flow, Lava Flow.
Geophysical (continued)	Landslide	LA	The down-slope 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 down-slope 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 Flood, Storm Surge, Jökulhlaup, Glacial Lake Burst
	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 Soil.
	Soil (Local) Subsidence	SS	The gradual, downward vertical movement of the ground surface over a localised 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 Rock.
Atmospheric	Storm	ST	A significant perturbation of the atmospheric system, often involving heavy precipitation and violent winds.	Tropical Cyclone, Hurricane, Typhoon, Mid-Latitude Storm.

Hazard Group	Hazard	Code	Definition	Component Hazards (where applicable)
	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).	
Atmospheric (continued)	Hailstorm	HA	A significant perturbation of the atmospheric system, in which strong up-draughts occur within convective storms where there is an ample supply of supercooled water droplets. This results 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 air between areas of positive and negative charge is overcome (Alexander, 1993).	
	Extreme Temperature (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 Wave, Climatic Change
	Extreme Temperature (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 Wave, Climatic Change
Biophysical	Wildfire	WF	An uncontrolled fire fuelled by natural vegetation (Smith and Petley, 2009).	
Space/Celestial	Geomagnetic Storm	GS	A perturbation of the Earth's magnetosphere, because of changes in space weather, i.e., the intensity of solar wind.	
	Impact Event	IM	The impact of a celestial body with the Earth's surface.	Asteroid, Meteorite.

Although this list of natural hazards presents 21 of the most common and important hazards, it is recognised 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, ground based volcanic gases), anthropogenic hazards (e.g., over-abstraction of groundwater,

desertification, deforestation, mining subsidence) and technological hazards (e.g., nuclear meltdown, dam failure, power failure, communications failure).

Most hazards within our study could also be divided into sub-categories. For example, landslides could be sub-divided 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 2.2](#) would generate results applicable across multiple types of regimes (e.g., tectonic, climatic, hydrologic). The further development and extension of this research, including the incorporation of additional hazards, is discussed in [Section 2.7](#).

### 2.2.5 Visualisation of Information

As noted by Kappes *et al.* (2012), the effective visualisation 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 visualisation methods can be seen in the studies reviewed in [Section 2.2.3](#), 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 visualisation 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 colour 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 chapter, we develop and present two key ways of visualising hazard interaction relationships, using both matrices and network diagrams. In the first form of visualisation, a series of matrices are presented in [Sections 2.3 to 2.6](#), where each matrix examines and constrains interactions between the 21 natural hazards set out in [Section 2.2.4](#). 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 visualisation ([Section 2.3.4](#)), network diagrams, displays each of the 21 hazards as a node, using colour and line pattern to display different relationships.

Within each visualisation, careful attention was paid to appropriate and constructive visualisation (e.g., Bostrum *et al.*, 2008), in order to maximise the range of end-users, improve their experience when using these visualisations and allow for straightforward interpretation of information (Kappes *et al.*, 2012). The use of complementary colours, symbols and shapes helps increase the likelihood of visualisations being intuitive and simple-to-understand, effectively synthesising information drawn from many scientific disciplines. It is anticipated that the matrices ([Sections 2.3 to 2.6](#)) in particular offer relevant and important information to a variety of end-users, including those working on hazard assessment, DRR and disaster management.

## 2.3 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 2.2](#). This section begins by outlining the review procedures adopted within this research ([Section 2.3.1](#)), before setting out the results in a matrix form ([Section 2.3.2](#)), discussing mechanisms and case studies ([Section 2.3.3](#)) and analysing hazard type linkages ([Section 2.3.4](#)).

### 2.3.1 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 2.3](#) describes each of these criteria and notes how the methodology we applied in this chapter fulfilled them. Our review includes both those references cited at the end of this thesis and over 200 references cited in [Appendix A](#).

**Table 2.3. Criteria for a systematic review (from Boaz *et al.*, 2002).** Key review criteria and a qualitative description of how we met these criteria in reviewing the range of hazard interactions within this study.

Criteria (from Boaz <i>et al.</i> , 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 ( <a href="#">Section 2.3.3</a> ) 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 scrutinised to see whether its inclusion could be justified. Highly controversial interactions were outlined in the matrix footnotes.
Synthesises the research findings in the included studies	Findings were synthesised 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 non-specialists.
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 pre-determined 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.

### 2.3.2 Hazard Interaction Matrix

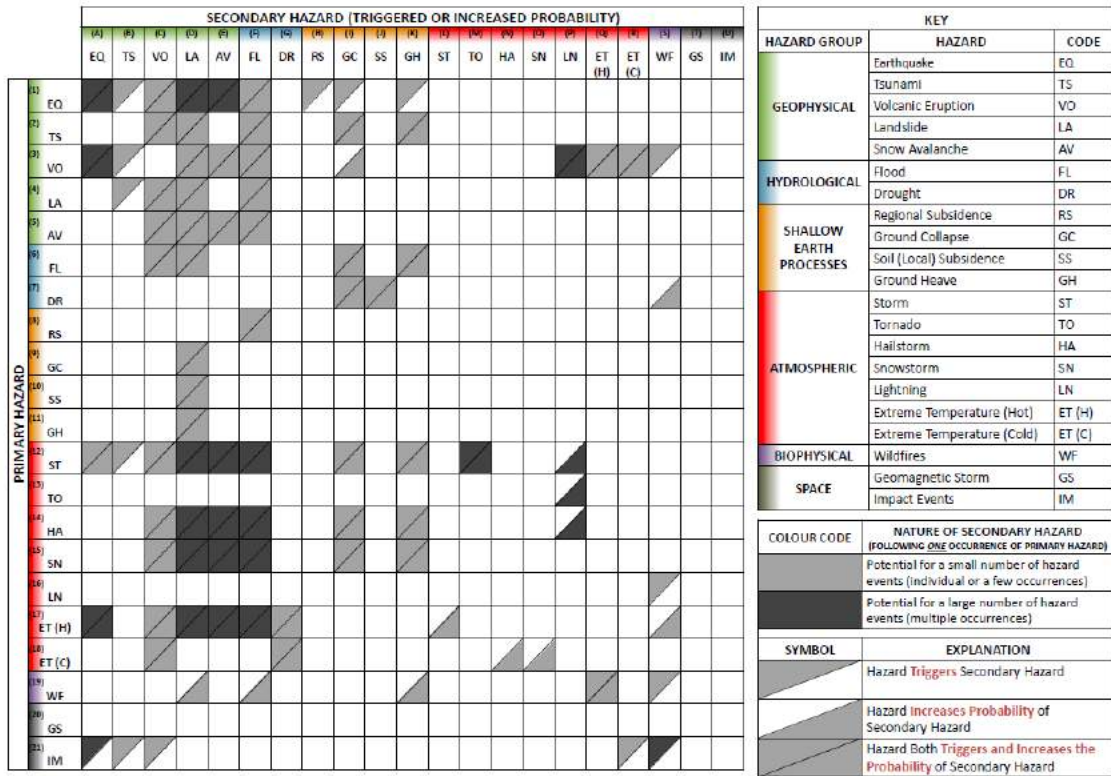
Through our systematic review, for each of the 21 hazards chosen for this study we identified multiple hazard interactions. These are presented in a matrix form in [Figure 2.2](#). This  $21 \times 21$  matrix identifies 90 natural hazard interactions (out of a possible 441), including both triggered 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 2.2](#) 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 colours (**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 primary hazard-secondary hazard coupling. Of the 90 interactions identified in this  $21 \times 21$  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 snow-melt event could trigger thousands of individual landslides. We observe that 66 (73%) of the 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 2.2** 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 visualisation used in **Figure 2.2** 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).



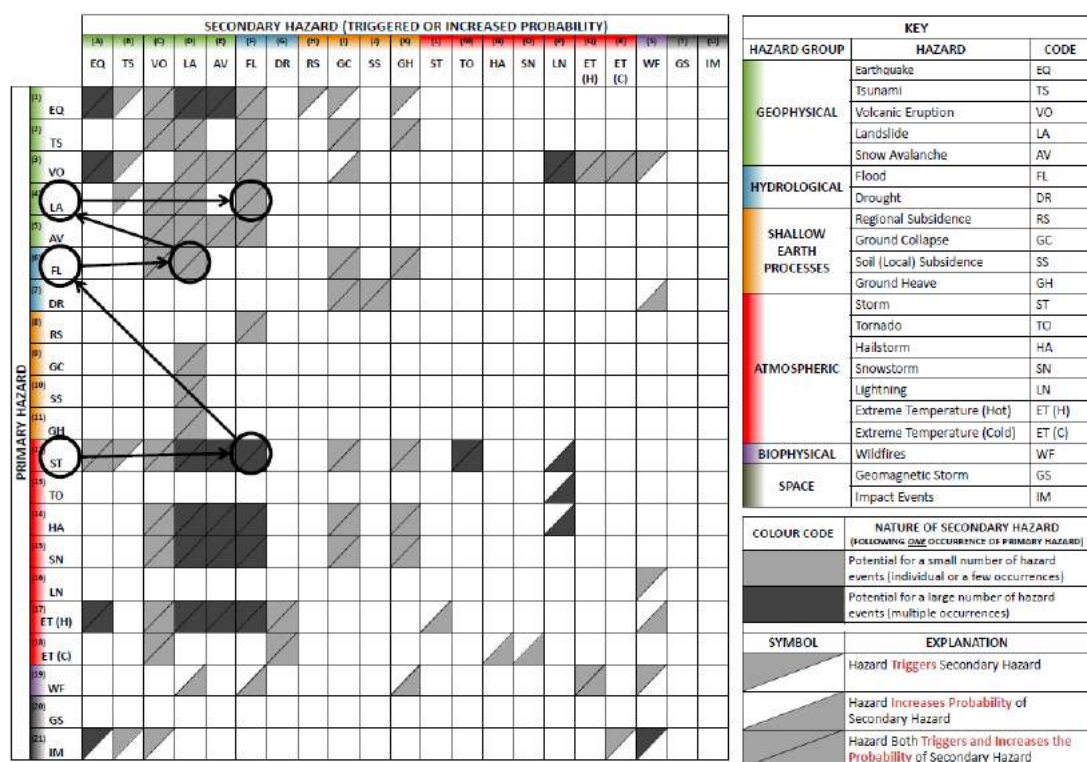
**Footnotes**

- [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 2.2. 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.

In addition to using **Figure 2.2** 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 (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 2.2**, 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 2.3**. 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 visualisation could be used to represent the complex case studies presented in **Section 2.2.1** (e.g., Japan, 1792; USA, 1964) where a hazard triggered a number of 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.



**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 2.3. 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 2.2**. 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 visualisation of the 21 hazard types described in this section and shown in [Figure 2.2](#) will be used for the rest of this chapter, when exploring other aspects of the hazards. In the first of these, we describe the hazard interaction mechanisms ([Section 2.3.3](#)).

### 2.3.3 Hazard Interaction Mechanisms and Case Studies

As part of the construction of [Figure 2.2](#), 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 [Appendix A, Table A.1](#). 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, 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 2.2](#), 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 2.2](#), we identified multiple key case studies in the academic or grey literature, and noted these in [Table A.1](#). 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 2.2.1b](#). More than 60 additional case studies, noted in [Table A.1](#), 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

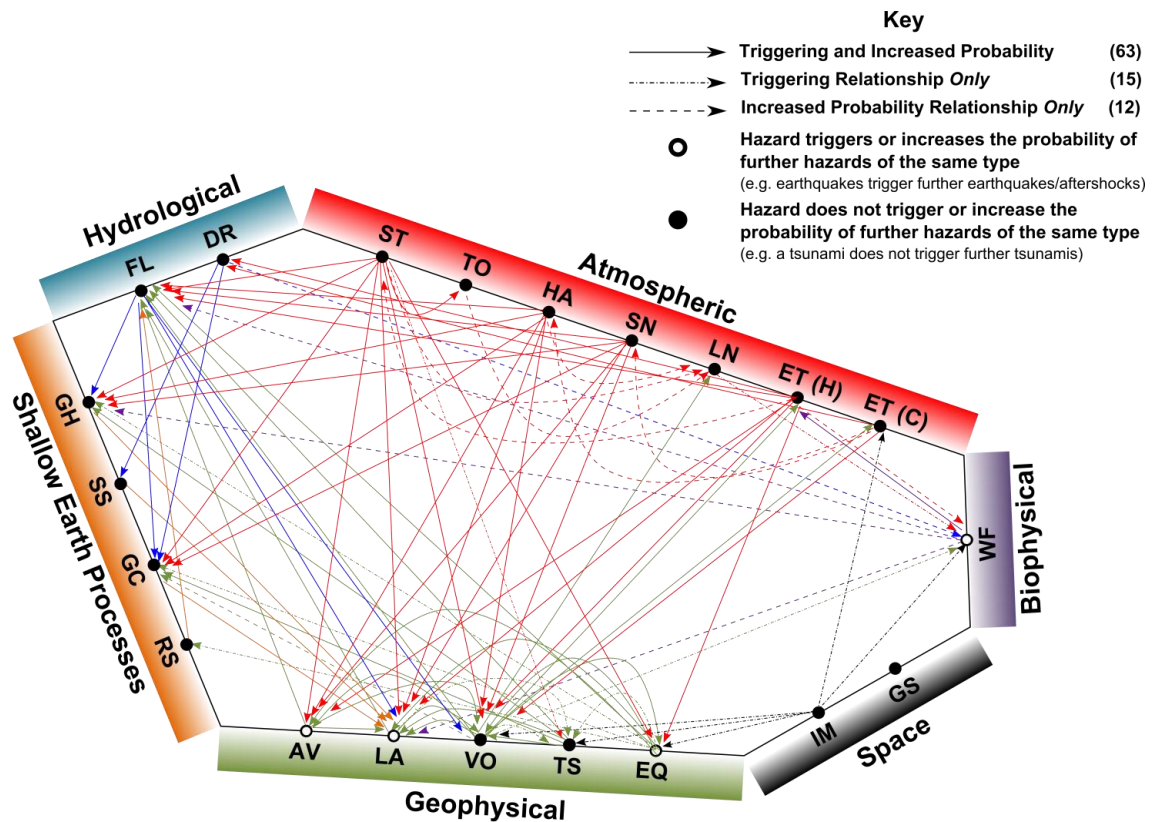
in our survey, or that the interaction mechanism is not extensively discussed within appropriate case study analysis literature.

### 2.3.4 Hazard Type Linkages

The hazard interaction relationships identified and visualised in [Figure 2.2](#), can also be represented in the form of a network diagram ([Figure 2.4](#)) which visualises the significant interrelationships between the six hazard groups we have chosen. In [Figure 2.4](#), 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 out 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 coloured 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:

- i. *Solid line*: 63 cases where both triggering and increased probability are possible.
- ii. *Dashed-dotted line*: 15 cases where only a triggering relationship is possible.
- iii. *Dashed line*: 12 cases where only an increased probability relationship is possible.

For example, there is a red dashed–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.

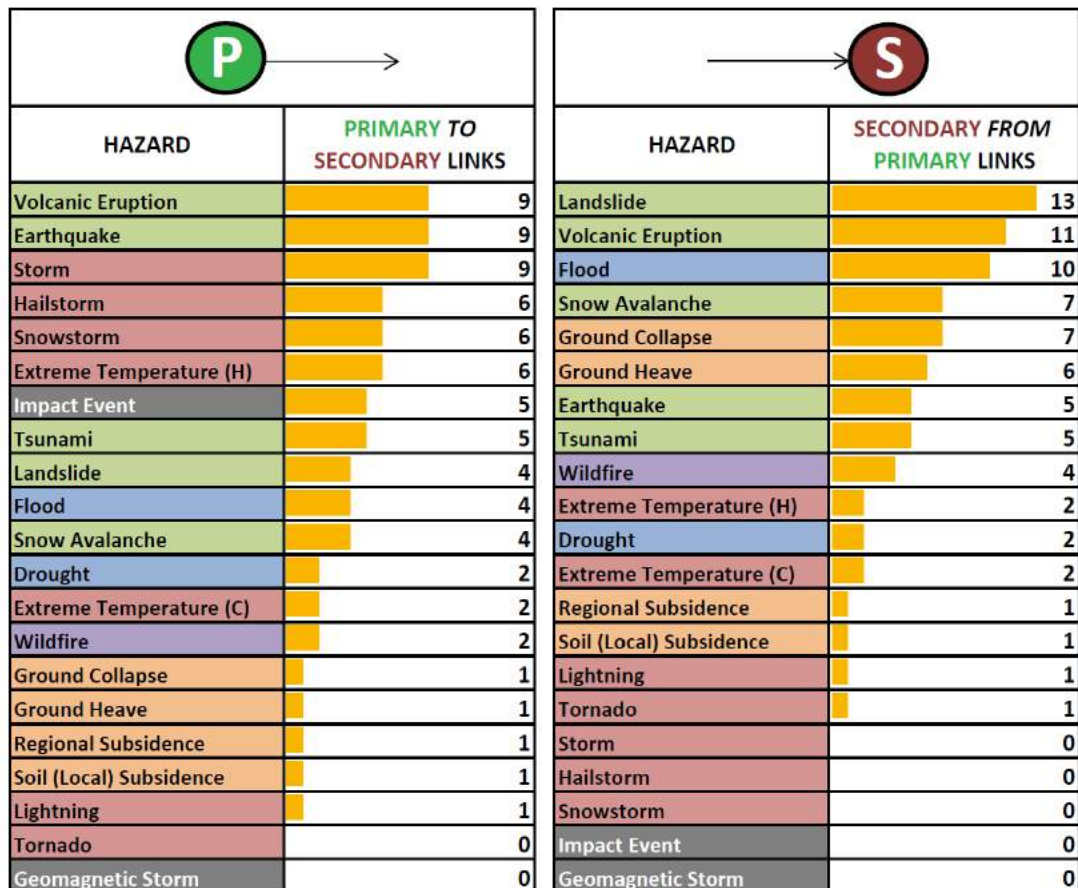


**Figure 2.4. Hazard type linkages.** A network diagram showing the potential hazard type linkages between 21 natural hazards: EQ = earthquake, TS = tsunami, VO = volcanic eruption, LA = landslide, AV = snow avalanche, RS = regional subsidence, GC = ground collapse, SS = soil (local) subsidence, GH = 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, IM = impact events. Hazards groups follow the same colour coding as in Figure 2.2. 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 (dashed–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.

From Figure 2.4 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 analysed 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 dashed-dotted lines from [Figure 2.4](#) 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 in [Figure 2.5](#). 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 2.4](#)). Together these three primary hazards accounted for 27 (almost a third) of the 78 total possible links where a primary hazard triggers a secondary hazard.



**Figure 2.5.** 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 2.2](#)) and hazard type linkages ([Figure 2.4](#)) the number of primary hazard to triggered secondary hazard links is summated for each primary hazard within this study, and then ranked (left). This is repeated for each secondary hazard, summating and ranking triggered secondary hazard from primary hazard links (right).

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 2.5**) 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 due to storms, snowstorms and hailstorms. Case studies for some of these interactions are included within **Appendix A, Table A.1**; 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 2.5.2**.

**Figure 2.5** can also be used to examine the total number of hazards within each of our six groups of hazards vs. the summated number of triggering and triggered hazards in that group. **Table 2.4** 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 2.4**, we present the non-normalised hazard group 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 normalised by dividing by the total number of hazards within the group. Again, these groups are ordered according to their ranking.

We find (**Table 2.4**, 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 2.4**, 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 2.4**) can be contrasted with the individual hazard rankings (**Figure 2.5**), in which the hazard group is visualised through the standard group colours 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, that this might supplement existing methods for deciding upon the allocation of resources for mitigation or risk reduction measures.

**Table 2.4. Ranking of hazard groups in terms of number of times included hazards trigger and are triggered by other hazards (non-normalised and normalised).** 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 (top). These results are normalised (bottom) by dividing total values by the summated total of hazard types within the hazard group ( $n$ ).

Total (Non-Normalised)					
Hazard Group	Number of Hazards Within Group ( $n$ )	Primary to Secondary Links	Hazard Group	Number of Hazards Within Group ( $n$ )	Secondary from Primary Links
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

Total (Normalised by Dividing by Number of Hazards Within Group, $n$ )					
Hazard Group	Number of Hazards Within Group ( $n$ )	Primary to Secondary Links	Hazard Group	Number of Hazards Within Group ( $n$ )	Secondary from Primary Links
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

## 2.4 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:

- i. The *spatial location* (where the secondary hazard occurs).
- ii. The *timing* (when the secondary hazard occurs).
- iii. 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, 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 utilised 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 2.2.1b](#)) an evaluation of regions where subsidence had occurred would give us information about locations with an increased susceptibility to flooding. Similarly, if an earthquake epicentre 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 2.2](#) 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 (2012) utilised 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 (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 of the three forecasting factors (spatial location, timing, magnitude), a classification system was derived as outlined in [Table 2.5](#). 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.

**Table 2.5. Scale for classifying ability to characterise secondary hazards (in terms of location, timing and magnitude) given information from a primary hazard.** This Likert-type scale is composed of a null category and a three-point bivalent scale, used to characterise 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 [Appendix A \(Table A.2\)](#).

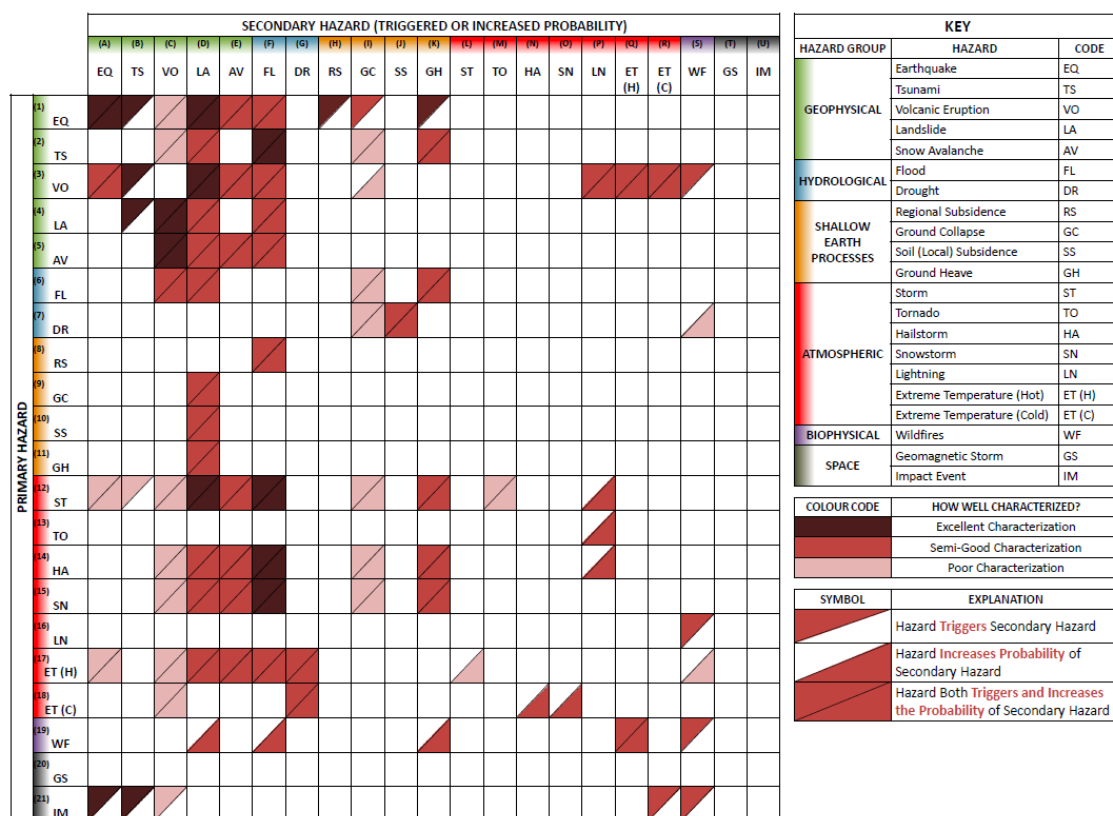
Forecasting Factor Ability	Description (ability to characterise secondary hazard given information from the primary hazard)	Numerical Value
None	There exists no knowledge to help constrain the particular forecasting factor.	0
Low	The knowledge to help constrain the forecasting factor is minimal or purely 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

In [Table 2.5](#), 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, magnitude). Classifications on all three factors, for each triggered and increased probability secondary hazard, are included in the [Appendix A \(Table A.2\)](#). The summation of the three numerical values from each forecasting factor gives an overall rating 0–9. This enabled hazards to be categorised 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 characterise the secondary hazard given information from the primary hazard. Each of these categories was colour coded, with the results displayed in a matrix form ([Figure 2.6](#)), where the matrix has the same structure and layout as [Figure 2.2](#) (see [Section 2.3.1](#) for a brief narrative). The matrix shown in [Figure 2.6](#) uses different colour saturations to show relationships with a poor (pale-red), semi-good (medium-red) and excellent (dark-red) ability to characterise secondary hazards.

The classification presented in [Figure 2.6](#) is designed to allow a rapid, coarse-resolution overview of the differential capabilities to characterise (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 characterised (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 characterised, 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-wise 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-wise 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, 1895; Utsu, 1961). These relationships allow, in our [Figure 2.6](#), 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 2.2.1b](#)), 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 2.6. Ability to characterise 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 2.2. These hazards are coded, as explained in the key. This matrix outlines current ability to characterise 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, intensity). Based on the literature, each of the three factors (location, timing, magnitude) is given a forecasting ability value of 0–3 (Table 2.5). 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 2.1](#)). 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 characterisation of drought to ground collapse a ‘poor’ in [Figure 2.6](#).

While the visualisation used in [Figure 2.6](#) provides a rapid, coarse resolution summary of how well we are able to characterise 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 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 2.7](#).

## **2.5 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, 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 2.5.1](#)) and then presents the results of this review for triggered hazard interactions in a matrix form ([Section 2.5.2](#)).

### **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 2.6](#)):

- i. The *spatial overlap* of each hazard combination.
- ii. 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 2.6**) give an indication of the *Overlap–Likelihood* Factor (**Section 2.5.2**) 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.

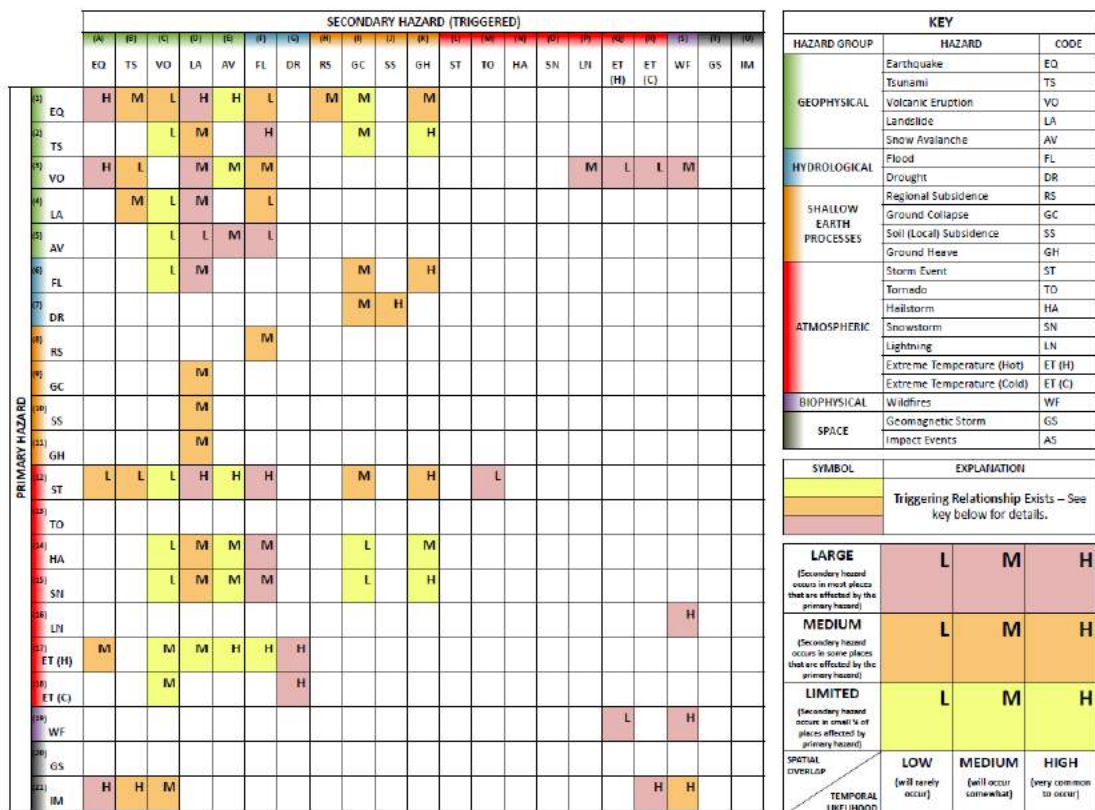
The assessment of each of these two parameters was undertaken using a mixture of assessment methodologies and criteria, also outlined in **Table 2.6**. The determination of *spatial overlap* (large, medium, limited) was assessed at a coarse resolution using a selection of global hazard distribution maps (**Appendix A, Table A.3**). The assessment of *temporal likelihood* (high, medium, 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 thesis and the **Appendix A**. 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 analysing 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.

**Table 2.6. Parameters selected to assess the spatial overlap and temporal likelihood of each triggering relationship.** A description of both parameters (*spatial overlap*, *temporal likelihood*) chosen to assess globally the *Overlap-Likelihood* Factor (Section 2.5.2) 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.

Parameter	Description	Assessment Methodology	Assessment Criteria and Classification
<i>Spatial Overlap</i>	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 catalogue 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:  <i>Large</i> (~70–100%) - Secondary hazard occurs in most places that are affected by primary hazard.  <i>Medium</i> (~30–70%) - Secondary hazard occurs in some places that are affected by primary hazard.  <i>Limited</i> (~0–30%) - Secondary hazard occurs in a small percentage of places affected by primary hazard.
<i>Temporal likelihood</i> (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.  <i>(N.B. This parameter is analogous to the Cumulative Act Effect Model (Reason, 1990) otherwise known as the ‘Swiss Cheese Model’. This suggests failure occurs when individual weaknesses within levels of a system momentarily align to create a ‘trajectory of accident opportunity’).</i>	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, complimented 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.	<i>High</i> = Widespread case studies or examples of the primary hazard triggering the secondary hazard.  <i>Medium</i> = Some case studies or examples of the primary hazard triggering the secondary hazard.  <i>Low</i> = Occurrences in the literature of the primary hazard triggering the secondary hazard are either rare or non-existent but believed to be hypothetically possible.

### 2.5.2 Triggered Hazard Interactions: Spatial Overlap-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 2.7**, using a similar layout and structure as previous matrices (**Figures 2.2** and **2.6**). The main difference between previous matrices and **Figure 2.7** is that **Figure 2.7** only visualises 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.



**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 2.7. Spatial overlap and temporal likelihood of triggering relationships occurring.** A  $21 \times 21$  matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis, as introduced in **Figure 2.2**. 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 2.6**), 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.

To construct **Figure 2.7**, we take the two parameters (each with three classes) described in **Table 2.6** and give them colours and codes: *Spatial overlap* was colour 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 recognised 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 2.7** 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 5 cells (medium *spatial overlap*, high *temporal likelihood*) to a maximum of 17 cells (medium *spatial overlap*, medium *temporal likelihood*). The range of *spatial overlap* and *temporal likelihood* combinations is also demonstrated by the following examples:

- i. **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 sub-aerial 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 2.2.1d**).
- ii. **Cell 12K (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 hours.

- iii. **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 (1990) when discussing depressurization of magma chambers on Hawaii, and a possible phreatomagmatic eruption triggered by a flank collapse.

The two-parameters (*spatial overlap*, *temporal likelihood*) utilised in [Figure 2.7](#) (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 2.3.4](#), [Figure 2.5](#)) 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 2.5](#) 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 2.7](#) 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 2.7](#) 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 2.3.4](#).

**Figure 2.8** 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 2.8(d)** visualises situations where wildfire is the secondary hazard. From **Figure 2.7** (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*  $\times$  *temporal likelihood* and corresponding *Overlap–Likelihood* Factor ( $OLF$ ) are as follows:

- i. *Volcano triggering wildfire*: 3 (large overlap)  $\times$  2 (medium likelihood) = 6;  $OLF = \mathbf{V}$
- ii. *Lightning triggering wildfire*: 3 (large overlap)  $\times$  3 (high likelihood) = 9;  $OLF = \mathbf{VI}$
- iii. *Wildfire triggering wildfire*: 3 (large overlap)  $\times$  3 (high likelihood) = 9;  $OLF = \mathbf{VI}$
- iv. *Impact event triggering wildfire*: 2 (medium overlap)  $\times$  3 (high likelihood) = 6;  $OLF = \mathbf{V}$

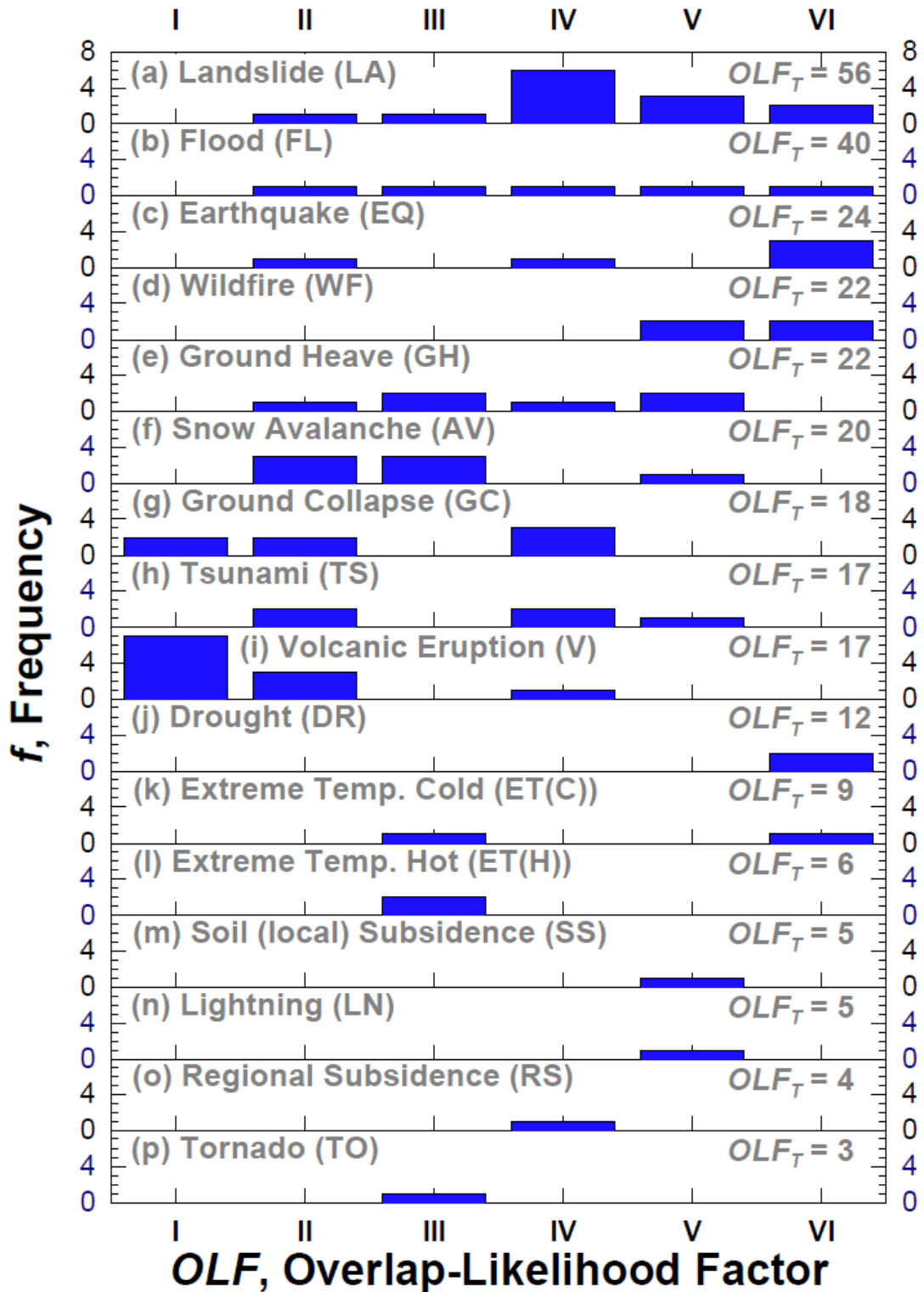
In other words, two values ( $f = 2$ ) of  $OLF = \mathbf{V}$  and two ( $f = 2$ ) of  $OLF = \mathbf{VI}$ , which are then visualised as a histogram in **Figure 2.8(d)**. This same procedure is carried out for the other 15 triggered secondary hazard types that have at least one primary hazard triggering it, and each is given as a histogram in **Figure 2.8**.

Through examining the series of *Overlap–Likelihood* Factor ( $OLF$ ) histograms in **Figure 2.8**, we can observe cases where there is a strong skew towards low  $OLF$  (e.g., **(i)** volcanic eruptions) and those with a strong skew towards 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  $\overline{OLF}$  (average  $OLF$ ) for each triggered secondary hazard:

$$OLF_T = \sum_{OLF=I}^{VI} (f_{OLF} \times OLF) \quad (1)$$

$$\overline{OLF} = OLF_T / n \quad (2)$$

where in Eq. (1)  $f_{OLF}$  is the frequency for each  $OLF$  from **I** to **VI**, and in Eq. (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  $OLF_T = (2 \times \mathbf{V}) + (2 \times \mathbf{VI}) = 22$ , and the average *Overlap–Likelihood* Factor  $\overline{OLF} = 22 / 4 = 5.5$ .



**Figure 2.8.** 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 2.5 and Figure 2.7). 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 (Eq. 1), with  $OLF_T$  given in the upper right of each hazard’s sub-panel.

In **Figure 2.9** 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 ( $\overline{OLF}$ ).

TRIGGERED HAZARD	TOTAL OVERLAP- LIKELIHOOD FACTOR ( $OLF_T$ )	# TRIGGERED SECONDARY FROM PRIMARY LINKS (from Figure 5) ( $n$ )	AVERAGE OVERLAP- LIKELIHOOD FACTOR ( $\overline{OLF}$ )
Landslide	56	13	4.3
Flood	40	10	4.0
Earthquake	24	5	4.8
Wildfire	22	4	5.5
Ground Heave	22	6	3.7
Snow Avalanche	20	7	2.9
Ground Collapse	18	7	2.6
Tsunami	17	5	3.4
Volcanic Eruption	17	11	1.5
Drought	12	2	6.0
Extreme Temperature (C)	9	2	4.5
Extreme Temperature (H)	6	2	3.0
Soil (Local) Subsidence	5	1	5.0
Lightning	5	1	5.0
Regional Subsidence	4	1	4.0
Tornado	3	1	3.0
Storm	0	0	0.0
Hailstorm	0	0	0.0
Snowstorm	0	0	0.0
Impact Event	0	0	0.0
Geomagnetic Storm	0	0	0.0

**Figure 2.9.** Ranking of individual triggered secondary hazards based on  $OLF_T$ , their total *Overlap–Likelihood* Factor. The 1<sup>st</sup> column gives the triggered secondary hazard. The 2<sup>nd</sup> column gives  $OLF_T$ , the total *Overlap–Likelihood* Factor, based on Eq. (1), and as given in **Figure 2.8**. The 3<sup>rd</sup> column gives the number of triggered secondary from primary hazard links,  $n$ , as given in **Figure 2.5**. The 4<sup>th</sup> column is the average *Overlap–Likelihood* Factor (Eq. 2):  $\overline{OLF} = OLF_T / n$ .

Notable differences and some similarities can be observed between the new adjusted rankings presented in **Figure 2.9** and those discussed in **Section 2.3.4** and presented in **Figure 2.5**. We highlight three triggered secondary from primary hazard examples: volcanic eruptions, wildfires and landslides:

- i. *Volcanic Eruptions* (drop in rankings): An initial assessment of volcanic eruptions ([Figure 2.5](#), right) ranked them 2<sup>nd</sup> 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 2.7](#)) of each of these 11 interactions is taken into account, we can construct a histogram ([Figure 2.8\(i\)](#)) that shows that 10 out of 11 of these interactions have  $OLF = \text{I or II}$ , resulting in  $OLF_T = 17$  and  $\overline{OLF} = 1.5$ . Whereas in [Figure 2.5](#), volcanic eruptions ranked 2<sup>nd</sup>, based on  $OLF_T$ , in [Figure 2.9](#), they ranked joint 7<sup>th</sup>.
- ii. *Wildfires* (rise in rankings): Alternatively, in [Figure 2.5](#), wildfires ranked 7<sup>th</sup>, whereas in [Figure 2.9](#) they rank 4<sup>th</sup> with  $OLF_T = 22$  (and corresponding  $\overline{OLF} = 5.5$ ).
- iii. *Landslides* (same ranking): In contrast to the above two examples, landslides were ranked 1<sup>st</sup> in [Figure 2.5](#) and 1<sup>st</sup> in [Figure 2.9](#), 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).

## 2.6 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 2.6.1](#)) or increases the probability ([Section 2.6.2](#)) 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 [Appendix A, Table A.1](#). Classifications derived below were

determined by considering and using the [Table A.1](#) descriptions of the generic mechanisms or physical processes by which one hazard triggers or increases the probability of a secondary hazard.

### 2.6.1 Intensity Relationships for Triggered Hazards

In this section, we examine those relationships where a secondary hazard has been triggered by a primary hazard and visualise the possible intensity relationships between the primary and triggered secondary hazard. In [Table 2.7](#), 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 chapter, and can also be derived from an examination of the interaction mechanisms discussed in [Section 2.3.3](#). However, we also recognise that other relationships might exist.

**Table 2.7. Possible triggering intensity relationships.** 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 2.8](#).

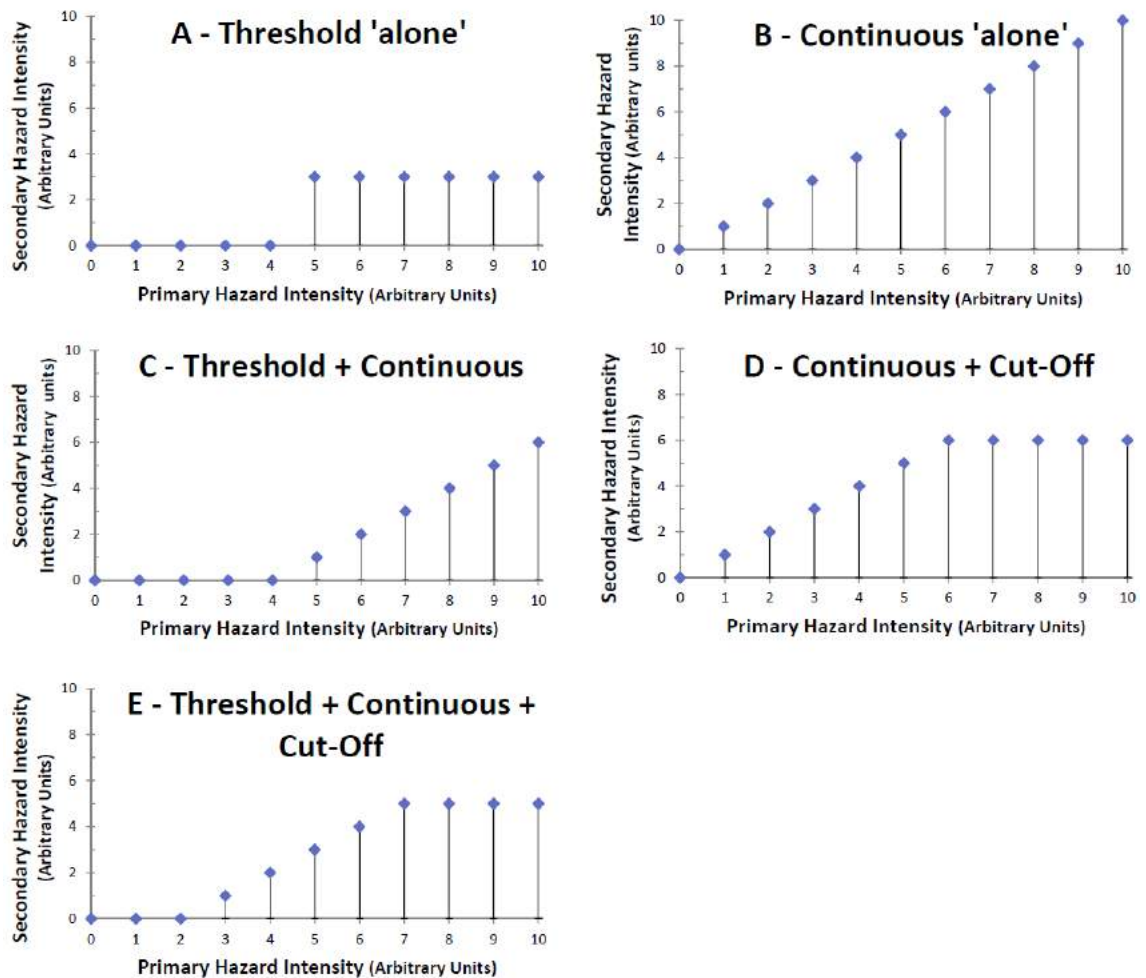
Intensity Relationship	Relationship Description
Threshold ‘alone’	The secondary hazard will only occur if the intensity of the primary hazard is at or exceeds a minimum amount (a threshold). The intensity of the secondary hazard does not get greater if the intensity of the primary hazard gets greater.
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 + Cut Off	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 means the intensity of the secondary hazard will not increase any further.
Threshold + Continuous + Cut Off	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.

Five of the relationships in **Table 2.7** are visualised graphically in **Figure 2.10**, 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 + cut-off, (E) threshold + continuous + cutoff. The sixth category in **Table 2.7** is labelled ‘complex,’ where a high level of dependency on a specific location means it is difficult to represent this graphically. The five relationships shown in **Figure 2.10** include various permutations of three key factors:

- i. *Threshold*: a minimum amount of energy is needed from the primary hazard in order to initiate the secondary hazard.
- ii. *Continuous relationship*: the intensity of the secondary hazard will increase as the intensity of the primary hazard also increases.
- iii. *Cut-off 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 recognised that the hypothetical relationships described in **Table 2.7** and visualised in **Figure 2.10** 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 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 2.7** or **Figure 2.10**. 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.

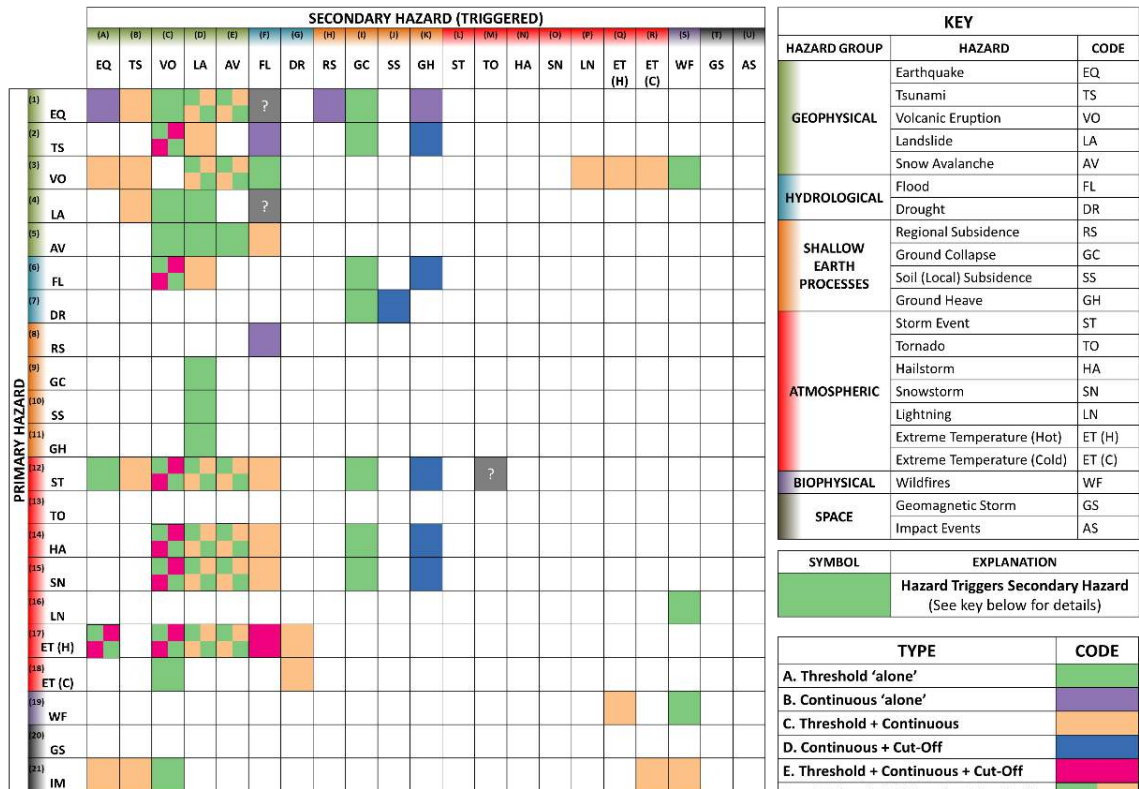


**Figure 2.10. Possible triggering intensity relationships.** Simplified cartoon graphs (using arbitrary units) of possible relationships between the intensity of the primary hazard and the intensity of the secondary hazard for cases where one hazard triggers another. Descriptions of each of these relationships can be found within [Table 2.7](#).

In [Figure 2.11](#), 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 2.2, 2.6, 2.7](#)). Each of the six relationships is represented using a different colour code: **threshold 'alone' = green**; **continuous 'alone' = purple**; **threshold + continuous = orange**; **continuous + cut-off = blue**; **threshold + continuous + cut-off = pink**; **complex/location-specific = grey**. Where there are multiple relevant relationships, both colours are assigned.

[Figure 2.11](#) 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 amongst the other triggering intensity types, with just 1 to 7 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.



**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.
- [3] 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 2.11. 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 are one or a mixture of the following: **threshold ‘alone’ = green; continuous ‘alone’ = purple; threshold + continuous = orange; continuous + cut-off = blue; threshold + continuous + cut-off = pink; complex/location-specific = grey.**

In order to demonstrate how these triggering intensity relationships relate to the underlying physical mechanisms, **Table 2.8** outlines an example of each intensity relationship using the

classifications in **Figure 2.11**. 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 2.8. Examples of each triggering intensity relationship.** 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.

<b>Intensity Relationship</b>	<b>Example</b>	<b>Example Description</b>
Threshold 'alone' (Colour 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 than the intensity of the initial landslide, the primary hazard.
Continuous 'alone' (Colour 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 (Colour 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 larger landslides triggering larger tsunamis. This classification depends on the assumption that the water displacement required for a tsunami to be classed as such is above a certain size.
Continuous + Cut Off (Colour 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 cut-off 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 (Colour 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 cut-off value. The eruption will not increase in intensity as a result of increases in the primary hazard.
Complex (Location Specific) (Colour 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.

The relationships presented in [Figure 2.11](#) 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 behaviour 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 visualisations could be used are now discussed. In 1969, a tropical depression stalled in Virginia, USA, depositing 780 mm of rainfall in 8 hours 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 visualisations 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 2.2.1d](#)) the visualisation 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 visualisations presented here, stakeholders might better visualise the possible evolution of secondary hazard intensities, or use them to improve the understanding of and preparedness for secondary hazards.

### **2.6.2 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 2.6.1](#) where we examine how the intensity of a primary hazard directly relates to the actual intensity of a triggered secondary hazard.

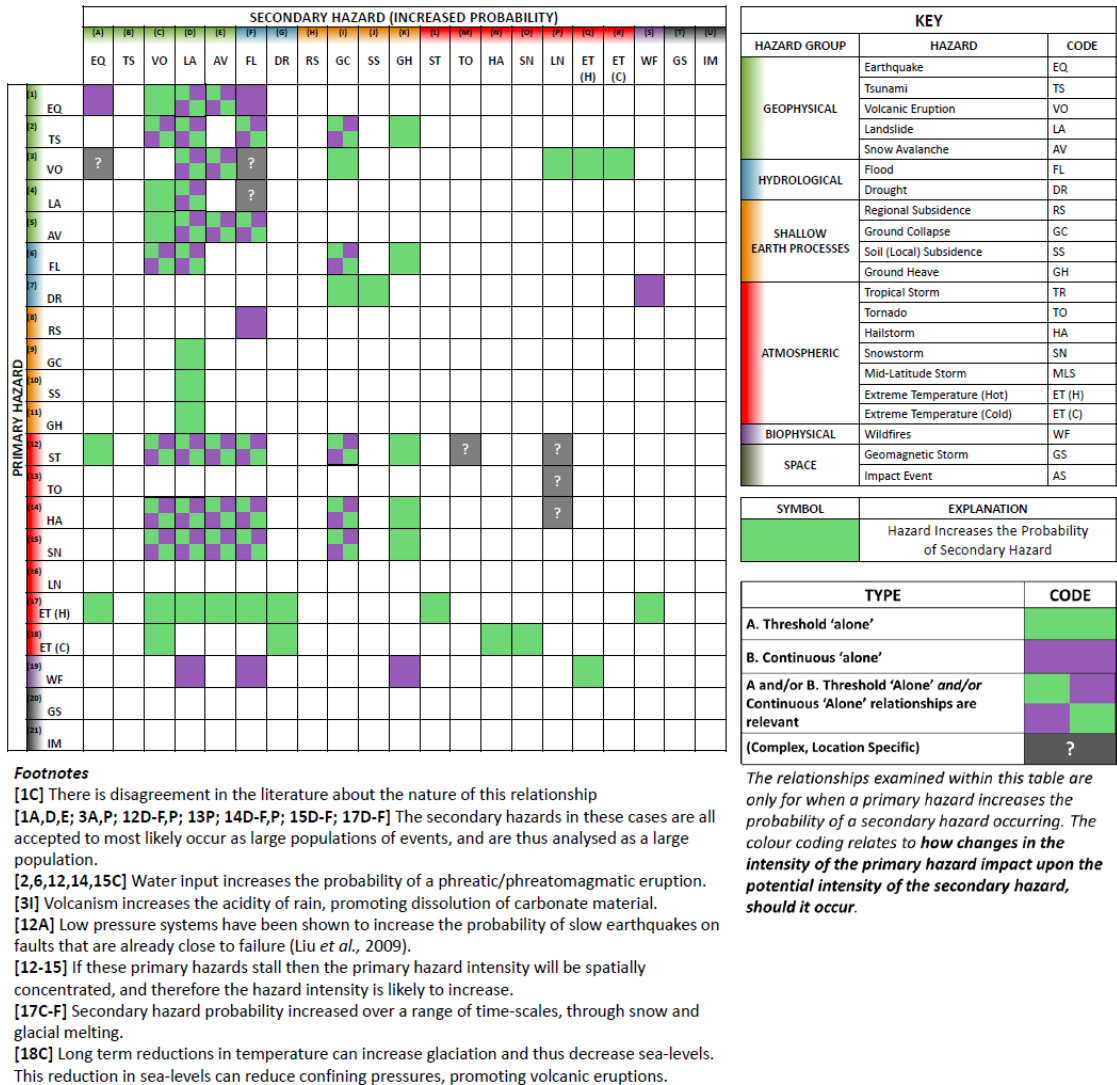
In **Table 2.9** we consider three increased probability relationship types between the primary and potential secondary hazard intensities: threshold ‘alone’, continuous ‘alone’ and complex (location specific). A threshold ‘alone’ relationship is where the primary hazard changes the natural environment 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 non-linearity may feature.

**Table 2.9. Intensity relationships where one hazard increases the probability of another hazard.** 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 2.10**.

Intensity Relationship	Relationship Description
Threshold ‘alone’	A primary hazard occurs and causes the threshold ( <i>point at which the secondary hazard occurs</i> ) 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.

In **Figure 2.12**, 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 2.2, 2.6, 2.7, 2.11**). Each relationship is represented using a different colour 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 colour is assigned. **Figure 2.12** 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 2.6.1 (for triggering relationships), we observe that there is a much smaller range of possible relationships identified.



**Figure 2.12. Increased probability 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, 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 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 visualised in Figure 2.12 relate to the underlying physical mechanisms, Table 2.10 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 2.2.1b), can be characterised 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 behaviour.

**Table 2.10. Examples of each increased probability intensity relationship.** 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 Relationship	Example	Example Description
Threshold ‘alone’ (Colour Code: Green)	Volcanic eruption increasing the probability of climatic changes	A volcanic eruption can eject a significant amount of sulphur particles. The bigger the eruption, the more sulphur 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’ (Colour 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’ (Colour 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 towards 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’).

## 2.7 Discussion

Within this study, we have reviewed, classified and visualised 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 visualisations that support our understanding of four key aspects of work relating to natural hazard interactions:

- i. *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 2.3](#)).
- ii. *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 2.4](#)).
- iii. *A determination of spatial overlap and temporal likelihood for each triggered secondary hazard*, given that the primary hazard has already occurred ([Section 2.5](#)).
- iv. *An assessment of the simplified relationships between the intensity of a primary hazard and the intensity of a secondary hazard* ([Section 2.6](#)), where the secondary hazard is either triggered or the probability increased by the primary hazard.

Furthermore, throughout these earlier sections and in the [Appendix A \(Table A.1\)](#), we have presented multiple case studies that motivate this work. [Appendix A](#) also includes a discussion of generic mechanism descriptions ([Table A.1](#)), a detailed breakdown of the classifications (spatial location, timing, and magnitude) used to assess our ability to characterise hazard interactions ([Table A.2](#)), and an outline of global hazard distribution maps ([Table A.3](#)).

In this section, we begin by discussing the limitations and uncertainties of the information generated within each aspect of this research ([Section 2.7.1](#)). We then establish the importance of this research within the context of a multi-hazard framework ([Section 2.7.2](#)), outlining a framework and presenting an overview of this discipline. We describe three potential users for the information and visualisations generated, ([Section 2.7.3](#)) and end by discussing four possible future research directions ([Section 2.7.4](#)).

### **2.7.1 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 (a) knowledge bias, (b) exclusion and resolution of hazards, (c) use of older and grey literature, (d) the contrast between slow vs. rapid onset secondary hazards and (e) 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 visualise this information within this work.

(a) *Knowledge bias*: The nature of multi-hazard interaction research requires an awareness and understanding of multiple disciplines in order to avoid a bias towards certain hazards or hazard groups. The collation of >200 references ([Section 2.3.3](#)) required to populate [Appendix A \(Table A.1\)](#) and those primary-secondary hazard matrices derived from this information (including [Figures 2.2, 2.6, 2.7, 2.11](#) and [2.12](#)) 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.

(b) *Exclusion and resolution of hazards*: A limitation, initially outlined in [Section 2.2.4](#) 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 2.2](#)), 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 2.3](#)) and the hazard interaction matrix presented in [Figure 2.2](#). This omission will then be carried through in subsequent sections and analyses. For example, in the case study from Guatemala, initially outlined in [Section 2.2.1d](#), 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 2.2.4](#), 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 2.2](#). 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 2.7.4](#)).

(c) *Use of older and grey literature*: Research presented within this chapter required the overview of a wide literature base (discussed in [Section 2.3.1](#) and presented in [Appendix A, Table A.1](#)),

using 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 minimised 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 2.2.1a](#), 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, media reports). While this adds further uncertainty regarding the accuracy of utilised information, the inclusion was justified based on:

- i. The requirements of a systematic review ([Table 2.3](#)) to use multiple sources of information.
- ii. The significant reporting of hazard events in non-academic databases (e.g., media reports).
- iii. 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](#).

*(d) Contrast between slow vs. 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 utilise information about the primary hazard to determine the necessary forecasting parameters of the rapid onset secondary hazards ([Figure 2.6](#)), and reduce the usefulness of the information about hazard *spatial overlap* and *temporal likelihood* ([Figure 2.7](#)) within a disaster management context. The information presented in [Figures 2.6](#) and [2.7](#) can still be utilised 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 vs. rapid onset hazards is a limitation to the utility of the information presented here, it does not impact upon the overall results.

(e) *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 characterising a primary hazard event (e.g., spatial location, timing, magnitude) will have uncertainty associated with them. For example, in [Section 2.1](#) and [Figure 2.1](#), 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 characterise secondary hazards, these uncertainties will be carried through and thus increase the uncertainties associated with secondary hazard characterisation. 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 (a) to (d) above are generally epistemic, where the overall uncertainty could be reduced if further research and improved classifications were to be undertaken. Factor (e), 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, modelling and sampling would improve our understanding of the particular slope's behaviour 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 (a) to (e)) 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 visualise 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:

- i. *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 2.3](#)), 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 [Appendix A, Table A.1](#).
- ii. *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 2.2, 2.6, 2.7, 2.11](#) and [2.12](#))
- iii. *Characterisation of secondary hazard location, timing and magnitude.* In [Section 2.4](#) and [Figure 2.6](#), we discuss, review and visualise our ability to characterise secondary hazards (in terms of spatial location, timing and magnitude) given information about the primary hazard. The matrix presented in [Figure 2.6](#) 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 characterisation 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 2.2](#) (hazard interactions) with [Figure 2.6](#) (characterisation of the secondary hazard based on the primary hazard), we note that the majority of those relationships that are excellently characterised are relationships with a low degree of uncertainty about their existence (e.g., earthquakes triggering tsunamis, storms triggering flooding). In contrast, those relationships with a higher degree of uncertainty include more cases where our ability to characterise the secondary hazard is poor (e.g., earthquakes triggering volcanic eruptions, storms triggering earthquakes).

We recognise that the hazard interaction matrices and linkage statistics produced above have limitations and uncertainties, but we believe that within the context of these limitations, the framework we propose can better integrate hazard interactions within a multi-hazard framework.

### 2.7.2 Hazard Interactions Within a Multi-Hazard Framework

As outlined in [Section 2.1](#), hazard and risk assessments often take a ‘single-hazard’ approach to assess hazard potential, in which hazards are treated as isolated, independent phenomena. The research presented in this chapter 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 complimented by a better understanding of hazard interactions. In this section, we outline a framework for a ‘multi-hazard’ approach, building on single-hazard approaches, and discuss the contribution we believe this overview of hazard interactions can make to such a framework.

‘Multi-hazard’ approaches utilise a more holistic methodology to evaluate hazard potential and overall risk. Although multi-hazard approaches are widely encouraged (e.g., UN, 2002; UNISDR, 2005; Government Office for Science, 2012) it is not common for the term multi-hazard to be defined or such approaches to be outlined. This has resulted in the term multi-hazard being used in many different ways, leading to some confusion within the natural hazards community. Some authors have used the term ‘multi-hazard’ 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.*, 2009; Mahendra *et al.*, 2010). 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 emphasise an important aspect of multi-hazard research, the identification of all possible and spatially relevant hazards, there are other important factors within a multi-hazard approach to assess hazard potential or risk. These factors include the integration of natural hazard interactions.

The approaches outlined above could be more helpfully described as ‘multi-layer single hazard’ approaches. This is in contrast with a multi-hazard approach to assess hazard potential. In a ‘multi-layer single hazard’ approach multiple different hazards are examined but these are still treated independently. In a multi-hazard approach, multiple different hazards are examined, and the interactions between these hazards are also recognised.

Kappes *et al.* (2012) notes two proposed frameworks for multi-hazard approaches that take into account the interactions of natural hazards. These are taken from (i) Delmonaco *et al.* (2006) and (ii) Kappes (2011):

- i. Delmonaco *et al.* (2006) suggest that multi-hazard approaches should document the possible occurrences of multiple hazard types, by analysing 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.

- ii. 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; Kappes *et al.*, 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 multi-hazard assessment. These include (i) allowing different hazards to be compared, (ii) interrelationships between hazards to be noted, (iii) physical vulnerability assessments to be validly contrasted, and (iv) the synthesis, communication and visualisation 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 ‘multi-hazard’ approach. These will be built upon in order to encapsulate and communicate key components of a multi-hazard approach to assess hazard potential and risk.

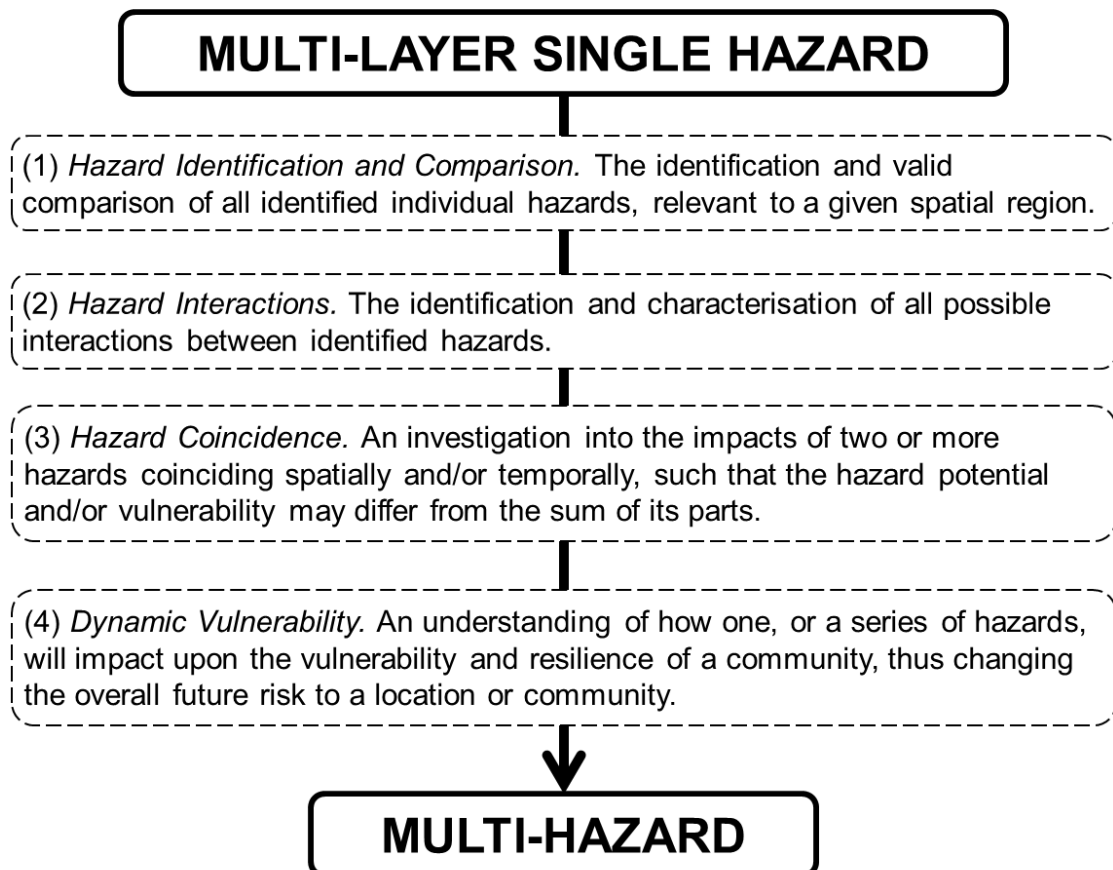
A multi-hazard methodology allows a comprehensive understanding of the holistic hazard potential or risk (if also taking into account vulnerability) to a specific geographical location. We propose four key factors that should be taken into account in order to fully understand and constrain the total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

- i. *Hazard Identification and Comparison.* The identification and valid comparison of all identified individual hazards, relevant to a defined spatial area.
- ii. *Hazard Interactions.* The identification and characterisation of all possible interactions between identified hazards.
- iii. *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.
- iv. *Dynamic Vulnerability.* The recognition that vulnerability is constantly changing as a result of changing societal dynamics (e.g., urbanization, population growth, 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’ multi-hazard risk assessment, incorporating these factors, could therefore be stated as follows: ‘A multi-hazard risk assessment should identify all possible

and relevant hazards and the valid comparison of their contributions to hazard potential, including the contribution to hazard potential from hazard interactions and spatial/temporal coincidence of hazards, while also taking into account the dynamic nature of vulnerability to multiple stresses.'

In **Figure 2.13**, this working framework is related to what has previously been defined as a 'multi-layer single hazard' approach. It is suggested that a spectrum exists between these two end-members (multi-layer single hazard approach and a full multi-hazard approach). **Figure 2.13** recognises that in order for a hazard assessment to make the transition from a multi-layer single hazard risk assessment to a multi-hazard risk assessment it is necessary to incorporate the four key factors outlined above.



**Figure 2.13. Multi-Hazard Framework.** This figure represents the progression from a multi-layer single hazard approach to a multi-hazard approach. This involves four key aspects, including assessing (i) how to compare all relevant individual hazards, (ii) hazard interactions, (iii) spatial/temporal coincidence of natural hazards, and (iv) dynamic vulnerability to multiple stresses.

The analysis of these four factors makes a thorough and complete multi-hazard 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 multi-hazard 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 multi-hazard 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 assess hazard potential and risk dominates research, policy-making and practice within the natural hazards community.

Most research that has examined multi-hazard 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 literature suggests 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, 2006; Grunthal *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 multi-hazard approaches and yet these relationships are regularly observed in case studies, such as those from Japan, USA, Philippines and Guatemala ([Section 2.2.1](#)). Our review and analysis of hazard interactions contributes to the development of a holistic multi-hazard approach, aiding the identification and initial classification of hazard interactions required to strengthen such approaches.

### 2.7.3 Potential Users

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

- i. *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, hydrosphere), it is helpful for the scientific community to visualise and understand these interactions. We believe this will help to foster improved communication between hazard specialists and encourage a more interdisciplinary approach. Visualisations 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 characterise secondary hazards in terms of location, timing and magnitude requires improvement) and collaborative partnerships.

- ii. *Disaster Management/DRR 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 visualisation 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 2.7.4](#)). The global approach, and wide-ranging framework proposed within this study can be modified and utilised within a more local-scale study. Furthermore, it has been proposed that the improvement of approaches to assess multi-hazard risk would improve DRR (UN, 2002; UNISDR, 2005; Government Office for Science, 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.
- iii. *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 2.3](#)) 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.

#### 2.7.4 Future Research Directions

In this study we have completed a critical review, analysis and visualisation 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:

- i. *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, 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).

- ii. 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), tectonic regimes (extensional, compressional), or geological/geomorphological settings (quaternary deposits, fluvial, coastal, arid environments) could be developed and utilised within both risk management and reduction.
- iii. Develop *improved, alternative or expanded classifications* of our ability to characterise secondary hazards ([Section 2.4](#)), spatial overlap and temporal likelihood ([Section 2.5](#)) and intensity relationships ([Section 2.6](#)). 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 (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.
- iv. 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 visualisations developed within this study to other information and data (key references, equations, case studies, 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.

## 2.8 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 multi-hazard 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 visualisation framework, using matrices and hazard linkage analyses, has been developed in order to represent this information.

As outlined in [Section 2.1.1](#), there are significant differences in terms of each hazard's spatio-temporal 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, 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 visualisation framework that:

- i. Supports the better understanding, integration and quantification of natural hazard interactions.
- ii. Reinforces the importance of a holistic approach to assess hazard potential by visualising 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.
- iii. 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.
- iv. 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.

# Chapter 3. Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies\*

## Summary

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

\* **Published in *Earth System Dynamics* in 2016.** Minor edits have been made to ensure consistency in reference style and language with the rest of the thesis. The substance of the chapter remains unchanged. Gill, J. C., and Malamud, B. D. (2016, in press) Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies, *Earth System Dynamics*, doi:10.5194/esd-2015-94.

## 3.1 Introduction

In this article we present both research and commentary to support the integration of hazard interactions and their networks (cascades) into multi-hazard methodologies. Building on the work of others (Delmonaco *et al.*, 2007; Kappes *et al.*, 2010; Kappes *et al.*, 2012; Marzocchi *et al.*, 2012; Gill and Malamud, 2014) we advocate for a multi-hazard approach that goes beyond the simple overlay of multiple single hazards, to an approach that also encompasses interactions between these hazards. We present here an enhanced framework for considering such interactions and integrating these into multi-hazard methodologies, supporting efforts to improve management of those aspects of the Earth system that are relevant to disaster risk reduction (DRR). Examples from primary research and published literature, together with commentary about multi-hazard approaches, are included throughout.

Following this introduction, [Section 3.2](#) examines the differences between single hazard, multi-layer single hazard, and full multi-hazard risk approaches. In [Section 3.3](#) we define and describe three distinct hazard and process groups (natural hazards, anthropogenic processes, technological hazards/disasters) that can be considered in multi-hazard methodologies. This is followed by [Section 3.4](#) which discusses and visualises three principal interaction relationships between these hazards and processes (triggering relationships, increased probability relationships, catalysis/impedance relationships), with a detailed description of their differences and examples of each. Then in [Section 3.5](#) we discuss how individual interactions can join together to form networks of hazard interactions (cascades), using four case studies (one from Nepal and three from Guatemala) and two theoretical examples, to consider different features of interaction networks and how these can be visualised using hazard interaction matrices and hazard/process flow diagrams. We also comment on the benefits of assessing networks of hazard interactions to support DRR. Conclusions are outlined in [Section 3.6](#).

## 3.2 Multi-Hazard Risk Assessments

### 3.2.1 Single vs. Multi-Hazard

Single hazard approaches to assess hazard potential, in which hazards are treated as isolated and independent phenomena, are commonplace. Their prevalence, however, can distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate risk (Tobin and Montz, 1997; ARMONIA, 2007; Kappes *et al.*, 2010; Budimir *et al.*, 2014; Mignan *et al.*, 2014). If a community is susceptible to more than one hazard, management decisions will benefit by reflecting the differential hazard potential and risk from each of these, and not just focus on

them as individual entities. Focusing on a small portion of the whole Earth system, rather than the dynamics of its entirety, may result in decisions being made that increase people's vulnerability to other, ignored hazards. The development of enhanced 'multi-hazard' risk approaches (integrating all aspects of hazard interactions together with vulnerability and exposure) could offer a way by which the DRR community can address these problems.

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

The term 'multi-hazard' may appear to be unambiguous to some and not require a definition. It is, however, a term that is frequently used in different contexts by different members of the natural hazards and DRR community. It has been used to describe the independent analysis of multiple different hazards (e.g., landslides, earthquakes, pyroclastic density currents, tephra fall, flooding) relevant to a given area (e.g., Granger *et al.*, 1999; Perry and Lindell, 2008). It has also been used when referring to the identification of areas of spatial overlap, by superimposing hazard layers (e.g., Dilley *et al.*, 2005; Shi *et al.*, 2015). These can be better thought of as 'multi-layer single hazard' approaches (Gill and Malamud, 2014), where an 'all-hazards-at-a-place' framework (Hewitt and Burton, 1971) seeks to understand the discrete risks due to multiple natural hazards.

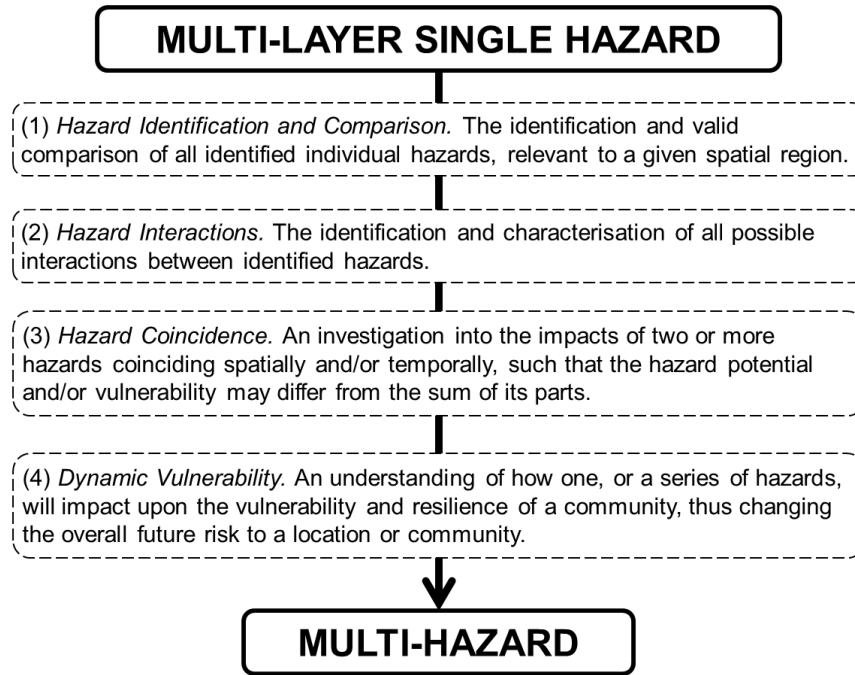
The identification of all possible and spatially relevant hazards is an important feature of a full multi-hazard assessment, but we believe should not be the sole defining characteristic of such an approach. Multi-hazard assessments may also recognise the non-independence of natural hazards (Kappes *et al.*, 2010), noting that significant interactions exist between individual natural hazards. In a previous study (Gill and Malamud, 2014) we took 21 different natural hazards and identified 90 possible interactions between the 441 ( $21 \times 21$ ) combinations. Here, we will further consider (Section 3.3 to 3.4) interactions that may also exist between natural hazards, anthropogenic processes (human activity) and the built environment. We will also consider (Section 3.5) interactions that can occur successively to form networks of hazard interactions, also referred to as hazard cascades or chains (e.g., Xu *et al.*, 2014; Choine *et al.*, 2015).

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

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

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

Multi-hazard methodologies, therefore, should ideally evaluate all identified individual hazards relevant to a defined spatial area and characterise all possible interactions between these identified hazards. **Figure 3.1**, from Gill and Malamud (2014) shows four distinct factors required to transition from a multi-layer single hazard assessment to a detailed, full multi-hazard risk assessment (which includes hazard interactions, vulnerability and exposure). In addition to identifying all hazards and their interactions, this working framework also proposes an assessment of concurrent hazards (such as a tropical storm and volcanic eruption coinciding spatially and temporally), and the recognition that vulnerability is dynamic (which we discuss more in **Section 3.5.3**).



**Figure 3.1. Multi-hazard risk framework** (from Gill and Malamud, 2014, reproduction of Figure 2.13). Shown is the progression from a multi-layer single hazard approach to a full multi-hazard risk approach that includes: (i) hazard identification and comparison, (ii) hazard interactions, (iii) spatial/temporal coincidence of natural hazards, and (iv) dynamic vulnerability to multiple stresses (when progressing from the assessment of hazard to the assessment of risk).

Many current hazard assessments that are labelled as ‘multi-hazard’ do not consider all the factors given in Figure 3.1, in either a qualitative or quantitative manner. This may be a consequence of limited existing methodologies to assess each of the steps proposed in Figure 3.1 of a multi-hazard approach. Those methodologies that do exist are sometimes complex, requiring significant amounts of data. Some accessible methodologies to allow the comparison of natural hazards, however, can be found within the literature (e.g., Granger *et al.*, 1999; Van Westen *et al.*, 2002; Greiving *et al.*, 2006; Grunthal *et al.*, 2006; Marzocchi *et al.*, 2009). Methodologies to identify and visualise potential natural hazard interactions also exist (e.g., Tarvainen *et al.*, 2006; Han *et al.*, 2007; De Pippo *et al.*, 2008; Kappes *et al.*, 2010; van Westen *et al.*, 2014, Gill and Malamud, 2014, Liu *et al.*, 2016), including a progression towards more quantitative approaches (e.g., Neri *et al.*, 2013; Marzocchi *et al.*, 2012). In this chapter, we will consider multi-hazard risk frameworks, with a focus on the hazard interaction component of the risk framework (and not so much of a focus on vulnerability and exposure).

### 3.2.2 From Global to Local Multi-Hazard Approaches

The hazard interactions literature outlined in Section 3.2.1 includes studies for different spatial extents, including global (e.g., Gill and Malamud, 2014), continental (e.g., Tarvainen *et al.*, 2006)

and local or sub-national (e.g., De Pippo *et al.*, 2008). The scale of interest for a particular multi-hazard approach determines how interactions are characterised. Approaches may be based on an examination of an individual event (e.g., a given earthquake triggering landslides in a given region), or draw on a large population of individual events to infer the probabilistic behaviour of a relationship (e.g., considering many earthquake triggered landslide events over different regions, and from this the dependence of the number of landslides triggered based on the earthquake magnitude). The latter approach is used to consider in general how one hazard will influence another. Both approaches are beneficial in different contexts. For example, a probabilistic viewpoint is likely to support the characterisation of possible interactions in a general, globally relevant way, as we often consider them in this chapter. When adapting global, multi-hazard approaches for use in regional and local contexts, a different population of individual events is required to infer the probabilistic behaviour of a relationship specific to that context. In many regions, although the database of events is likely to better reflect site-specific conditions, it may be small, consisting of just a few (sometimes zero) individual events, depending on the period of time considered.

Another possible contrast between globally-relevant multi-hazard approaches and location-specific, multi-hazard approaches is the forecasting time window (Marzocchi *et al.*, 2012) or temporal resolution (Kappes *et al.*, 2012). In globally-relevant approaches that draw upon many individual events, generalisations across forecasting time windows (both short- and long-term time windows) are used to construct the multi-hazard framework, with the inclusion of interactions relevant at all temporal resolutions. When developing location-specific multi-hazard assessments, clear temporal limits should be established (Selva, 2013), depending on the purpose of the multi-hazard approach. When constructing location-specific assessments of hazard potential, Marzocchi *et al.* (2012) propose that the modelling of hazard interactions is more necessary in the short term (e.g., hours to days) than the long term (e.g., many decades to centuries). They argue that in the short term, the occurrence of a primary hazard (e.g., storms) can significantly modify the probability of secondary hazards (e.g., floods, landslides), compared to the long-term, where primary hazards (e.g., earthquakes, landslides) are already considered in the long-term assessment of the secondary hazard (e.g., tsunamis). In other words, they discuss that in a long-term perspective (e.g., the tsunami hazard over the next 50 years), databases already contain information of the fact that most tsunamis are triggered by earthquakes, and there is no need to make additional calculations to calculate the long-term tsunami hazard. It is therefore less necessary in the long term (compared to short term) to model possible interactions as databases of past single hazard occurrences already reflect the triggered nature of these hazards. In the long term, however, it is important to consider the temporal proximity of successively occurring hazards (e.g., earthquake → tsunami) in order to better evaluate possible risks and losses. We will

further explore short-term and long-term time windows in relation to natural hazard interactions (primary hazard triggering a secondary hazard) in [Section 3.4.1](#). The importance of interactions in both short- and long-term contexts can aid the understanding of natural hazards, hazard education, communication and DRR.

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

### 3.3 Hazard and Process Groups

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

- i. *Natural hazards.* A natural process or phenomenon that may have negative impacts on society (UNISDR, 2009). Examples include earthquakes, volcanic eruptions, landslides, floods, subsidence, tropical storms and wildfires.
- ii. *Anthropogenic processes.* Intentional human activity that is non-malicious, but that may have a negative impact on society through the triggering or catalysing of other hazardous processes. The word *process* here (and used in many other places in the text) is taken to mean “*a continuous and regular action or succession of actions occurring or performed in a definite manner, and having a particular result or outcome; a sustained operation or series of operations*” (OED, 2015). Examples include groundwater abstraction, vegetation removal, quarrying and surface mining, urbanisation and subsurface construction (tunnelling).
- iii. *Technological hazards/disasters.* The unintentional, non-malicious or negligent failure of technology or industry. Examples include structural collapse, nuclear reactor failure, urban fires, chemical pollution and dam collapse. The term technological

hazards/disasters is used as it is difficult to separate hazard from other components of a disaster, such as the physical vulnerability of infrastructure.

Examples for each of these three groups (natural hazards, anthropogenic processes, technological hazards/disasters), based on the definitions set out above, are given in [Table 3.1](#).

**Table 3.1. Examples of hazard/process types.** Hazard and process type examples, grouped into three categories: Natural Hazards (classification of 21 hazards from Gill and Malamud, 2014), Anthropogenic Processes and Technological Hazards/Disasters.

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

We now discuss in more detail ([Section 3.3.1](#) to [3.3.3](#)) each of these three groups, particularly potential overlap between the words ‘*anthropogenic process*’ and ‘*technological hazard*’ with additional brief comments in [Section 3.3.4](#).

### 3.3.1 Natural Hazards

The meaning of the phrase *natural hazards*, considered both individually and as a group of processes is reasonably well understood (e.g., Alexander, 1993; Smith, 2013). The broad definition of a natural hazard, as set out by UNISDR (2009), is well accepted and encompasses those natural processes that are widely considered to potentially have a negative impact on society and the natural environment. Differences may exist in the level of organisation, or the resolution of classification, used to describe each single hazard. For example, in their National Risk Register, the UK Cabinet Office (2013) divides floods into coastal flooding and in-land flooding. Differences may also exist in how single hazards are clustered. For example, landslides may be clustered with other single hazards within one or more of the following broader hazard types: geophysical, geomorphological, hydrological, and/or hydro-meteorological. These differences in resolution of classification and clustering are normally due to different purposes and characteristics of interest to a specific project, rather than any significant differences of understanding in the process.

### 3.3.2 Anthropogenic Processes

Anthropogenic processes are less well defined and characterised as a group, compared to the group labelled ‘natural hazards’. There are numerous references to individual human activities exacerbating or triggering particular natural hazards in the literature. For example, Owen *et al.* (2008) refer to the role of road construction in exacerbating landslide initiation during the 8 October 2005 Kashmir earthquake; Glade (2003) refer to the role of land cover changes in the triggering of landslides during rainstorms in New Zealand; and Knapen *et al.* (2006) refers to the role of vegetation removal in triggering landslides in Uganda. Induced seismicity is a further example of an anthropogenic process triggering a natural hazard. Anthropogenic processes believed to induce seismicity include reservoir construction (Simpson, 1976), groundwater abstraction (González *et al.*, 2012), and wastewater injection (Ellsworth, 2013; Hough and Page, 2015). Each of these examples involves an intentional, non-malicious human activity that has the potential to have a negative impact on society through the triggering or catalysing of hazards. UNISDR (2009) defines the occurrence of specific natural hazards arising from overexploited or degraded natural resources as ‘socio-natural’ hazards. By definition, these are generated by the interaction of anthropogenic processes with the natural environment. The inclusion of anthropogenic processes within multi-hazard approaches is therefore important and justified. They are very relevant to the modelling of Earth system dynamics and hazardous environments.

### 3.3.3 Technological Hazards/Disasters

Although often referred to in the context of disaster studies (e.g., Fleischhauer, 2006; Tarvainen *et al.*, 2006; Bickerstaff and Simmons, 2009), technological hazards/disasters are also less well defined and characterised than the group ‘natural hazards’. Some definitions or descriptions of technological hazards and disasters do exist (e.g., Kaspersen and Pijawka, 1985; Gunn, 1990; UNISDR, 2009), but these often lack clarity or they conflict with one another. For example, some definitions include intentional anthropogenic activities within their definition of technological hazards/disasters. Gunn (1990) refers to technological disasters as being human-initiated consequences of breakdown, technical fault, errors, or involuntary and voluntary human acts that have negative consequences. The latter (voluntary human acts) includes those examples that we have defined in [Section 3.3.2](#) as anthropogenic processes. Subsurface mining, for example, is a voluntary human act that can result in environmental damage, such as subsidence. This subsidence can vary in intensity from slight to severe (Bell *et al.*, 2000).

The UNISDR (2009) definition of technological hazards also states that hazards originate from technological or industrial conditions, including human activities that may cause environmental

damage, health impacts, economic disruption and other negative consequences. This could include human activities such as subsurface mining, groundwater abstraction and vegetation removal. Therefore, the UNISDR (2009) definition of technological hazards also appears to include examples that we have categorised as anthropogenic processes.

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

- i. *Routine hazard events of technology*, where there is exposure to underlying chronic hazardous activity over an extensive time period. These can normally be managed by established procedures.
- ii. *Technology failures*, resulting in the need for an emergency response.
- iii. *Technological disasters*, resulting in significant loss of life or injury, social disruption or relocation.

The last two (technology failures, technological disasters) are distinguished based on the scale of impact, with technological failures able to evolve into technological disasters if losses are sufficiently large. Although included within the broad category of technological hazards in Kasperson and Pijawka (1985), there is significant overlap between their definition of *routine hazard events of technology* and our definition of anthropogenic processes, outlined in [Section 3.3.2](#). For example, in [Table 3.1](#) we note surface mining to be an anthropogenic process. This classification is based on our definition of anthropogenic processes being intentional human activities that are non-malicious but may have a negative impact on society through the triggering or catalysing of hazardous processes ([Section 3.3](#)). Surface mining can also be considered to be a *routine hazard event of technology* as defined by Kasperson and Pijawka (1985), in that the mining is a technological process where there is exposure to underlying chronic hazardous activity, which can be managed by established procedures.

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

### 3.3.4 Additional Hazards or Processes

In [Section 3.3.1](#) to [3.3.3](#) it was noted that both anthropogenic processes and technological hazards/disasters are non-malicious; the negative consequences are not the desired outcome. Events that are malicious or deliberately destructive (e.g., terrorism, arson, aspects of warfare and criminal activity) are not included within either ‘anthropogenic processes’ or ‘technological hazards/disasters’, but may trigger the occurrence of other hazards or processes. For example, the deliberate, and malicious detonation of a bomb close to a dam (this is not an anthropogenic process, as it is malicious) may trigger the dam to collapse (technological hazard), resulting in substantial flooding (natural hazard).

In the context of the rest of this article we focus on interaction relationships between the three groups just discussed (natural hazards, anthropogenic processes, technological hazards/disasters) and the development of possible networks of hazard interactions (cascades).

## 3.4 Interaction Relationships

### 3.4.1 Classifying Interaction Types

Multiple interactions exist between the hazard and process examples outlined in the three groups (natural hazards, anthropogenic processes, technological hazards/disasters) discussed above. Kappes *et al.* (2012) note a wide variety of terms used to describe such interactions (e.g., interrelationships, interconnections, coupled events) and specific sets of interacting hazards (e.g., coinciding hazards, triggering effects). Here we continue to use the term ‘interactions’ to describe the possible inter- and intra-relationships for hazards and processes. We note that the term ‘interaction’ communicates the potential for unidirectional and bidirectional relationships. In unidirectional relationships first the ‘primary’ hazard occurs and then the ‘secondary’ hazard. An example is a tropical storm triggering a flood. In this case the flood may trigger further hazards (e.g., ground collapse, ground heave), but there is no feedback from the flood back to the tropical storm. In bidirectional relationships, feedback mechanisms may occur where a primary hazard triggers a secondary hazard which exacerbates the primary hazard, therefore triggering further episodes of the secondary hazard. An example of this would be a landslide blocking a river, resulting in a flood, but then the water upstream of the blockage interacting with the original landslide, breaking it down, and the water potentially triggering further landslides.

We use the term ‘interaction’, therefore, to refer to the unidirectional and bidirectional effect(s) between one hazard/process and another hazard/process, and note examples of three distinct types of interaction relationships:

- 
- i. *Triggering relationships* (e.g., lightning triggering a wildfire; groundwater abstraction triggering regional subsidence; a flood triggering a landslide which then triggers a further flood).
  - ii. *Increased probability relationships* (e.g., a wildfire increasing the probability of landslides; regional subsidence increasing the probability of flooding).
  - iii. *Catalysis/impedance relationships* (e.g., urbanisation catalysing storm-triggered flooding; storms impeding urban fire triggered structural collapse).

While we distinguish *triggering* relationships and *increased probability* relationships as two different types of interactions, we acknowledge that there are similarities between them as they both represent a change in probability of a secondary hazard (e.g., landslide), given a primary hazard (e.g., earthquake). We would suggest that these two interaction types can be characterised by two end members, with a continuum between them. A *triggering* relationship can be characterised as having a probability associated with a threshold being reached or passed. An *increased probability* relationship is characterised by a probability associated with a change in environmental parameters that moves towards, but does not reach a particular threshold. Although there are similarities, we would suggest that it is beneficial to consider both triggering and increased probability relationships as separate interaction types. We propose two ways by which one can differentiate between a hazard/process triggering another hazard/process, and a hazard/process increasing the probability of another hazard/process:

- i. *Direct vs. indirect sequence of events between the primary and secondary hazard.* In some cases, it is possible to differentiate between triggering and increased probability relationships by considering direct vs. indirect sequences of events between the primary and secondary hazards/processes. An example of a (roughly) direct sequence is the addition of water to geological material on a hillslope, which can directly trigger landslides (heavy rain → landslides). In contrast, an example (roughly) of an indirect sequence is the influence of ground subsidence on flooding. Subsidence in itself may not trigger a flood; however, it could make flooding more likely to occur in the event of a river spilling over its banks. Direct sequences tend to be triggering relationships, whereas indirect sequences tend to be increased probability relationships.
- ii. *Temporal sequence.* It is also possible to differentiate between some triggering and increased probability relationships by considering the timing of the sequence of events, and taking both forward looking and retrospective views. Take the following time sequence (arbitrary units and lengths of time for the windows):

**Time Window 1** | [*Primary Hazard Window*] | **Time Window 2A** | **Time Window 2B**

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As an illustrative example, we will take an earthquake as the primary hazard, and a triggered landslide population event as the secondary hazard, and will discuss perspectives from before the primary hazard occurs (**Time Windows 1**) and two time periods after the primary hazard occurs (**Time Windows 2A** and **2B**):

- **While in Time Window 1, consider what may happen in Time Windows 2A and 2B** [forward looking]. Prior to an earthquake [primary hazard] occurring [**Time Window 1**], and based on past historical knowledge of the region (e.g., a 50 year historical catalogue of past earthquakes), it can be stated that there is a given probability of an earthquake occurring and that given an earthquake, landslides [secondary hazard] may occur (i.e., they are triggered by the earthquake) in the time period of minutes to days [**Time Window 2A**] after the earthquake. Furthermore, while in **Time Window 1**, we can state that more landslides may occur (i.e., an increased probability) much later after an earthquake event (months to years) [**Time Window 2B**] due to changes in the parameters governing the stability of the slope (Havenith, 2014). We cannot know whether landslides [secondary hazard] will be directly triggered by the earthquake [primary hazard] until after the earthquake has occurred (i.e., until the end of **Time Window 2A**), but we can postulate that the earthquake might trigger landslides.
- **While at the end of Time Window 2A, consider what has occurred in Time Window 2A** [retrospective] **and what may happen in Time Window 2B** [forward looking]. Looking retrospectively at **Time Window 2A**, the period just after the earthquake [primary hazard] has occurred, we have identified any landslides [secondary hazard] that were triggered by the earthquake. We can also look forward to **Time Window 2B** and state that there is now an increased probability of landslides due to changes in the parameters governing the stability of slopes in the region.
- **While at the end of Time Window 2B, consider what has occurred in Time Windows 2A and 2B** [retrospective]. At this position in time, we can retrospectively assess what landslides have been triggered by the earthquake, either directly triggered in the minutes to days after the earthquake event (**Time Window 2A**), or resulting from earthquake-induced changes to the landscape which result in broader changes to landslide susceptibility over longer time periods (**Time Window 2B**).

When generalising across these three time windows (**1, 2A, 2B**), recognising that an earthquake [primary hazard] can both trigger and increase the likelihood of landslides [secondary hazard] occurring in [**Time Windows 2A and 2B**] can be a useful concept, particularly for decision making at an operational level.

In summary, while causal triggering relationships can only be ‘known’ retrospectively, there is still a good justification for distinguishing between triggering and increased probability relationships when using forward-looking approaches. For any given window of time after a primary hazard, those interested in hazard interactions (e.g., scientists, hazard managers) may want to know what the likelihood is of landslides occurring (being triggered), as well as whether there is a change in the likelihood of landslides beyond this window of time (increased probability). Although attribution or identifying a causal relationship between a specific primary hazard (e.g., a given earthquake) and a specific secondary hazard (e.g., a given tsunami) is clear in some cases, other times attribution is not so clear (e.g., the increase in probability of landslides as a result of a wildfire). This challenge of attribution is currently in the forefront of the climate change community, where attempts are made to determine the existence of causal relationships between anthropogenic climate change and specific extreme events (Stott *et al.*, 2013; Shepherd, 2016).

We now discuss each of these three interaction relationships in more detail, giving examples and introducing two visualisations. These interaction relationships are also used in [Section 3.5](#), when discussing networks of interactions (cascades).

### 3.4.2 Triggering Relationships

Triggering relationships are one form of causal relationship, where the occurrence of a primary event can result in secondary events occurring. For example, a tropical storm or hurricane (a primary natural hazard) may trigger many landslides (a secondary natural hazard) due to the rapid increase in ground saturation, such as in the case of Hurricane Mitch in 1998 where heavy rain associated with the hurricane resulted in thousands of landslides being triggered in Guatemala (Bucknam *et al.*, 2001). As noted in [Section 3.4.1](#), feedback mechanisms can also exist where a triggered secondary hazard exacerbates the primary hazard and results in further occurrences of the primary and/or secondary hazard being triggered.

Triggering interactions can occur between a diverse range of hazards and processes. Gill and Malamud (2014) considered just natural hazards, and identified 78 possible triggering pairings between 21 natural hazards (the same natural hazards as those given in [Table 3.1](#)). The inclusion of both ‘anthropogenic processes’ and ‘technological hazards/disasters’ would result in many

more triggering relationships than the 78 identified by Gill and Malamud (2014) for natural hazards, as there would not only be triggering relationships within each of the two additional groups ('anthropogenic processes', 'technological hazards/disasters'), but also a significant number arising between all three groups.

We also highlight that each triggering relationship identified will have different likelihoods associated with it. Relationship likelihood will be dependent on site-specific conditions (e.g., geology, hydrology, neotectonics, the extent of human activity). From a probabilistic viewpoint, generalising across multiple individual events for each triggering relationship, we can also infer that some triggering relationships are more likely to occur than others. For example, Gill and Malamud (2014) use a nine-point scale to classify the *spatial overlap* and *temporal likelihood* of each of the 78 primary-secondary natural hazard triggering relationships that they identified. An example of a triggering relationship with low *spatial overlap* and low *temporal likelihood* is a landslide triggering a volcanic eruption. An example of a triggering relationship with high *spatial overlap* and high *temporal likelihood* is a storm triggering a landslide.

Of importance in the context of characterising triggering relationships are the spatial and temporal scales of interest. When considering interactions in a specific local/regional setting, different interaction behaviours will occur at different spatial and temporal scales. For example, an anthropogenic process, such as agricultural practice change, could occur at multiple scales. An individual farmer ploughing a new field (approximate spatial scale of 0.1–1 km<sup>2</sup>, temporal scale of days to weeks) is likely to have a different influence compared to a societal transition from manual to machine-dominated farming (approximate spatial scale of 10<sup>4</sup>–10<sup>7</sup> km<sup>2</sup>, temporal scale of years to centuries). Differences in the scale of interest of agricultural practice change would result in diverse characterisations of the possible triggering relationships. In the context of this chapter we are not focusing on a specific local/regional study or at a specific spatial/temporal scale, but rather considering a global overview of interactions, generalising across many spatial and temporal scales.

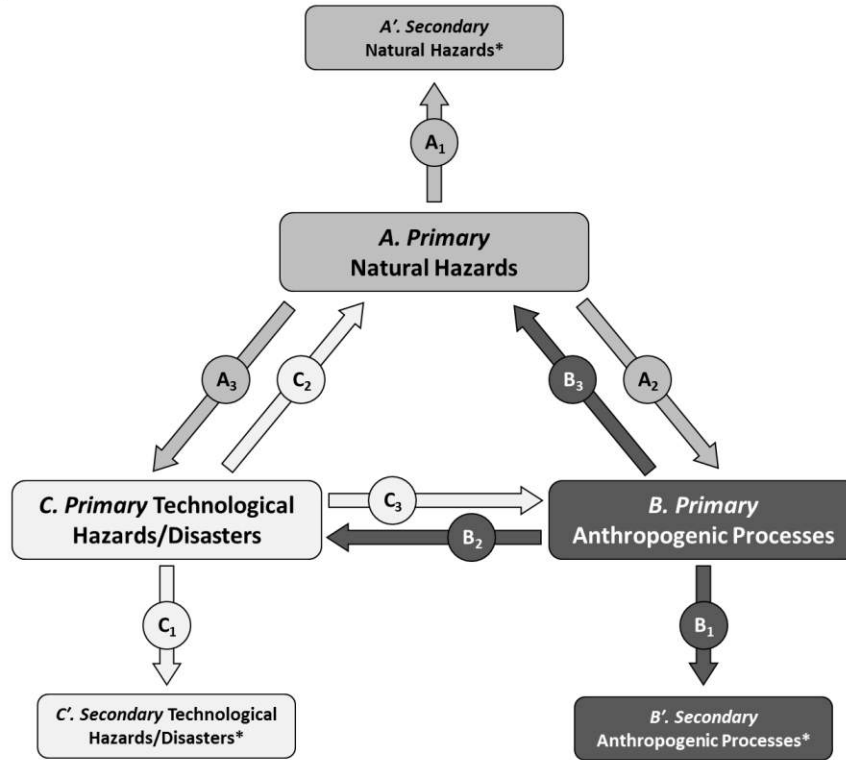
Another important factor for consideration when characterising triggering relationships, is the relative timing of different stages. For example, some anthropogenic processes may involve multiple stages, including an initial decision-making or survey stage before ground disturbance. In this example, it is possible that a given anthropogenic process may trigger other processes to occur before, simultaneously with, or after any ground disturbance has occurred. Where an associated process is stated to occur 'before' a primary anthropogenic process, it is normally occurring after at least one preliminary stage of the primary anthropogenic process. Associated processes can therefore be considered to be triggered by an occurrence of a primary anthropogenic process. For example, subsurface construction, such as tunnelling, may require drainage and

dewatering to take place before the tunnelling commences. The need for drainage or dewatering would be determined during preliminary ground reconnaissance and site investigation.

When considering combinations between the three groups of hazards/processes (natural hazards, anthropogenic processes, technological hazards/disasters), we identify nine possible triggering relationships between these groups and visualise these in **Figure 3.2**, a hazard/process flow diagram. Triggering relationships are illustrated using block arrows, with the internal arrow fill colour indicating the group of hazards or processes to which the ‘trigger source’ belongs. Medium-grey is used for natural hazards (labelled **A**), dark-grey is used for anthropogenic processes (labelled **B**), and light-grey is used for technological hazards/disasters (labelled **C**). We use a prime (**A'**, **B'**, **C'**) to indicate secondary hazards/processes triggered by the same primary hazard or process (**A**, **B**, **C**). Examples of all nine possible interactions are given in a table below **Figure 3.2**, with codes (i.e., **A<sub>1</sub>–A<sub>3</sub>**, **B<sub>1</sub>–B<sub>3</sub>**, **C<sub>1</sub>–C<sub>3</sub>**) relating to arrow labels derived from the hazard or process type of the ‘trigger source’ (i.e., **A**, **B**, **C**), and followed by sequential subscript numbering. Numbering in our hazard/process flow diagram starts (**A<sub>1</sub>**, **B<sub>1</sub>**, **C<sub>1</sub>**) with the triggering relationship between the same primary and secondary hazard or process type (e.g., a primary *natural hazard* triggering a secondary *natural hazard*) and progresses clockwise. These nine possible triggering relationships demonstrate an important set of interaction relationships that could be included within a multi-hazard methodology.

### 3.4.3 Increased Probability Relationships

Another type of causal relationship can be observed when a primary natural hazard, anthropogenic process or technological hazard increases the probability of another such event occurring. These situations involve a primary hazard or process altering one or more environmental parameters so as to change the temporal proximity or specific characteristics of an individual or population of secondary hazards or processes (Kappes *et al.*, 2010; Gill and Malamud, 2014). Examples relating to specific natural hazards include an earthquake increasing the susceptibility of a slope to landslides, regional subsidence increasing the probability of flooding, or wildfires increasing the probability of ground heave. Gill and Malamud (2014) took the 21 different natural hazards in **Table 3.1**, and identified 75 possible relationships where a primary natural hazard could increase the probability of a secondary natural hazard. The inclusion of anthropogenic processes and technological hazards/disasters will also result in many more increased probability relationships.



**Internal Arrow Fill**

- Interaction relationships initiated by natural hazards.
- Interaction relationships initiated by anthropogenic processes.
- Interaction relationships initiated by technological hazards/disasters.

\*Secondary hazards may initiate further interactions.

**Examples for Interaction Relationships A<sub>1</sub>–C<sub>3</sub>**

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

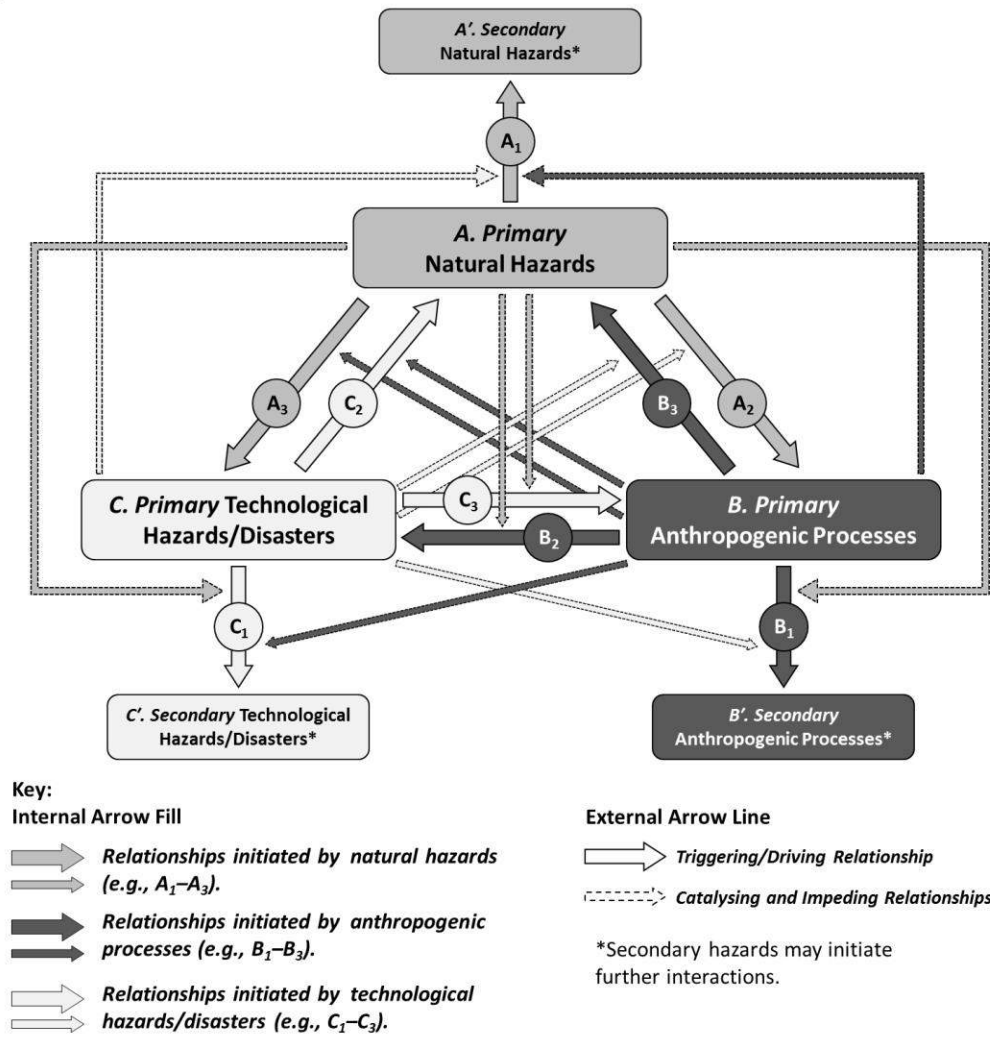
**Figure 3.2. Interaction relationships (triggering) framework using a hazard/process flow diagram.** A framework for hazard/process interactions is given here, which highlights triggering relationships between three groups: (A) natural hazards, (B) anthropogenic processes and (C) technological hazards/disasters. Arrows are used to illustrate interaction relationships, with the arrow fill colour indicating the ‘source’ or initiation of the trigger (medium-grey: natural hazards; dark-grey: anthropogenic processes; light-grey: technological hazards/disasters). We use a prime (A', B', C') to indicate secondary hazards/processes triggered by the same primary hazard/process group (A, B, C). Arrows are labelled (A<sub>1</sub>–A<sub>3</sub>, B<sub>1</sub>–B<sub>3</sub>, C<sub>1</sub>–C<sub>3</sub>) according to the hazard or process type of the ‘trigger source’ (i.e., A, B, C), and followed by sequential subscript numbering. Numbering starts (A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub>) with the triggering relationship between the same primary and secondary hazard or process type (e.g., a primary natural hazard triggering a secondary natural hazard) and progresses clockwise. Examples of each interaction are given in the table at the bottom of the figure, where the vertical axis indicates the source of the primary hazard/process (A, B, C), and the horizontal axis indicates which subscript is being referred to (1, 2, 3).

### 3.4.4 Catalysing and Impedance Relationships

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

In addition to the nine triggering interaction relationships previously identified (**Figure 3.2**), a further 12 possible catalysing and impedance relationships can be considered, which we visualise in **Figure 3.3**, also a hazard/process flow diagram. In **Figure 3.3**, we contrast triggering relationships (9 thick block arrows with solid outlines), and catalysing/impedance relationships (12 thin block arrows with dashed outlines). The internal arrow fill colour again indicates the group of hazards or processes to which the catalyst/impeder belongs (medium-grey: natural hazards; dark-grey: anthropogenic processes; light-grey: technological hazards/disasters).

**Figure 3.3** highlights the range of possible interaction relationships between the three broad groups of hazards/processes, using a hazard/process flow diagram. Within each type of interaction relationship there exist specific interactions that are rare and others that are very common, with a wide spectrum between these two end members. Location-specific conditions influence the likelihood of any given interaction relationship. The likelihood of each catalysing relationship will depend on (i) the likelihood of the primary hazard/process occurring, (ii) the likelihood of the primary hazard/process triggering a secondary hazard, and (iii) the likelihood of a given hazard/process catalysing this interaction pairing. Consider, for example, the unloading of slopes through road construction catalysing earthquake or storm-triggered landslides (thin, dark-grey arrow from **B** to **A<sub>1</sub>** in **Figure 3.3**). In **Section 3.3.2** we introduced this example, describing how Owen *et al.* (2008) had found that road construction catalysed the triggering of landslides during the 8 October 2005 Kashmir earthquake. In regions that are susceptible to landslides, the influence of road construction is well documented (e.g., Montgomery, 1994; Devkota *et al.*, 2013; Brenning *et al.*, 2015). It is a catalysing relationship that is common in many parts of the world. Overall, the differential likelihood of any relationship will depend on the range of location-specific parameters. Only through the careful assessment of all possible single hazards and processes can relevant interactions be identified and assessed.



**Figure 3.3. Interaction relationships (triggering, catalysing and impeding) framework using a hazard/process flow diagram.** Interactions in the form of triggering relationships (Figure 3.2), and catalysing/impedance interactions are possible between (A) natural hazards, (B) anthropogenic processes and (C) technological hazards/disasters. We use a prime (A', B', C') to indicate secondary hazards/processes triggered by the same primary hazard/process group (A, B, C). We contrast here triggering relationships (thick block arrows with solid outlines) and catalysing/impedance relationships (thin block arrows with dashed outlines). The internal arrow fill colour indicates the group of hazards or processes to which the catalyst/imperder belongs (medium-grey: natural hazard; dark-grey: anthropogenic process; light-grey: technological hazard/disaster). Descriptions of arrow labels (A<sub>1</sub>-A<sub>3</sub>, B<sub>1</sub>-B<sub>3</sub>, C<sub>1</sub>-C<sub>3</sub>) can be found in Figure 3.2 caption. Examples are given in Section 3.4.4.

Examples of some specific catalysing and impeding interaction relationships are presented below. Here we state which hazard or process group (e.g., anthropogenic process) is acting as the catalysing or impeding agent, whether it is a catalysis or impedance relationship, and which triggering relationship identified in Section 3.4.2 is being catalysed or impeded (e.g., A<sub>1</sub>, B<sub>1</sub>, C<sub>1</sub>, as labelled and described in Section 3.4.2). We then give a more specific example.

- i. *Anthropogenic processes catalysing triggering relationship A<sub>1</sub>* (thin dark-grey arrow from B to A<sub>1</sub> in Figure 3.3): Example: urbanisation catalyses storm-triggered flooding.

- 
- ii. *Technological hazards/disasters catalysing triggering relationship  $A_1$*  (thin light-grey arrow from  $C$  to  $A_1$  in [Figure 3.3](#)): Example: dam collapse catalyses flood triggered landslides.
  - iii. *Natural hazards catalysing triggering relationship  $B_1$*  (thin medium-grey arrow from  $A$  to  $B_1$  in [Figure 3.3](#)): Example: floods catalyse urbanisation triggered agricultural practice change.
  - iv. *Natural hazards impeding triggering relationship  $C_1$*  (thin medium-grey arrow from  $A$  to  $C_1$  in [Figure 3.3](#)): Example: storm impedes structural collapse triggered urban fires

### 3.5 Networks of Hazard Interactions (Cascades)

In [Section 3.4](#), we discussed three different interaction relationships (triggering, increased probability, catalysing/impedance) between specific natural hazards, anthropogenic processes and technological hazards/disasters. However, in addition to having a paired relationship (e.g., one primary natural hazard triggering a secondary natural hazard) these interactions can be joined together to form a network of hazard and/or process interactions. For simplification of language, we simply call these ‘*networks of hazard interactions*’ or ‘*interaction hazard networks*’. Such networks have also been referred to as hazard chains (e.g., Han *et al.*, 2007; Xu *et al.*, 2014), cascades (e.g., Choine *et al.*, 2015) or multi-hazard networks of interacting hazards (Gill and Malamud, 2014). Networks of hazard interactions may consist of short or long chains of interactions, and may include single or multiple branches.

In [Section 3.5.1](#) we introduce four case study examples of networks of hazard interactions, one example from Nepal and three from Guatemala. In [Section 3.5.2](#) we illustrate the wide variation in spatial and temporal extent, frequency and impacts of such networks of hazard interactions, using three of these case studies. In [Section 3.5.3](#) we then use our hazard interaction matrix and hazard/process flow diagrams to visualise networks of hazard interactions, using two of these case studies and three theoretical examples. Finally, in [Section 3.5.4](#), we discuss why we believe evaluating networks of hazard interactions is important.

#### 3.5.1 Case Study Examples (Nepal and Guatemala)

Networks of hazard interactions are relevant in many locations around the world. Guatemala is an example of a location where multiple different networks of hazard interactions can be identified. We have identified examples of the wide range of hazards and processes in Guatemala

using 21 semi-structured interviews with Guatemalan hazard professionals and personal field observations, during two months of fieldwork in 2014.

- Specific natural hazards: earthquakes, volcanic eruptions, landslides, floods, droughts, tropical storms, extreme temperatures, subsidence, ground collapse and wildfires.
- Relevant anthropogenic processes: deforestation, inadequate drainage, agricultural practices and building/road construction practices.
- Technological hazards/disasters of relevance: structural collapses, urban fires, chemical pollution and transport accidents.

Specific hazards or processes influencing Guatemala may last for decades (e.g., eruptive activity of Santiaguito, Bluth and Rose, 2004) or days (e.g., Tropical Storm Agatha, Stewart, 2011), impacting large areas (e.g., landslides across thousands of square kilometres; Harp *et al.*, 1981) or small areas (e.g., 20 m ground collapses, Stewart, 2011). A wide range of possible interactions exist in Guatemala between specific natural hazards, anthropogenic processes and technological hazards/disasters. In **Table 3.2** we present four case study examples of networks of hazard interactions, with three examples from Guatemala, and one additional example from Nepal. The examples in **Table 3.2** are ordered according to their use in subsequent sections.

Many other examples of networks of hazard interactions (cascades) can be observed in the published scientific literature, technical reports, press releases and other forums. It is beyond the scope of this article to compile a comprehensive list of these cascades; however, many can be found in the references noted at the end of this article. We proceed to use the four case study examples outlined above, together with three further theoretical examples, to illustrate two important concepts relating to networks of hazard interactions.

**Table 3.2. Case study examples of networks of hazard interactions (cascades).** Four examples of networks of interactions (one from Nepal and three from Guatemala), ordered according to their use in subsequent sections.

Case Study Details			
#	Title	Hazards	Narrative Summary
1	$M_w = 7.8$ Nepal earthquake (April 2015)	Earthquake, landslides, floods	The 25 April 2015 $M_w = 7.8$ Gorkha earthquake in Nepal, triggered a $M_w = 7.3$ aftershock on 12 May 2015 (Bilham, 2015; Collins and Jibson, 2015). The initial earthquake is reported to have triggered 553 aftershocks with $M_w > 4$ in the 45 days after the 25 April 2015 $M_w = 7.8$ Gorkha earthquake (Adhikari <i>et al.</i> , 2015). The main shock and aftershocks rapidly triggered snow avalanches and thousands of landslides, with some blocking rivers and causing upstream flooding (Collins and Jibson, 2015). Earthquakes also increased the probability of further landslides, triggered by monsoon rains (Bilham, 2015, Collins and Jibson, 2015).

Case Study Details			
#	Title	Hazards	Narrative Summary
2	Santiaguito lahars and triggered flooding, Guatemala (approximately annual)	Volcanic activity, rain, lahars, floods	Rainfall mobilisation of ash and tephra deposits on active volcanic flanks, such as Santiaguito, frequently result in lahars. These lahars subsequently trigger floods through increased sedimentation, the addition of large amounts of tephra material to the hydrological system (Harris <i>et al.</i> , 2006). This network of hazard interactions (cascades) can be observed on an approximately annual basis, during the rainy season, while Santiaguito is active.
3	Tropical Storm Agatha and eruption of Volcano Pacaya, Guatemala (May 2010)	Volcanic activity, tropical storm, landslides, floods, ground collapse, structural collapse	Tropical Storm Agatha reached the Pacific coastline of Guatemala on 29 May 2010 (Stewart, 2011). It was associated with strong winds and torrential rains (Stewart, 2011; Stewart and Cangialosi, 2012), triggering landslides (Wardman <i>et al.</i> , 2012) and flooding in the Southern Highlands of Guatemala, and contributing to a rare, localised (20 m diameter), rapid-onset ground collapse event in Guatemala City (Stewart, 2011). 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 on 27 May 2010 (Wardman <i>et al.</i> , 2012), ejecting ash and debris across Guatemala City. Ash blocked the drainage system, exacerbating flooding during Tropical Storm Agatha (United Nations, 2010). The combination of fresh ash, volcanic debris and heavy rain, generated lahars and structural collapse (Daniell, 2011; Wardman <i>et al.</i> , 2012).
4	$M_w = 7.5$ Guatemala earthquake (1976)	Earthquake, ground collapse, landslides, floods	This $M_w = 7.5$ earthquake triggered multiple aftershocks, and movement on other faults close to Guatemala City (Espinosa, 1976; Plafker <i>et al.</i> , 1976). The earthquake triggered some rapid subsidence or ground collapse (Plafker <i>et al.</i> , 1976) and more than 10,000 landslides, rock falls and debris flows (Harp <i>et al.</i> , 1981). Many of these mass movements occurred along poorly built road and rail cuttings, blocking vital transport routes (Plafker <i>et al.</i> , 1976). Some of the mass movements also blocked rivers and triggered upstream flooding (Plafker <i>et al.</i> , 1976; Harp <i>et al.</i> , 1981). Breaches of these landslide dams also resulted in further flooding (Harp <i>et al.</i> , 1981).

### 3.5.2 Variations in Spatial and Temporal Extent, Frequency and Impact of Networks of Hazard Interactions (Cascades)

In the example case studies described in [Section 3.5.1 \(Table 3.2\)](#), we observe variation in the spatial and temporal extent, frequency and impact of networks of hazard interactions. Networks of hazard interactions (cascades) can vary over many orders of magnitude both spatially and temporally. For example, a tropical storm (lasting several days) may trigger landslides across a small localised area or an entire region (e.g., Central America). One of these triggered landslides may further block a river causing a small, localised flood or weaken the structural integrity of a dam and cause a large regional flood. We illustrate the wide variation in spatial and temporal extent, frequency of networks of hazard interactions and impacts of such networks using Case Study 1 ( $M_w = 7.8$  Nepal earthquake and triggered hazards, April 2015), Case Study 2

(*Santiaguito lahars and triggered flooding, Guatemala, approximately annual*), and Case Study 3 (*Tropical Storm Agatha and eruption of Volcano Pacaya, Guatemala, May 2010*).

In the 2015  $M_w = 7.8$  ‘Gorkha earthquake, Nepal’ (Case Study 1, [Section 3.5.1](#)), thousands of landslides were triggered across a wide spatial extent (30,000 km<sup>2</sup>), with at least 69 of these landslides forming landslide dams (Collins and Jibson, 2015). Many of these dams impounded water, causing flooding, with surface areas ranging from 50 m<sup>2</sup> to 35,000 m<sup>2</sup> (Collins and Jibson, 2015). Landslides were both triggered in the minutes and days after the earthquake, but also the susceptibility of slopes was changed so as to make landslides more likely in the months to years after the earthquake (Bilham, 2015, Collins and Jibson, 2015)

The regular eruptions of Santiaguito in Guatemala and subsequent lahars/flooding (Case Study 2, [Section 3.5.1](#)) also illustrate variation across spatial and temporal scales. Volcanic activity may extend over a sub-national, national or multi-national spatial level, and be either short-lived or persist for many decades. The Santiaguito dome in Guatemala, for example, has seen unsteady, extrusive activity since 1922 (Bluth and Rose, 2004), mainly impacting the southwest of Guatemala. Volcanic activity at Santiaguito, in combination with regular rainfall, results in lahars each rainy season which have an impact on the fluvial system at distances of up to 60 km from Santiaguito, including causing flooding (Harris *et al.*, 2006). While in Guatemala in 2014, we confirmed this network of hazard interactions using personal field observations and discussions in seven semi-structured interviews with hazard monitoring and civil protection officials.

Finally, consider the example of Tropical Storm Agatha and the eruption of Volcano Pacaya (May 2010) in Guatemala (Case Study 3, [Section 3.5.1](#)) which also demonstrates variations in spatial/temporal scale. Tropical Storm Agatha had an impact across multiple nations in Central America (a scale of hundreds of thousands square kilometres). In contrast, one secondary hazard associated with this storm was a localised ground collapse event, with a 20 m diameter (Stewart, 2011).

Networks of hazard interactions (cascades) can also vary in terms of their frequency and impact. For example, they can be observed in low frequency, high-impact events such as the 2015  $M_w = 7.8$  ‘Gorkha earthquake, Nepal’ (Case Study 1, [Section 3.5.1](#)). These internationally publicised events help to raise the profile of networks of hazard interactions (cascades) to an international audience. The 2015  $M_w = 7.8$  ‘Gorkha earthquake, Nepal’ and resulting secondary hazards resulted in more than 8700 fatalities and 3.5 million people displaced (Bilham, 2015). Networks of hazard interactions (cascades) are also observed in localised, high-frequency events, such as the regular eruptions of Santiaguito in Guatemala and subsequent lahars/flooding (Case Study 2 in [Section 3.5.1](#)). This annual network of interacting hazards (cascades), although not commonly associated with high numbers of fatalities, does have the potential to impact livelihoods of those

living in this vicinity and the wider economy (Harris *et al.*, 2006). During Tropical Storm Agatha (May 2010) in Guatemala (Case Study 3 in [Section 3.5.1](#)), a diversity of impacts included at least nine triggered landslides that caused fatalities (Kirschbaum *et al.*, 2012), as well as the economic costs associated with flooding in Guatemala City and structural collapse caused by the combination of ash and heavy rain (United Nations, 2010; Daniell, 2011; Wardman *et al.*, 2012).

As demonstrated through discussion of these case studies, networks of hazard interactions (cascades) are relevant at diverse spatial and temporal scales, can be both high and low frequency events, and have impacts ranging from fatalities to impacts on livelihoods.

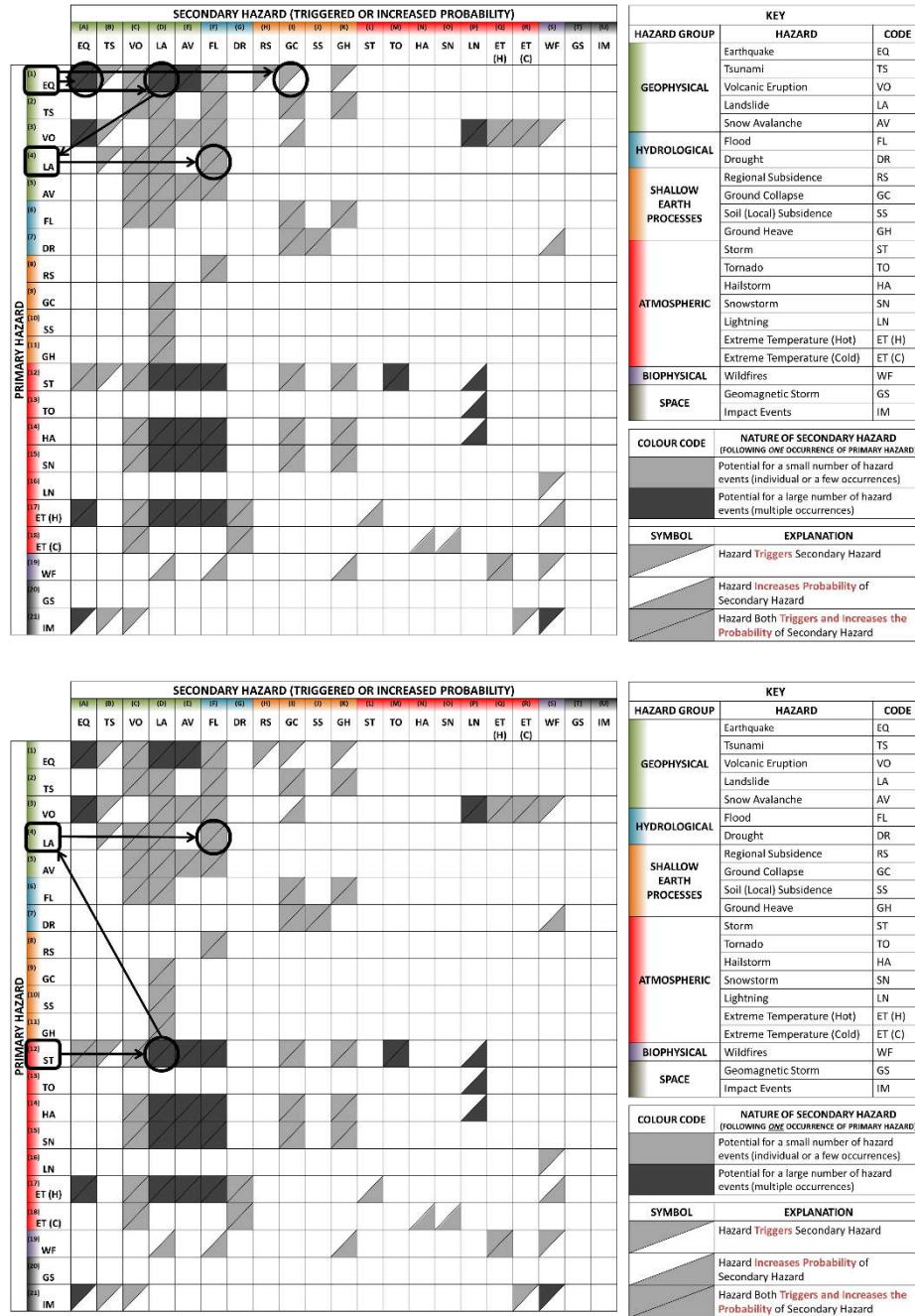
### 3.5.3 Visualising Networks of Hazard Interactions (Cascades)

Given the prevalence of networks of hazard interactions, we consider here how these networks can be visualised to support multi-hazard assessments of interacting natural hazards. In this section we present two ways of visualising networks of hazard interactions, using Case Study 2 (*Santiaguito lahars and triggered flooding, Guatemala, approximately annual*), Case Study 4 (*1976  $M_w = 7.5$  Guatemala earthquake*) and other hypothetical examples.

In [Section 2.3.2](#) ([Figure 2.3](#)), we developed one method of visualising networks of hazard interactions through the use of a  $21 \times 21$  hazard interaction matrix, showing possible interactions between 21 different ‘primary’ and ‘secondary’ natural hazards, and then overlaid onto this relevant information about the network of hazard interactions. In [Figure 3.4](#) we show this methodology, representing two of the case study examples introduced in [Section 3.5.1](#). [Figure 3.4](#) shows two examples of networks of hazard interactions (cascades), both from the Southern Highlands of Guatemala.

**Figure 3.4 (top)** visualises some of the hazards and hazard interactions relevant to the 1976  $M_w = 7.5$  Guatemala earthquake (Case Study 4 in [Section 3.5.1](#)). An earthquake (row 1, **EQ**) triggered other earthquakes (column A, **EQ**), landslides (column D, **LA**), and ground collapse (column I, **GC**). The landslides (row 4, **LA**) subsequently blocked rivers and caused flooding (column F, **FL**).

**Figure 3.4 (bottom)** visualises some of the hazards and hazard interactions associated with lahar-triggered flooding around the volcano Santiaguito (Case Study 2 in [Section 3.5.1](#)). Heavy rainfall (row 12, **ST**) mobilises volcanic material to trigger lahars (column D, **LA**). These lahars (a form of mass movement) (row 4, **LA**) result in significant volcanic material entering rivers and causing flooding (column F, **FL**).

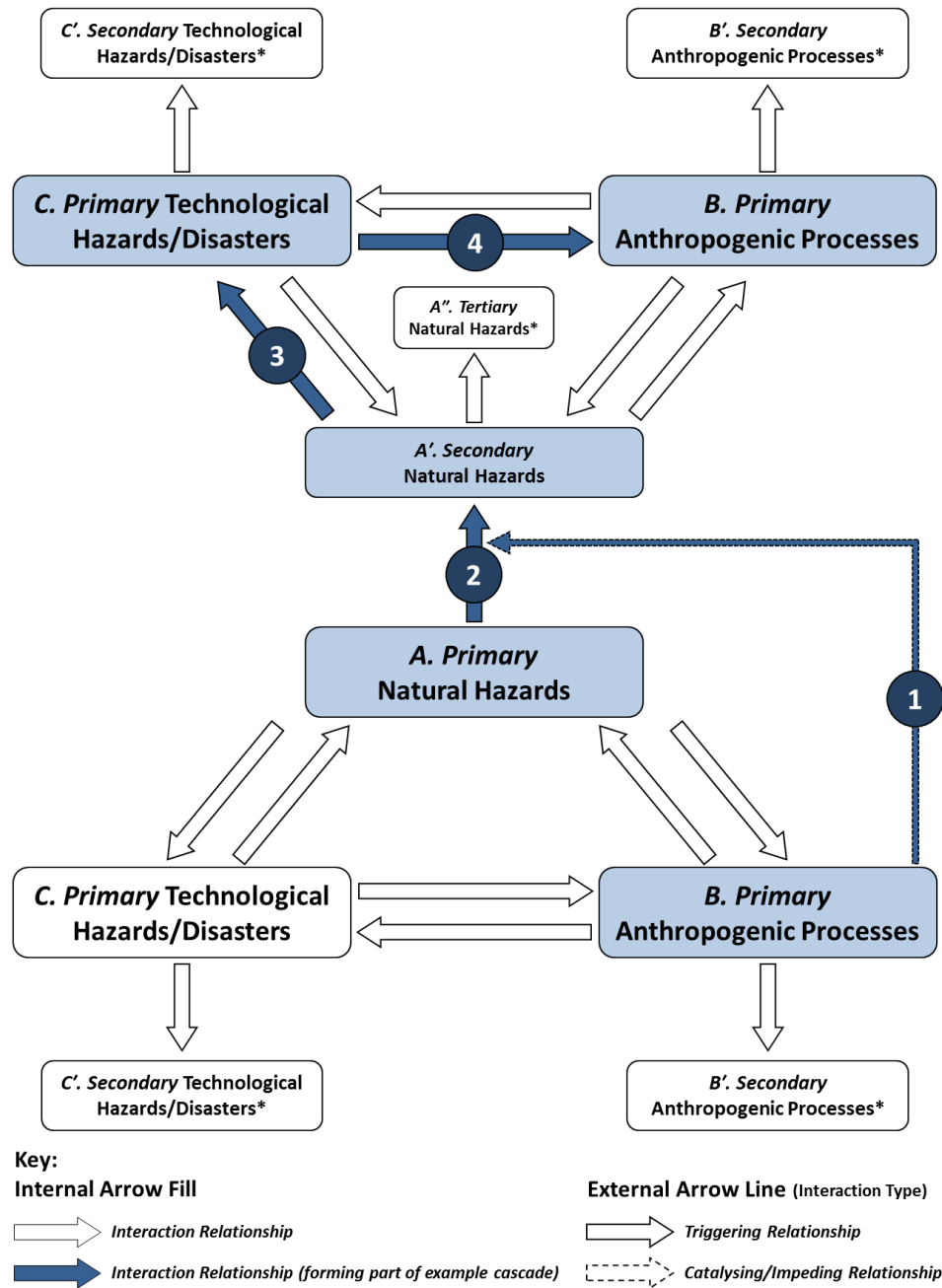


**Figure 3.4.** Two examples of networks of hazard interactions (cascade systems) using a hazard interaction matrix. Hazard interaction networks based on (*top*) the 1976 Guatemala earthquake sequence, and (*bottom*) lahar-triggered flooding associated with Santiaguito, Guatemala. Both network examples are placed on a  $21 \times 21$  hazard interaction matrix, adapted from Gill and Malamud (2014), and described in detail within the caption of [Figure 2.3](#). In the top example (described in [Section 3.5.2](#)), based on information from Espinosa (1976), Plafker *et al.* (1976) and Harp *et al.* (1981), we use rectangles, circles and arrows to illustrate the network of hazard interactions for an earthquake (EQ) triggering further earthquakes (EQ), landslides (LA) and rapid subsidence/ground collapse (GC). The Landslides (LA) were then noted to have blocked rivers, causing flooding (FL). The bottom network of hazard interactions example (also described in [Section 3.5.2](#)), is based on information from Harris *et al.* (2006) and confirmed by personal field observations and seven semi-structured interviews with hazard monitoring and civil protection officials while the authors were in Guatemala in 2014. The bottom example shows (again using rectangles, circles and arrows) rain storms (ST) triggering lahars (LA) on the flanks of Santiaguito. These lahars enter the hydrological system and result in flooding (FL) downstream.

The hazard/process flow diagram visualisations previously introduced in [Section 3.4](#) ([Figures 3.2](#) and [3.3](#)) can also be used to represent complex networks of hazard interactions involving a mixture of natural hazards, anthropogenic processes and technological hazards/disasters. We use the structure of [Figures 3.2](#) and [3.3](#), with appropriate replication within the same figure to allow for longer and more complex networks of hazard interactions, and give two theoretical examples (A and B, described further below) in [Figures 3.5](#) and [3.6](#) of a complex network of hazard interactions. The two hazard/process flow diagram examples in [Figures 3.5](#) and [3.6](#) show all possible triggering interactions (thick block arrows with solid outlines) and (for simplification) only relevant catalysing/impedance interactions (thin block arrows with dashed outlines). Possible networks of hazard interactions are visualised using light-blue boxes to highlight the relevant hazards/processes (i.e., nodes within a network), and dark-blue arrows to highlight the relevant interactions (i.e., links within a network).

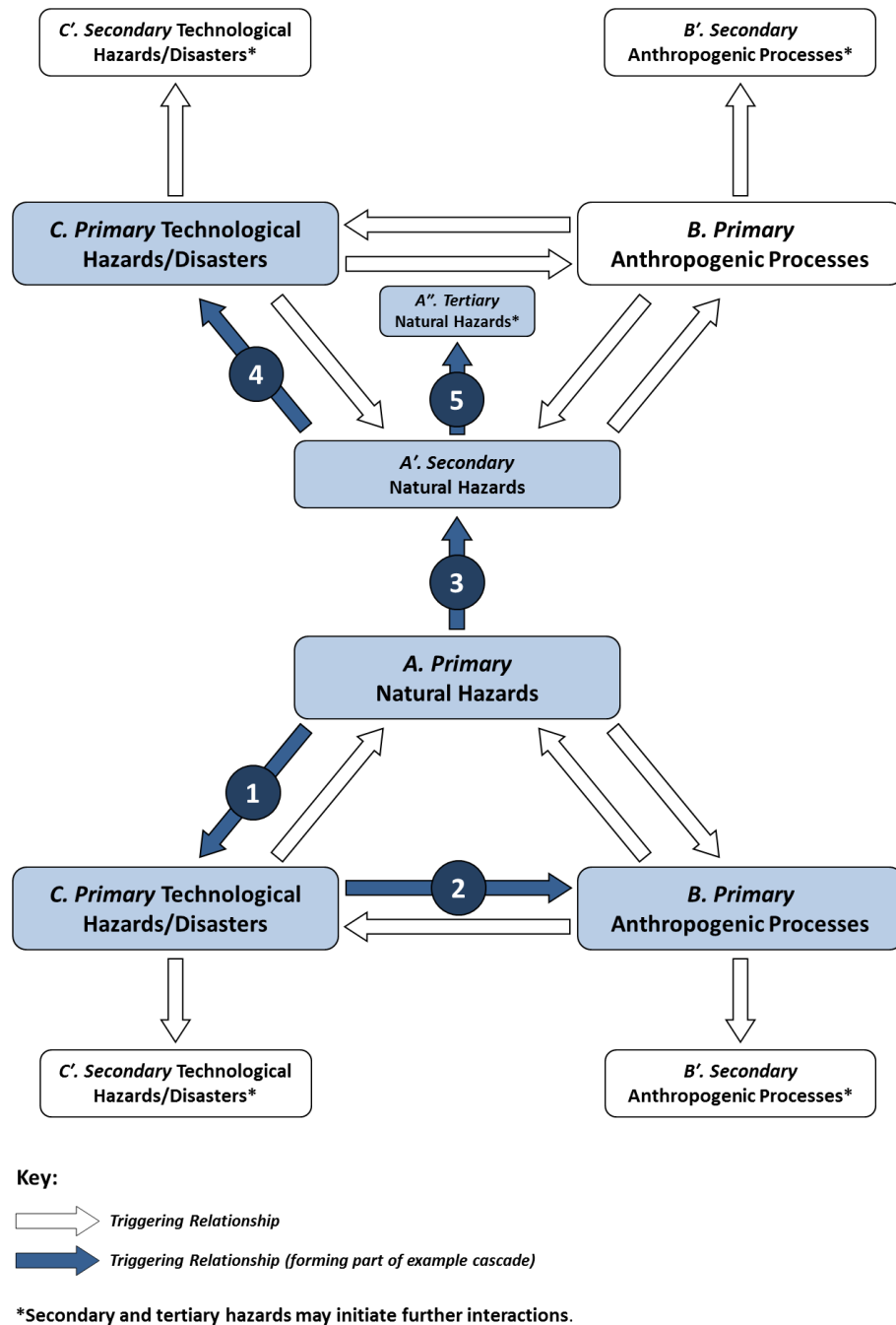
*Theoretical network of hazard interactions, Example A (four links, arrows labelled 1 to 4) using a hazard/process flow diagram.* [Figure 3.5](#) shows a primary anthropogenic process catalysing (thin arrow **1**) the triggering relationship between a primary and secondary natural hazard (thick arrow **2**), with the secondary natural hazard then triggering (thick arrow **3**) a primary technological hazard, which in turn triggers (thick arrow **4**) a primary anthropogenic process to occur. An analogous example of this interaction network would be urbanisation increasing overland flow and therefore catalysing (**1**) storm-triggered floods (**2**), with the floods then triggering (**3**) an embankment to collapse, which in turn triggers (**4**) anthropogenic drainage and dewatering.

*Theoretical network of hazard interactions, Example B (five links, arrows labelled 1 to 5) using a hazard/process flow diagram.* The network of hazard interactions in [Figure 3.6](#) is more complex, with three branches and five interaction relationships highlighted. This example shows a primary natural hazard triggering (thick arrow **1**) a primary technological hazard, which in turn triggers (thick arrow **2**) a primary anthropogenic process. The same primary natural hazard may trigger (thick arrow **3**) a secondary natural hazard. This secondary natural hazard could then trigger (thick arrow **4**) a primary technological hazard and (thick arrow **5**) tertiary natural hazards. An analogous example of this interaction network would be an earthquake triggering (**1**) a structural collapse, which in turn results in (**2**) increases in infilled (made) ground. The earthquake may also trigger (**3**) landslides, which could trigger (**4**) a road traffic accident and (**5**) flooding.



\*Secondary and tertiary hazards may initiate further interactions.

**Figure 3.5. Network of hazard interactions (Example A) using a hazard/process flow diagram.** Using the visualisation frameworks constructed in Figures 3.2 and 3.3, an example of an interaction network (cascade) can be presented. Three hazard/process groups are included: (A) natural hazards, (B) anthropogenic processes and (C) technological hazards/disasters. Arrows are used to illustrate interaction relationships, with both triggering relationships (thick block arrows with solid outlines) and relevant catalysing/impedance relationships (thin block arrows with dashed outlines). For clarity of communication, those catalysing/impedance relationships not of relevance to the specific example are not included. See Figures 3.2 and 3.3 caption explanations for further details. Arrows within the example network of hazard interactions are labelled (1–4) and shaded dark blue to highlight the relevant pathway. In this example, a primary anthropogenic process catalyses (1) the triggering relationship between a primary and secondary natural hazard (2), with the secondary natural hazard then triggering (3) a primary technological hazard, which in turns triggers (4) a primary anthropogenic process to occur.



**Figure 3.6. Network of hazard interactions (Example B) using a hazard/process flow diagram.** Using the visualisations constructed in **Figures 3.2** and **3.3**, an example of an interaction network (cascade) can be presented. In this example the network is more complex than in Example A (**Figure 3.5**), with three branches and five interaction relationships highlighted here. Three hazard/process groups are included: **(A)** natural hazards, **(B)** anthropogenic processes and **(C)** technological hazards/disasters. Arrows are used to illustrate interaction relationships, with both triggering relationships (thick block arrows with solid outlines) and relevant catalysing/impedance relationships (thin block arrows with dashed outlines). For clarity of communication, those catalysing/impedance relationships not of relevance to the specific example are not included. See **Figures 3.2** and **3.3** caption explanations for further details. Arrows within the example network of hazard interactions are labelled (1–5) and shaded dark blue to highlight the relevant pathway. This example shows a primary natural hazard triggering (1) a primary technological hazard, which in turn triggers (2) a primary anthropogenic process. The same primary natural hazard may trigger (3) a secondary natural hazard. This secondary natural hazard could then trigger (4) a primary technological hazard and (5) tertiary natural hazards.

The overlay of networks of hazard interactions from case studies in [Section 3.5.1](#) on hazard interaction matrices ([Figures 3.4](#)), and the overlay of theoretical examples on hazard/process flow diagrams ([Figures 3.5](#) and [3.6](#)) can be complemented by other visualisation techniques. For example, when a quantitative evaluation of possible outcomes of interaction relationships is possible, probability trees can be used to assess networks of hazard interactions (e.g., Neri *et al.*, 2008; Marzocchi *et al.*, 2009; Neri *et al.*, 2013). Probability trees are used to visually represent the possible outcomes of an event and add associated probabilities. All three methods are useful for communicating information about specific chains of events. The two visualisation techniques that we have presented here, together with existing probability trees, allow simple and more complex networks of hazard interactions to be evaluated and visualised.

### **3.5.4 Importance of Networks of Hazard Interactions (Cascades)**

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

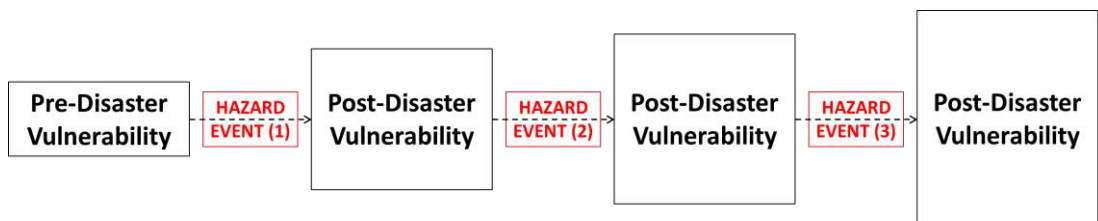
#### ***3.5.4a Risk Assessments and Risk Management Benefit by Better Matching Observed Reality***

An analysis of past occurrences of hazards and disasters shows that interaction networks are often part of the structure of disasters. The need to better match observed reality, by including interaction networks, is applicable to events of diverse spatial and temporal extent, frequency and impact, as has been discussed in [Section 3.5.2](#). The frequency of occurrence of specific networks of hazard interactions demonstrates that more could be done to understand and characterise them. Following the 2015 Gorkha (Nepal) earthquake, the European Geosciences Union (EGU) issued a statement (EGU, 2015) calling for a multi-hazard, integrated approach to risk assessment and the management of natural hazards. This statement also notes the need for agreement within the geoscience community on how to model cascades of natural hazards. This call joins many previous calls (Delmonaco *et al.*, 2007; Kappes *et al.*, 2012; Marzocchi *et al.*, 2012; Gill and Malamud, 2014; Liu *et al.*, 2016) encouraging the assessment of interacting natural hazards, and their integration into multi-hazard methodologies. Assessing interaction networks is therefore important as they are a fundamental part of hazard and disaster events.

### 3.5.4b Changes to Social and Physical Vulnerability During Links of a Multi-Hazard Cascade Event

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

This changing vulnerability within a network of hazard interactions can be represented visually, as shown in [Figure 3.7](#), where a series of three hazard events occur in succession and an assumption is made that each hazard event will increase subsequent levels of vulnerability. Before and between these three hazard events, a representation of vulnerability is given, where we illustrate the vulnerability magnitude as proportional to the height of the rectangle.



**Figure 3.7. Example of vulnerability changes within a network of hazard interactions (cascade).** A representation of changing vulnerability during a hazard cascade, where the magnitude of vulnerability is proportional to the size of the box. Following a disaster event, pressures on society, infrastructure and coping capacity are likely to be increased, and thus the vulnerability of a community and its systems/assets to further shocks or hazards may increase.

[Figure 3.7](#) shows the dynamic nature of vulnerability as one progresses along a network of interacting hazards. In this representation, we have assumed that there are increases in vulnerability as the chain of events progresses, but we note that this will not always be the case. On the ground these changes to social and physical vulnerability may be observed in different ways. For example, buildings may have sustained significant damage so that they are more likely to collapse during an aftershock. Hospitals may be at maximum capacity following an earthquake and therefore not able to respond effectively if a subsequent typhoon results in further casualties.

Injuries sustained by a community during an earthquake may mean that they have a reduced capacity to evacuate if a tsunami is subsequently triggered.

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

#### ***3.5.4c Allocation of Resources for DRR***

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

### **3.6 Conclusions**

In this research and commentary article, we have sought to advance the understanding of enhanced multi-hazard frameworks, which we believe to be of relevance to improved Earth systems management. We advocate an approach that goes beyond multi-layer single hazard approaches to also encompass interaction relationships and networks of interactions (cascades). This study has described this integrated approach, noting that to do otherwise could distort management priorities, increase vulnerability to other spatially relevant hazards or underestimate risk. The development of an enhanced framework to assess and characterise interactions and networks of interactions first required a description of three principal groups of hazards/processes, including natural hazards, anthropogenic processes and technological hazards/disasters. These three groups can interact in a range of different ways, with three interaction relationships discussed in the context of this article: triggering relationships, increased probability relationships, and catalysis/impedance of other hazard interactions. In addition to those

circumstances where one stimulus triggers one response, it is highly likely that more than one of these interactions can be joined together to form a network of interactions, chain or cascade event. We have developed enhanced frameworks to visualise these interactions and networks of interactions (cascades) in two different ways (hazard/process flow diagrams in [Figures 3.2, 3.3, 3.5, and 3.6](#), and hazard interaction matrices in [Figures 3.4](#)). These frameworks, visualisations and associated commentary:

- i. Reinforce the importance of enhanced multi-hazard approaches, integrating hazard interactions and networks of interactions to better model observed dynamics of the Earth system.
- ii. Offer a more holistic approach to assess hazard potential, helping to improve management of those aspects of the Earth system that are relevant to DRR.
- iii. Support the research community to consider future research directions in the context of multi-hazard research in regional settings.

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

# Chapter 4. Anthropogenic Processes, Natural Hazards and Multi-Hazard Interactions

## Summary

This chapter presents a broad overview, characterisation and visualisation of the role of 18 anthropogenic process types in triggering and influencing 21 natural hazards, and natural hazard interactions. Anthropogenic process types are defined as being intentional, non-malicious human activities. Examples include groundwater abstraction, subsurface mining, vegetation removal, chemical explosions and infrastructure (loading). Here we present a systematic classification of anthropogenic process types, organising them into three groups according to whether they are subsurface processes, surface processes, or both. Within each group we identify sub-groups (totalling eight): subsurface material extraction, subsurface material addition, land use change, surface material extraction, surface material addition, explosions, hydrological change, and fires. We use a classification of 21 natural hazards developed in [Chapter 2](#), with hazards organised into six hazard groups (geophysical, hydrological, shallow Earth processes, atmospheric, biophysical and space hazards). Examples include earthquakes, landslides, floods, regional subsidence and wildfires. Using these anthropogenic process types and natural hazards we do the following: (i) Describe and characterise 18 anthropogenic process types, and identify 64 interactions that may occur between two different anthropogenic processes, which could result in the simultaneous or successive occurrence of an ensemble of different anthropogenic process types. (ii) Identify, through an assessment of more than 120 references, from both grey- and peer-review literature, 57 examples of anthropogenic processes triggering natural hazards. We cite location-specific case studies for 52 (91%) of the 57 identified interactions. (iii) Examine the role of anthropogenic process types catalysing or inadvertently impeding a given natural hazard interaction. Impedance of natural hazard interactions does not include deliberate hazard reduction activities (e.g., engineered defences). We use the example of vegetation removal to demonstrate our methodology for assessing the role of anthropogenic process types on natural hazard interactions. Through (i)–(iii) above, this study aims to enable the systematic integration of anthropogenic processes into existing and new multi-hazard and hazard interaction frameworks. As natural hazards occur within an environment shaped by anthropogenic activity, it is argued that the consideration of interactions involving anthropogenic processes is an important component of an applied multi-hazard assessment of hazard potential.

## 4.1 Introduction

Earth systems include the lithosphere, atmosphere, hydrosphere and biosphere. Human activities influence many of the processes that shape these systems (Crutzen, 2002; Zalasiewicz *et al.*, 2010; Goudie, 2013; Lewis and Maslin, 2015). Of particular concern to the disaster risk community are the anthropogenic influences on the occurrence, frequency and intensity of natural hazards, such as earthquakes, landslides, floods, subsidence and sinkholes. The principal aims of this chapter are to describe, classify and analyse the interactions of selected anthropogenic processes with a diverse range of natural hazards in a multi-hazard context. This characterisation is then put into the context of improving multi-hazard assessments of hazard potential and disaster risk, including interaction frameworks. In this introduction we first define four key terms used throughout the chapter, introduce further context to the discussion of human influence on Earth systems, noting some initial examples, and summarise the chapter's organisation.

In the context of this chapter, key terms are defined as follows:

- i. *Natural hazard*. A natural process or phenomenon that may have negative impacts on society (UNISDR, 2009). Examples include earthquakes, volcanic eruptions, landslides, floods, drought, subsidence, tropical storms and wildfires.
- ii. *Anthropogenic process*. "Intentional human activity that is non-malicious, but that may have a negative impact on society through the triggering or catalysing of other hazardous processes" (defined in Gill and Malamud, 2016). The word process here (and throughout the text) is taken to mean "a continuous and regular action or succession of actions occurring or performed in a definite manner, and having a particular result or outcome; a sustained operation or series of operations" (OED, 2015). Examples include groundwater abstraction, vegetation removal, quarrying and surface mining, urbanisation and subsurface construction (tunnelling).
- iii. *Interaction*. The effect(s) of one process or phenomena (either natural or anthropogenic) on another process or phenomena (either natural or anthropogenic).
- iv. *Multi-hazard*. All possible and relevant hazards and their interactions, in a given spatial region and/or temporal period (Kappes *et al.*, 2010; Gill and Malamud, 2014; Duncan *et al.*, 2016). Here we are primarily considering natural hazards, but recognise that a full multi-hazard framework may include other hazard types (e.g., technological).

We now briefly discuss human influence on Earth systems. The total human population on Earth has recently exceeded 7.2 thousand million people (US Census Bureau, 2015) with estimates of total human population from the beginning of humanity to 2011 approximately 108 thousand

million people (Haub, 2011). The influence that this human population has had on the global climate, through increased greenhouse gas emissions, is widely noted (Crutzen, 2002; Steffen *et al.*, 2007). Human activity has also, however, changed the Earth's surface and immediate subsurface, sometimes catastrophically (Guthrie, 2015). Humans are important environmental agents (Steffen *et al.*, 2007; Price *et al.*, 2011), with anthropogenic processes (e.g., as discussed above, vegetation removal, infrastructure development, groundwater abstraction) existing in every inhabited region of the world. Anthropogenic processes may influence the occurrence, frequency or intensity of natural hazards. Identifying and understanding anthropogenic processes and their spatio-temporal relevance is therefore of importance when (i) assessing the potential of natural hazards occurring, (ii) developing holistic multi-hazard frameworks for a given region, and (iii) determining possible disaster risk reduction (DRR) measures.

As an example of considering the influence of anthropogenic processes on natural hazards, consider a slope that is susceptible to landslides. Multiple anthropogenic processes could change the extent to which it is susceptible to slope failure and thus increase or decrease the overall likelihood of a landslide occurring or its size. Examples of some anthropogenic processes that are known to increase landslide susceptibility include vegetation removal, changes in agriculture, implementation of development projects, construction unloading and inadequate drainage (Alexander, 1992; Glade, 2003; Sarkar and Kanungo, 2004; Tarolli and Sofia, 2016). Road construction, which may combine one or more of these anthropogenic processes, is noted to increase landslide susceptibility close to roads both during and after construction (Montgomery, 1994; Devkota *et al.*, 2012; Brenning *et al.*, 2015). Many other instances of anthropogenic processes influencing natural hazards are described in the literature, with examples referred to throughout this chapter.

If anthropogenic processes trigger the occurrence of particular natural hazards, these 'primary' natural hazards may in turn trigger secondary natural hazards, generating a network of natural hazard interactions (cascade) with the anthropogenic process as the source trigger. Furthermore, anthropogenic processes may also increase or decrease the likelihood of a particular natural hazard interaction, i.e., the coupling relationship between a primary and secondary natural hazard. For example, an earthquake or heavy rain can trigger many thousands of landslides, with the number of triggered landslides related to anthropogenic processes such as road construction and vegetation removal (Glade, 2003; Owen *et al.*, 2008; Brenning *et al.*, 2015). The widespread prevalence of anthropogenic processes and their ability to accelerate or decelerate natural hazard processes strongly suggests that understanding the 'hazardousness' of a region (Hewitt and Burton, 1971; Regmi *et al.*, 2013) cannot be done effectively without taking these processes into consideration. Further broad analyses of these important networks of interactions can assist in the

development of holistic multi-hazard frameworks, integrating information on all relevant hazards and their interactions.

This chapter is organised as follows: [Section 4.2](#) presents background information, describing in detail the anthropogenic processes examined, their interactions and the possible mechanisms by which they might interact with natural hazards. [Section 4.3](#) presents the results of a review to identify and visualise the triggering relationships between 18 anthropogenic process types and 21 natural hazards. [Section 4.4](#) presents a methodology for assessing and visualising the influence of anthropogenic processes on the interactions between natural hazards, through catalysis and impedance relationships. Discussion and limitations are presented in [Section 4.5](#), including a description of the integration of anthropogenic processes into multi-hazard frameworks. Final conclusions are noted in [Section 4.6](#).

## 4.2 Anthropogenic Processes

Understanding the influence of anthropogenic processes on natural hazards first requires the development of a systematic overview and characterisation of anthropogenic processes. In this section we begin by introducing past research on anthropogenic process classifications ([Section 4.2.1](#)), followed by a description of peer-review and grey literature review procedures used in both this and future sections ([Section 4.2.2](#)), a presentation of our final classification of anthropogenic processes considered in this study ([Section 4.2.3](#)), a short discussion of some of these anthropogenic processes in the context of their definition as intentional, non-malicious processes ([Section 4.2.4](#)), an overview, characterisation and visualisation of *anthropogenic process-anthropogenic process* interactions ([Section 4.2.5](#)), and a discussion of the two types of *anthropogenic process-natural hazard* interaction considered in this study ([Section 4.2.6](#)).

### 4.2.1 Past Research on Anthropogenic Processes

A few broad classifications or reviews of anthropogenic processes exist. Here we introduce two of these classifications, based on (i) artificial ground and (ii) land-use types, as examples of how groups of anthropogenic processes have been previously classified.

- i. *Classification of artificial ground (ground shaped by anthropogenic activity)*. Rosenbaum *et al.* (2003) divides artificial ground into five classes based on the mapping subdivisions used by the British Geological Survey: made ground, worked ground, infilled ground, disturbed ground and landscaped ground. Each of the classes used by

Rosenbaum *et al.* (2003) has a number of sub-classes or examples, based on topography and material type.

- ii. *Classification of land-use types.* This classification is based on how land is used and/or altered by natural and anthropogenic processes (FAO/UNEP, 1999). Land-use maps may be specific to individual countries. For example, a vegetation and land-use map produced for Guatemala by the Guatemala Ministry of Agriculture, Livestock and Food (2006) used seven classes: infrastructure, cultivation, pastures and shrubs, natural woodland, bodies of water, wetlands and floodplains and arid/sterile land. This combination of anthropogenic and natural activity can be visualised spatially using a cartographic approach and temporally by using maps published over a series of successive years. A temporal analysis of land-use would allow the study of land-use *change*, ascertaining the anthropogenic processes that resulted in this change.

In outlining these two examples, we emphasise that classifications of anthropogenic processes do exist. We seek to build on these in later sections to develop a classification that can be effectively used for the assessments of interactions to support multi-hazard frameworks. Alongside the two classification examples noted above, specific to different anthropogenic processes, Goudie (2013) gives a thorough review of the many ways in which humans have influenced the natural environment. Furthermore, there are many individual case studies of a specific anthropogenic process influencing a specific natural hazard in the literature. For example, the relationship between road construction and/or vegetation removal and landslides is discussed in Alexander (1992), Glade (2003), Sidle and Ochiai (2006), Owen *et al.* (2008), and Brenning *et al.*, (2015). Building on this range of contributions, we seek here to develop an overarching classification of a diverse range of anthropogenic processes for application to further research questions. In the context of this chapter, we apply our classification to an assessment of the influence of anthropogenic processes on natural hazards and natural hazard interactions.

## 4.2.2 Review Methodology and Database Development

In this chapter, we use an iterative methodology for four main tasks (ordered Task I to IV according to their appearance in this chapter):

- Task I. Develop a *systematic classification of anthropogenic process types* (Section 4.2.3).
- Task II. Determine *which anthropogenic process types interact with other anthropogenic process types* (Section 4.2.5).
- Task III. Determine *which anthropogenic process types trigger natural hazards* (Section 4.3).

Task IV. Explore ways to consider anthropogenic process types catalysing and impeding natural hazard interactions, with the example of vegetation removal (Section 4.4).

In our research methodology, the order in which these tasks were completed differs from the order in which they appear in this chapter. Our research methodology began with Task III (*anthropogenic process-natural hazard interactions*), which included the construction of a database of key literature sources. The iterative process used to complete Task III enabled the simultaneous development of a *systematic classification of anthropogenic processes* for Task I. The database developed in Task III was then used to support Tasks II and IV. In this Section 4.2.2, we discuss the tasks in terms of the order they were done as part of our research methodology. Then, for ease of communication, in subsequent sections (starting with Section 4.2.3, Task I) we have altered the order of detailed presentation of the tasks and their results from that which supported their development.

The classification and characterisation of *anthropogenic process-natural hazard interactions* (Task III) required the critical review of a broad range of both peer-review and grey literature. This included the assessment of technical reports, media articles and other grey literature, alongside published scientific literature. The guiding principles for a systematic review proposed by Boaz *et al.* (2002) were used to support this process, and are described in Table 4.1. In the context of this chapter, we are considering a review to be a critical analysis of diverse literature types to determine whether a specific interaction occurs or not. We are not seeking to complete a systematic review which identifies, analyses and includes every article on each interaction, rather identify and analyse evidence to determine whether an interaction should be included within our characterisation.

**Table 4.1. Criteria for a systematic review (from Boaz *et al.*, 2002).** Principal review criteria and a qualitative description of how we met these criteria in our study, in the context of characterising the influence of anthropogenic processes on natural hazards.

Criteria (from Boaz <i>et al.</i> , 2002)	How Criteria Met Within Our Methodology?
(i) Protocols must be used to guide the process	(i) Our procedure examined both discussion of anthropogenic triggering relationships and reported case studies to determine whether a particular anthropogenic activity triggers natural hazards and should be included within our analyses. Special care was taken to assess evidence reliability where case studies were limited or recorded in research/reports more than 50 years old.
(ii) Focused on answering a specific question	(ii) A specific question was posed within this study, and applied to each possible interaction pairing of anthropogenic activity and natural hazard. This question stated: “Does evidence exist that the specific anthropogenic activity may trigger the specific natural hazard in question?”.

Criteria (from Boaz <i>et al.</i> , 2002)	How Criteria Met Within Our Methodology?
(iii) Seeks to identify as much of the relevant research as possible	(iii) A wide literature base was used, including peer-reviewed literature, grey literature (technical and government reports) and media articles. Large literature databases (e.g., Google Scholar) were used to enable the identification of as much relevant research as possible.
(iv) Appraises the quality of the research included in the review	(iv) Quality approval was monitored through the cross referencing of case studies where possible. Multiple case studies relating to the triggering of a natural hazard by anthropogenic activity provided a stronger evidence base for the existence of a triggering relationship and its inclusion within this review. If few case studies were identified, the reliability of these was scrutinised to see whether its inclusion could be justified.
(v) Synthesises the research findings in the included studies	(v) Findings were synthesised and presented in visualisations, with care taken to present information in an accessible format, suitable for academics, policy makers and practitioners, including both specialists and non-specialists.
(vi) Aims to be as objective as possible about research to remove potential bias	(vi) Objectivity was promoted through the specific nature of the research questions and pre-determined protocols. An assessment of potential sources of bias was undertaken and measures identified to reduce or eliminate these.
(vii) Updated to remain relevant	(vii) The results of this review can be regularly updated as new information becomes apparent. This included adapting the classification of anthropogenic processes as more references were examined. It could also suggest future revised editions of research outputs (e.g., interaction frameworks) to reflect new research and understanding.

Guiding principle ‘ii’ in [Table 4.1](#) is to *focus a review on answering a specific question*. Our initial focus therefore was on addressing the question as to whether anthropogenic processes triggers a set of 21 natural hazard types (Task III, [Section 4.3](#)). These 21 natural hazard types were initially classified and described in [Chapter 2](#). In [Table 4.1](#) we therefore explain how each of these criteria was met within the context of determining the influence of anthropogenic processes triggering natural hazards. At the start of this review process an initial list of possible anthropogenic process types was drafted based on the experience of the authors. During the review of *anthropogenic process-natural hazard interactions*, a “pragmatic and iterative approach” (Wachinger *et al.*, 2013) was used to expand, refine and develop this classification of anthropogenic process types. As we identified and analysed further references, for example relating to the triggering of landslides, the classification of anthropogenic process types was refined. This approach enabled the development of a broadly applicable, comprehensive and systematic classification of 18 anthropogenic process types (Task I, [Section 4.2.3](#)). In total, the review of *anthropogenic process-natural hazard interactions* resulted in more than 120 references being identified and included in a database that shows the influence of anthropogenic processes in triggering natural hazards, all of which are noted in [Appendix B](#). These references include both older and more recent literature, and both peer-review publications and grey

literature (e.g., textbooks, conference proceedings, technical reports). The limitations of this diversity of literature are discussed in [Section 4.5.1](#).

The development of a systematic classification of anthropogenic process types, and a database of more than 120 references relating to the 18 anthropogenic process types, then facilitated an examination of which anthropogenic process types interact with other anthropogenic process types (Task II, [Section 4.2.5](#)). Some references in the database described these *anthropogenic process-anthropogenic process* interactions, and supported this critical review. The database was then used a final time to help examine the influence of vegetation removal on the catalysis and impedance of natural hazard interactions (Task IV, [Section 4.2](#)). Those references in the database relating to vegetation removal aided the determination of this specific anthropogenic process type catalysing/impeding natural hazards. These reviews again focused on determining whether a specific interaction occurs or not, and did not seek to identify, analyse and include every article relating to each possible interaction. In both cases, but to differing extents, literature was supported by the authors' relevant background knowledge and judgement. The processes used to complete these reviews are set out in more detail in [Section 4.2.5](#) and [Section 4.2](#) respectively.

### 4.2.3 Anthropogenic Process Classification (Task I)

Here we present our broad classification of anthropogenic processes covering multiple ways by which humans change the natural environment. This classification was developed using an iterative approach, refined to take into consideration the references introduced in [Section 4.2.2](#), discussing anthropogenic processes in both peer-review and grey literature. When considering how to classify anthropogenic processes within our classification, particularly whether two processes are sufficiently distinct from one another to be considered individual entries in the table, we looked for distinctness in the following: (i) spatial scale over which each process occurs, (ii) whether the anthropogenic process acts upon the surface/subsurface/both, and (iii) the nature of the anthropogenic input.

Our final classification consists of 18 anthropogenic process types and is given in [Table 4.2](#). The 18 process types are placed into three groups according to where (relative to the Earth's surface) the anthropogenic process types operate: *surface*, *subsurface*, *both*. Each of the 3 groups are then further classified into 2–3 sub-groups based on the physical mechanisms involved in the anthropogenic process type: (Subgroup 1 & 4) *material extraction*, (Subgroup 2 & 5) *material addition*, (Subgroup 3) *land-use change*, (Subgroup 6) *hydrological change*, (Subgroup 7) *explosion*, (Subgroup 8) *combustion (fire)*. Each of the eight subgroups includes one to four anthropogenic processes. [Table 4.2](#) shows this classification structure for the 18 anthropogenic

process types (group, sub-group, process type) considered within this study, introduces a coding and colour scheme for each process to improve clarity within subsequent visualisations, along with a description of each process with key words bolded.

**Table 4.2. Classification and description of 18 anthropogenic process types considered within this study.** An outline of eight sub-groups of anthropogenic processes (based on physical process type), organised into three groups (based on relevance to subsurface, surface or both). These eight sub-groups contain 18 different anthropogenic processes, each coded and described. Some aspects of anthropogenic activity (e.g., hydrological controls, or road and railway network construction and use) may consist of a combination of two or more of these processes.

Group	Sub-Group	Anthropogenic Process Type			
		#	Name	Code	Description
I. Subsurface Process	1. Subsurface Material Extraction	1.1	Groundwater Abstraction	GA	<b>Removal</b> of groundwater resources, resulting in reduction in pore pressures and changes to overall stress conditions.
		1.2	Oil/Gas Extraction	OGE	<b>Extraction</b> of hydrocarbons from the sub-surface, resulting in changes to stress conditions.
		1.3	Subsurface Infrastructure Construction	SC	<b>Extraction</b> of solid material from the sub-surface, due to construction (i.e., tunnelling), resulting in changes to stress conditions.
		1.4	Subsurface Mining	SM	<b>Extraction</b> of solid material from the sub-surface, resulting in changes to stress conditions.
	2. Subsurface Material Addition	2.1	Material (Fluid) Injection	MFI	<b>Addition</b> of material (fluids) to the subsurface, commonly used in the hydrocarbon and geothermal industries, for mining soluble products and waste disposal.
II. Surface Process	3. Land Use Change	3.1	Vegetation Removal	VR	<b>Removal</b> of tree cover for commercial and industrial purposes, and urban development.
		3.2	Agricultural Practice Change	AC	<b>Changes</b> in agriculture, including machinery introduction or crop changes. Aspects associated with deforestation.
		3.3	Urbanisation	UR	Highly <b>landscaped</b> environments due to a population increase in a given area.
	4. Surface Material Extraction	4.1	Infrastructure Construction (Unloading)	IC	<b>Removal</b> of mass on the land surface, through infrastructure development (e.g., cut and excavated slopes).
		4.2	Quarrying/Surface Mining (Unloading)	QSM	<b>Excavation</b> and/or <b>removal</b> of mass on the land surface (e.g., quarrying, surface mining).
	5. Surface Material Addition	5.1	Infrastructure (Loading)	IN	<b>Addition</b> of mass to the land surface, through infrastructure development.
		5.2	Infilled (Made) Ground	IMG	Material <b>placement</b> (e.g., mine and demolition waste, sediment) on the land surface and in surface voids to create infilled ground (e.g., bay-fill deposits).
5.3		Reservoir and Dam Construction	RD	<b>Construction</b> of reservoirs. These can result in increased surface loading and pore water pressures, along with changes to surface hydrology.	

Group	Sub-Group	Anthropogenic Process Type			
		#	Name	Code	Description
III. Subsurface & Surface Process	6. Hydrological Change	6.1	Drainage and Dewatering	DD	Artificial <b>lowering</b> of the water table through pumping or evaporation (often localised and temporary).
		6.2	Water Addition	WA	Poor <b>removal</b> of water or the intentional addition of surplus water, both contributing to increases in pore water pressures and erosive capacity.
	7. Explosion	7.1	Chemical Explosion	CE	Intentional <b>detonation</b> of conventional (non-nuclear) explosives. High energy release (heat, light, sound, and pressure).
		7.2	Nuclear Explosion	NE	Intentional <b>detonation</b> of nuclear material. Generation of destructive force by nuclear <b>fission</b> and <b>fusion</b> . Intense release of energy, high temperatures and contamination.
	8. Combustion (Fire)	8.1	Fire	FR	Intentional-nonmalicious <b>ignition</b> of fires. Can include surface (e.g., waste, agriculture) and subsurface (e.g., coal seams) material.

Each of the 18 selected anthropogenic process types given in [Table 4.2](#) can be observed at a range of different spatial and temporal scales. For example, agricultural practice change (Process 3.2) could incorporate both an individual farmer ploughing a new field (at an approximate spatial scale of 0.1–1 km<sup>2</sup> and temporal scale of days to weeks) and a societal transition from manual to machine-dominated farming (at an approximate spatial scale of 10<sup>4</sup>–10<sup>7</sup> km<sup>2</sup> and temporal scale of years to centuries). The varied spatial and temporal scale of these activities will likely have a direct influence on the resultant interactions of the anthropogenic process type with natural hazards. In many cases, an activity affecting a larger spatial area and lasting for a longer period of time is likely to have a greater influence on the natural environment than an activity affecting a smaller spatial area and lasting for a shorter period of time. This may not always be the case, as larger scale projects (e.g., a surface mine) may be under a greater regulatory capacity than a smaller scale project (e.g., an artisanal mine), with the smaller scale project therefore being more likely to result in a higher probability of a natural hazard occurring. The influence of policy and regulatory capacity is further discussed in [Sections 4.3.3](#) and [4.5.2](#).

A key issue when designing our classification of anthropogenic processes, are potential overlaps between anthropogenic process types considered. In [Table 4.3](#) we give two examples of potential overlap, relating to 5 of the 18 anthropogenic processes we considered, noting the principal differences between the anthropogenic processes and justifying their classification as separate processes

- i. *Example 1.* Groundwater abstraction (**GA**), oil and gas extraction (**OGE**) and drainage and dewatering (**DD**) all involve the removal of fluids from the subsurface.
- ii. *Example 2.* Fluid injection (**FI**) has similarities to water addition (**WA**), with both involving the addition of fluids.

**Table 4.3. Potential overlap between anthropogenic process types considered within this study.** Two examples (A: fluid removal; B: fluid addition) where a triplet or pair of anthropogenic processes are not completely distinct in some aspects, but there are sufficient differences in other aspects to label them as separate anthropogenic processes.

	Sub-Group	Anthropogenic Process Type			
		#	Name	Code	Notes as to why anthropogenic process type is distinct from others in the example
Example A (fluid removal)	<b>1. Subsurface Material Extraction</b>	1.1	Groundwater Abstraction	GA	The removal of subsurface water for a specific purpose (e.g., irrigation, drinking, industry), normally influencing scales of many square kilometres. The extent of recharge (predominantly natural) will determine the timeframe over which the water table is lowered.
		1.2	Oil/Gas Extraction	OGE	The removal of subsurface fluids commonly associated with other anthropogenic processes (e.g., fluid injection). There is no associated natural recharge, and therefore once the material is removed it can only be replaced by another anthropogenic process (e.g., fluid injection).
	<b>6. Hydrological Change</b>	6.1	Drainage and Dewatering	DD	The removal of unwanted water on the surface or subsurface. This could be a temporary or permanent process depending on the end-use of the land affected. In many construction processes the water table is artificially lowered and then allowed to return after pumping. In other projects it may be permanently lowered. These processes are often more localised.
Example B (fluid addition)	<b>2. Subsurface Material Addition</b>	2.1	Material (Fluid) Injection	MFI	The deliberate addition of fluids to the deep subsurface, often at high pressures.
	<b>6. Hydrological Change</b>	6.2	Water Addition	WA	Addition of water to the surface or shallow subsurface, occurring at a range of spatial scales and pressures.

We acknowledge that the list of 18 processes given in [Table 4.2](#) is not exhaustive. For example, we have not included carbon emissions as a process within our analysis. The relationship between

carbon emissions and anthropogenic climate change, which in turn can link to an increase or decrease in the occurrence of natural hazards has been covered in depth by others (McGuire and Maslin, 2012). In another example, for specific regions of the globe, additional anthropogenic processes may be of importance or it may be appropriate to classify the 18 anthropogenic process types into more specific sub-classes. For example, quarrying/surface mining could be sub-divided according to the type or spatial extent of mining, recognising that there are differences between an artisanal quarry compared to a large opencast mine. Despite these limitations, we believe that the three anthropogenic process groups, eight sub-groups and 18 individual process types described in **Table 4.2** offer a relatively comprehensive overview of human influences on the Earth system. Selected anthropogenic processes are spatially relevant in many regions of the world and the classification is easily scalable for application or modification by end-users.

#### **4.2.4 Intentional, Non-Malicious Processes**

In **Section 4.1** we defined anthropogenic processes as human activity that is intentional, non-malicious and may have a negative impact on society through the triggering or catalysing of other hazardous processes. Each of the 18 anthropogenic process types (**Table 4.2**) included within our analyses in this chapter are intentional processes that may subsequently result in negative consequences. They are conscious, deliberate or purposeful human activities, but with the motive behind the anthropogenic process not being to deliberately cause harm.

There are occasions where the processes listed in **Table 4.2** may occur either (i) unintentionally (i.e., inadvertent or accidental human activity) or (ii) as a result of an intentional but malicious act. Examples include:

- i. *Water Addition (WA)*. This could occur due to accidental activities, negligent construction or a lack of capacity to maintain the system (unintentional, not included in our analysis) or due to deliberate increases in overland- or subsurface flow (intentional and non-malicious, included within our analysis).
- ii. *Chemical Explosion (CE)*. This could occur due to an industry systems failure (unintentional, not included within our analysis), a terrorist attack (intentional and malicious, not included within our analysis), or to excavate material (intentional and non-malicious, included within our analysis).
- iii. *Nuclear Explosion (NE)*. This could occur due to an industry systems failure (unintentional, not included within our analysis), the deployment of a nuclear weapon (intentional and malicious, not included within our analysis), or during a subterranean

weapons test (intentional and non-malicious, included within our analysis). In the latter example we distinguish between aggressive and malicious, noting that the act of testing a nuclear weapon is likely to be understood as an illegal act of aggression by many individuals.

- iv. *Fire (FR)*. This could occur due to an industry systems failure (unintentional, not included within our analysis), arson (intentional and malicious, not included within our analysis), or as part of agriculture or waste management (intentional and non-malicious, included within our analysis).

To help define the limits of our review, the analyses in this chapter focus on those incidences where anthropogenic processes are intentional and non-malicious acts, and therefore unintentional and/or malicious acts are not included. It is important to recognise, however, that unintentional or malicious acts may also influence the occurrence, frequency or intensity of natural hazards.

#### **4.2.5 Anthropogenic Process-Anthropogenic Process Interactions (Task II)**

Using the 18 anthropogenic processes described in [Section 4.2.3](#) we proceed to Task II, where we characterise how each of these 18 anthropogenic processes can interact with the other 17 anthropogenic processes, using an interaction matrix visualisation ([Section 4.2.5a](#)) and a network linkage visualisation ([Section 4.2.5b](#)). The implications of these interactions are then briefly discussed ([Section 4.2.5c](#)).

##### **4.2.5a Interaction Matrix and Temporal Classification of Interactions**

Many examples exist of one anthropogenic process triggering or driving the occurrence of one or more *associated secondary* anthropogenic processes. In this context the term ‘triggering’ refers to the *primary* anthropogenic process resulting in the initiation or continuation of an *associated secondary* anthropogenic process. For example, agricultural practice change (**AC**) or urbanisation (**UR**) may trigger an increase in groundwater abstraction (**GA**) for irrigation or potable water supply respectively. The term *associated secondary* anthropogenic process is used in this context, rather than *secondary* anthropogenic process, as a given anthropogenic process may cause other anthropogenic processes to occur before, during and/or after the primary anthropogenic process. Examples include:

- i. *Before*. Subsurface construction (**SC**), such as tunnelling, may require drainage and dewatering (**DD**) to take place before it can commence. The need for drainage and

dewatering would be determined during preliminary ground reconnaissance and site investigation. Drainage and dewatering may then continue *during* the tunnelling process.

- ii. *During*. Fluid injection (**FI**) may occur simultaneously with oil/gas extraction (**OGE**).
- iii. *After*. Chemical explosions (**CE**) may subsequently trigger increases in infilled (made) ground (**IMG**) as rubble is cleared.

Some anthropogenic processes may involve multiple stages, including an initial decision-making or survey stage before ground disturbance. Where an *associated secondary* process is stated to occur ‘before’ a *primary* anthropogenic process, it is normally occurring after at least one preliminary stage of the *primary* anthropogenic process, even if there has been no change to the natural environment. *Associated secondary* processes can therefore be considered to be triggered by an occurrence of a *primary* anthropogenic process, even if they occur before the *primary* process. In later sections we refer to *secondary* natural hazards, rather than *associated secondary* natural hazards, as these occur after the *primary* natural hazard.

We now assess potential interactions between the 18 anthropogenic processes given in **Table 4.2**. We consider each of the 18 processes as *primary* anthropogenic processes, and then determine which of the other 17 anthropogenic processes have a *secondary* association with the primary process, and if there is an association, whether the association is before (**B**), during (**D**) and/or after (**A**) the primary process. To assess the potential interactions between anthropogenic processes, we draw on both background understanding/experience of industry practice and processes and relevant peer-review and grey literature that describes anthropogenic process types. For example, when considering *subsurface infrastructure construction* (**Table 4.2**, Process 1.3 **SC**, i.e., tunnelling) as a *primary* anthropogenic process, the *associated secondary* anthropogenic processes are first considered using prior experience, evaluating in turn whether each of the other anthropogenic processes could be triggered by the *primary* anthropogenic process. This draws on the authors’ experience and understanding of, in this example, engineering geology. This determination of possible interactions is complemented by using relevant literature. The database of more than 120 references introduced in **Section 4.2.2** (and included in **Appendix B**), and used in **Section 4.2.3** to develop our classification of anthropogenic processes, also discussed contexts in which multiple anthropogenic processes occur simultaneously or successively. For example, some of those references used to characterise *subsurface infrastructure construction* in the database describe diverse tunnelling projects (e.g., Hagedorn *et al.*, 2008; Zangerl, 2008; Türkmen and Ozguzel, 2003). These same references support the identification of *associated secondary* anthropogenic process types, including *infilled (made) ground* (Process 5.2, **IMG**, deposition of extracted material), *drainage and dewatering* (Process 6.1, **DD**, lowering the water

table to enable tunnelling), and chemical explosions (Process 7.1, **CE**, blasting). These three *associated secondary* anthropogenic process types were both reasonably inferred from background knowledge of this sector, but then also supported by examples from the literature.

In **Figure 4.1** we give an  $18 \times 18$  interaction matrix with *primary* anthropogenic processes on the vertical axis and *associated secondary* anthropogenic processes on the horizontal axis. The 18 anthropogenic process types on both axes are the same, and each set of processes are arranged into the same three groups and eight sub-groups introduced in **Table 4.2**. Where we identified through our review process a relationship between a *primary* anthropogenic process triggering an *associated secondary* anthropogenic process, the interaction matrix cell is shaded grey. Interactions between the ‘same’ process are not considered, so the total number of cells where an interaction could be identified is  $18 \times 17 = 306$ . As described above, using our experience and literature, we identified 64 cells (21% of the 306 possible) that have interactions between two anthropogenic processes. Each of these cells is shaded grey, and includes a temporal code describing whether the *associated secondary* anthropogenic process occurs before (**B**), during (**D**) and/or after (**A**) the *primary* anthropogenic process. A cell where a relationship has been identified will have one, two, or three of these letters shown (see bottom of **Figure 4.1** for summary statistics by combination of letters).

Our methodology is done at a coarse resolution, producing a coarse resolution review appropriate for this scale of analysis. The  $18 \times 18$  interaction matrix given in **Figure 4.1** offers a visual perspective on the most likely interactions between anthropogenic processes. It is limited in its completeness by the choice of 18 anthropogenic process types. As discussed in **Section 4.2.3**, it is possible that other anthropogenic processes exist and that these can be associated with other anthropogenic processes. It is also possible that interactions between the selected anthropogenic processes may be missing. This could be due to (i) low likelihood interactions existing between *primary* and *associated secondary* anthropogenic processes that are not recorded in some of the literature (mitigated to some degree by using large literature databases, and diverse types of literature), (ii) the authors disciplinary knowledge gaps resulting in missed interactions (mitigated to some degree by combining both expert judgement and literature analysis), and (iii) some interactions existing only at a local spatial scale and not the global scale of this analysis. While all of these limitations can possibly occur, we suggest that the consequences of a missed relationship are low. The primary purpose of the review and analysis in **Figure 4.1** is to consider the extent to which interactions occur and the influence of these interactions on the construction of a multi-hazard framework. The conclusions are likely to be reinforced by additional interactions.

From **Figure 4.1** we observe that complex relationships exist between different anthropogenic processes. Many anthropogenic processes are associated with other anthropogenic processes, occurring concurrently with others or sequentially. The 64 identified relationships (grey shaded cells in **Figure 4.1**) between anthropogenic process have the following summary statistics. These will be expanded and discussed in more detail in **Section 4.2.5b**.

- i. [Potential of *primary* process to trigger *associated secondary* process]. We find that 16 of 18 (89%) of the *primary* anthropogenic process types (vertical axis, **Figure 4.1**) have the potential to trigger one or more *associated secondary* anthropogenic process (horizontal axis). Of these, 9 of 18 (50%) of the *primary* anthropogenic process types (vertical axis) have the potential to trigger three or more *associated secondary* anthropogenic processes (horizontal axis).
- ii. [Potential of *associated secondary* processes to be triggered by *primary* process]. We find that 13 of 18 (72%) of the *associated secondary* anthropogenic process types (horizontal axis, **Figure 4.1**) have the potential of being triggered by *primary* anthropogenic processes (vertical axis), with 9 of 18 (50%) of the *associated secondary* anthropogenic process types (horizontal axis) having the potential of being triggered by three or more *primary* anthropogenic process types (vertical axis).

It is also possible to use the  $18 \times 18$  interaction matrix given in **Figure 4.1** to identify networks of interactions (cascades) whereby one anthropogenic process triggers another anthropogenic process, which subsequently results in a further anthropogenic process occurring. For example, urbanisation (**UR**) may trigger agricultural practice change (**AC**), which in turn triggers groundwater abstraction (**GA**) for enhanced irrigation.

From **Figure 4.1** we can additionally observe the distribution of temporal classifications relating to the 64 identified *primary-associated secondary* anthropogenic process interactions. The number of *associated secondary* anthropogenic processes occurring before (**B**), during (**D**) and after (**A**) *primary* anthropogenic processes occurs in the following number (%) of cases: [**B**] 32 (50%), [**D**] 47 (73%) and [**A**] 29 (45%) cases. In 26 (41%) of the *primary-associated secondary* interactions, the temporal sequence is either **B** (before), **D** (during) or **A** (after). In 32 (50%) of the *primary-associated secondary* interactions, the temporal sequence is either **B&D** (before & during) or **D&A** (during & after), and in 6 (9%) of the interactions, the temporal sequence is **B&D&A** (before & during & after). The interaction matrix and temporal classification of *anthropogenic process-anthropogenic process* interactions (**Figure 4.1**), presented above, suggests that these interactions are widespread and an important consideration when determining the influence of anthropogenic processes on natural hazards and natural hazard interactions.

		ASSOCIATED SECONDARY ANTHROPOGENIC PROCESS (BEFORE, DURING, AFTER PRIMARY ANTHROPOGENIC PROCESS)																			
		I. Subsurface Process									II. Surface Process						III. Subsurface & Surface Process				
		Material Extraction				Material Addition	Land Use Change			Material Extraction		Material Addition		Hydrological Change		Explosions		Fire			
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)		
		GA	OGE	SC	SM	MFI	VR	AC	UR	IC	QSM	IN	IMG	RD	DD	WA	CE	NE	FR		
PRIMARY ANTHROPOGENIC PROCESS	I. Subsurface Process	Material Extraction	(1.1) GA	Groundwater Abstraction																	
			(1.2) OGE	Oil/Gas Extraction	D						B D	B D		B D				D			
		Material Addition	(1.3) SC	Subsurface Infrastructure Construction												B D			D		
			(1.4) SM	Subsurface Mining	D							B D	B D		B D	D A	B D	B D		D	
	II. Surface Process	Land Use Change	(2.1) MFI	Material (Fluid) Injection										B D	B D						
			(3.1) VR	Vegetation Removal								A									
			(3.2) AC	Agricultural Practice Change	D A					B D							B			B D	
		Material Extraction	(3.3) UR	Urbanisation	D A					D A	B D	D A			B D	A	B D	B D	D A		
			(4.1) IC	Infrastructure Construction (Unloading)						B										D	
		Material Addition	(4.2) QSM	Quarrying/Surface Mining (Unloading)	D						B									D	
			(5.1) IN	Infrastructure (Loading)							B										
		Hydrological Change	(5.2) IMG	Infilled (Made) Ground																	
			(5.3) RD	Reservoir & Dam Construction																	
			(6.1) DD	Drainage & Dewatering	A															D A	
		III. Subsurface & Surface Process	Explosions	(6.2) WA	Water Addition															D A	
				(7.1) CE	Chemical Explosion																A
			Fire	(7.2) NE	Nuclear Explosion																A
				(8.1) FR	Fire																

**Key**

Code	Description
	Associated Secondary Anthropogenic Process is <b>Before, During</b> and/or <b>After</b> the Primary Anthropogenic Process – see below.
Temporal Classification (Before, During, After)	
B	Before
D	During
A	After
B D	Before, During
B A	Before, After
D A	During, After
B D A	Before, During, After

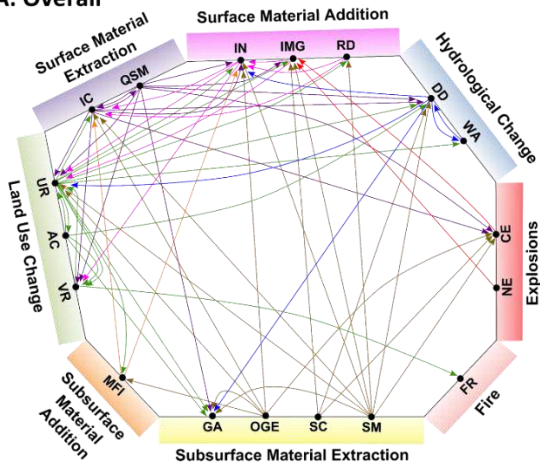
**Figure 4.1. Interactions between 18 anthropogenic process types.** An 18 × 18 interaction matrix featuring the same 18 anthropogenic process types on both the horizontal axis and vertical axis. These anthropogenic process types are organised into eight sub-groups, following the same colour coding as introduced in Table 4.2, and placed into three broader groups, depending on whether they act on the subsurface, surface or both. Grey shading is used to show where one primary anthropogenic process may trigger an associated secondary anthropogenic process to occur. Associated secondary anthropogenic processes may occur before (B), during (D), or after (A) the primary anthropogenic process. Although not included in this figure, in some cases, it is possible that one anthropogenic process may trigger further (or more intense) occurrences of itself. This figure indicates that anthropogenic processes often do not operate in isolation, but can occur in association with other anthropogenic processes.

### 4.2.5b Anthropogenic Process Linkages

In **Figure 4.1** we presented an interaction matrix as a way to visualise interactions between anthropogenic processes. An alternative way to visualise anthropogenic process interactions are network linkage diagrams composed of polygons, nodes along each of the sides of the polygons, and lines linking the nodes. In Gill and Malamud (2014) we used network linkage diagrams as a way of visualising natural hazard linkages. Such visualisation approaches, in contrast with interaction matrices, are potentially more difficult to use for extracting information. Network linkage diagrams, however, use a visualisation form that is more visually striking, and therefore help the reader to appreciate the large number of possible interactions through the ‘busyness’ of the visualisation. Furthermore, they allow the reader to more intuitively observe possible networks of hazard interactions (cascades). In **Figure 4.2**, we present network linkage diagrams, with each of the 18 individual anthropogenic process types from **Table 4.2** (e.g., vegetation removal, agricultural practice change) represented by a node. These nodes are distributed along the edge of an octagon, with each edge representing one of the eight sub-groups of anthropogenic processes (e.g., subsurface material extraction, land use change). As noted in **Section 4.2.3**, these sub-groups are placed into three broader groups according to where the anthropogenic process types operate relative to the Earth’s surface: *surface*, *subsurface*, *both*. In **Figure 4.2**, sub-groups within the same group are placed as adjoining edges. Individual octagon network linkage diagrams are also included in **Figure 4.2** for the three different groups introduced in **Table 4.2**: (I) Subsurface, (II) Surface and (III) Both (Subsurface and Surface).

Arrows are drawn from one node (anthropogenic process type) to another node (anthropogenic process type), where a *primary* anthropogenic process is believed to trigger an *associated secondary* anthropogenic process. The line starts at the *primary* anthropogenic process node and finishes at the *associated secondary* (triggered) anthropogenic process node regardless of whether the *associated secondary* anthropogenic process occurs before, simultaneously with or after the *primary* anthropogenic process. For example, quarrying/surface mining (**QSM**, the *primary* anthropogenic process) may trigger increased groundwater abstraction (**GA**, the *associated secondary* anthropogenic process) due to a need for water in the mining process. An arrow is therefore constructed between these nodes. Lines are coloured according to the sub-group of anthropogenic processes in which the relationship is initiated, matching the colour used for the edge of the octagon network linkage diagram. In the case of the sub-group ‘subsurface material extraction’, a dark yellow is used to improve visibility. In some cases, it is possible that one anthropogenic process may trigger further (or more intense) occurrences of itself. This is not represented in **Figures 4.1** and **4.2** which focus on *primary* anthropogenic processes triggering additional *associated secondary* processes.

**A. Overall**



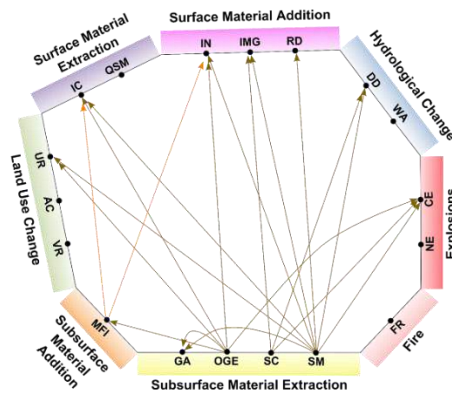
**Key**

→ Primary anthropogenic process drives associated anthropogenic process (before, during or after the primary process)

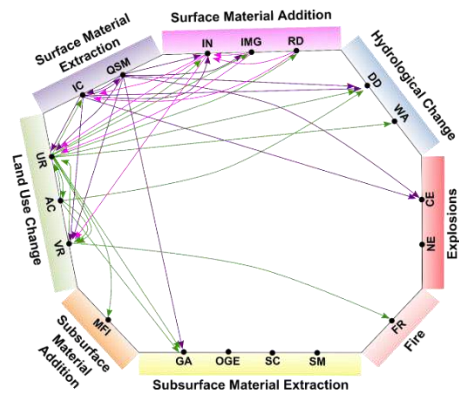
	Sub-Group	Anthropogenic Process	
		Code	Name
I. Subsurface	Subsurface Material Extraction	GA	Groundwater Abstraction
	OGE	Oil/Gas Extraction	
	SC	Subsurface Infrastructure Construction	
	SM	Subsurface Material Mining	
	Subsurface Material Addition	MFI	Material (Fluid) Injection
II. Surface	Land Use Change	VR	Vegetation Removal
	AC	Agricultural Change	
	UR	Urbanisation	
	Surface Material Extraction	IC	Infrastructure Construction (Unloading)
	QSM	Quarrying/Surface Mining (Unloading)	
III. Subsurface & Surface	Surface Material Addition	IN	Infrastructure (Loading)
	IMG	Infilled (Made) Ground	
	RD	Reservoir and Dam Construction	
	Hydrological Change	DD	Drainage and Dewatering
	WA	Water Addition	
	Explosions	CE	Chemical Explosion
	NE	Nuclear Explosion	
Fire	FR	Fire	

**B. Group**

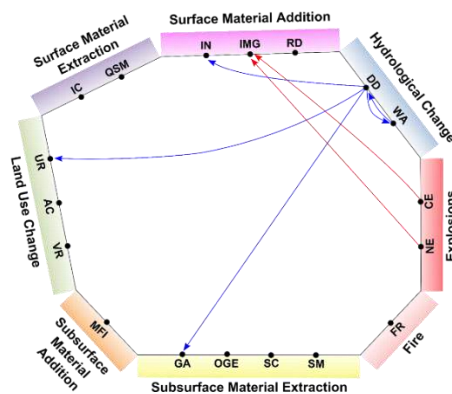
**I. Subsurface**



**II. Surface**



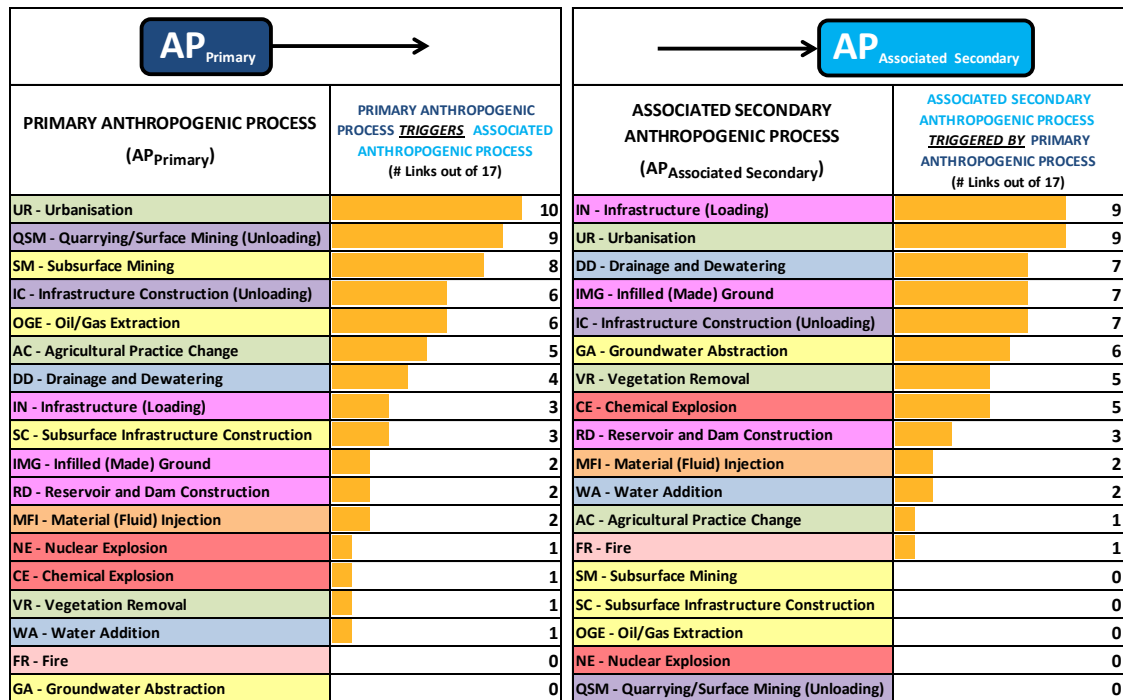
**III. Subsurface and Surface**



**Figure 4.2. Network linkage diagrams showing interactions between 18 anthropogenic process types.** Based on a design-structure presented in Gill and Malamud (2014). The principal octagon network linkage diagram (A) features 18 coded anthropogenic process types, with codes noted in the key (see also Table 4.2), and is an alternative visualisation of information presented in Figure 4.1. Individual octagon network linkage diagrams (B) are also included for the three different groups: (I) subsurface, (II) surface and (III) both (subsurface and surface). In all octagon network linkage diagrams, anthropogenic process sub-groups follow the same colour coding as introduced in Table 4.2. Arrows are used to show where a primary anthropogenic process type may trigger an associated secondary anthropogenic process type to occur. Lines are coloured according to the sub-group in which the relationship is initiated. The primary anthropogenic process type may trigger the associated secondary anthropogenic process type before, simultaneously with, or after the primary anthropogenic process type. Although not included in this figure, in some cases it is possible that one anthropogenic process type may trigger further (or more intense) occurrences of itself.

Building on the initial summary statistics presented in [Section 4.2.5a](#), a more detailed quantification and ranking of each anthropogenic process can be done based on a method undertaken by Tarvainen *et al.* (2006), De Pippo *et al.* (2008), and Gill and Malamud (2014). This method determines the extent to which each anthropogenic process triggers or can be triggered by other processes. The number of linkages is summed for each anthropogenic process in terms of the number of times a *primary* anthropogenic process triggers an *associated secondary* anthropogenic process, and the number of times an *associated secondary* anthropogenic process can be triggered by a *primary* anthropogenic process. For example, drainage and dewatering (**DD**) is a *primary* anthropogenic process that can trigger three other *associated secondary* anthropogenic processes: groundwater abstraction (**GA**), urbanisation (**UR**) and infrastructure (loading) (**IN**), as observed in [Figure 4.1](#). Conversely, drainage and dewatering (**DD**) is an *associated secondary* (triggered) anthropogenic process resulting from seven other *primary* anthropogenic processes: subsurface infrastructure construction (**SC**), subsurface mining (**SM**), agricultural practice change (**AC**), urbanisation (**UR**), infrastructure construction (unloading) (**IC**), quarrying/surface mining (**QSM**) and water addition (**WA**), as observed in [Figure 4.1](#).

The number of links for each of the 18 different primary anthropogenic process types included within this study were then ranked within [Figure 4.3](#), with each primary process type having a maximum possible of 17 associated secondary anthropogenic process types. This ranking shows that the anthropogenic processes triggering the greatest range of *associated secondary* anthropogenic processes are urbanisation (**UR**, 10 links), quarrying/surface mining (**QSM**, 9 links) and subsurface mining (**SM**, 8 links). *Associated secondary* anthropogenic processes triggered by the greatest number of other *primary* anthropogenic processes, are infrastructure (loading) (**IN**, 9 links), urbanisation (**UR**, 9 links), drainage and dewatering (**DD**, 7 links), infilled (made) ground (**IMG**, 7 links) and infrastructure construction (unloading) (**IC**, 7 links). The rankings presented in [Figure 4.3](#) do not take into account the relative likelihood of each anthropogenic process or each relationship between anthropogenic processes. Integrating location-specific information on likelihood, if available, would provide a useful summary of the relative importance of individual processes.



**Figure 4.3. Ranking of number of links for primary anthropogenic process types (AP<sub>Primary</sub>) and associated secondary anthropogenic process types (AP<sub>Associated Secondary</sub>).** A quantification and ranking of anthropogenic processes according to (left) the number of links of primary anthropogenic process *triggering* associated secondary anthropogenic process relationships, and (right) the number of links of associated secondary anthropogenic process *triggered by* primary anthropogenic processes. For example, infrastructure loading (IN) as a primary anthropogenic process has been identified to trigger three other associated anthropogenic processes (out of a possible 17 associated processes), but as a secondary anthropogenic process has been identified to have 9 primary processes that result in it being triggered (again, out of a possible 17). Figure compiled using information from [Figure 4.1](#). In this example, the associated secondary anthropogenic process may occur before, during, and/or after the primary anthropogenic process.

#### 4.2.5c Implications of Anthropogenic Process Interactions

The results derived from [Figures 4.1–4.3](#) have at least two implications for the study of natural hazards and the development of multi-hazard assessments of hazard potential, including interaction frameworks. These include:

- i. *Multiple anthropogenic processes may occur concurrently or sequentially.* Should concurring or cascading anthropogenic processes interact with the natural environment so as to trigger natural hazards, it may lead to multiple natural hazards occurring concurrently or sequentially. For example, urbanisation (which can increase the probability of flooding) may trigger groundwater abstraction (which can trigger ground subsidence). Ground subsidence can also increase the probability (or severity) of subsequent floods.

- ii. *Natural hazards may be exacerbated by multiple anthropogenic processes occurring concurrently.* If two or more concurring or cascading anthropogenic processes interact with the natural environment so as to trigger the same natural hazard, this may result in an impact greater or less than the sum of the components. For example, vegetation removal and infrastructure construction (unloading) may both individually result in landslides. If both of these anthropogenic processes occur simultaneously the number of landslides might be more (or less) than the sum of the result of both anthropogenic processes, had they occurred individually.

These, and other issues of relevance to DRR, are discussed in greater detail in [Section 4.5.2](#).

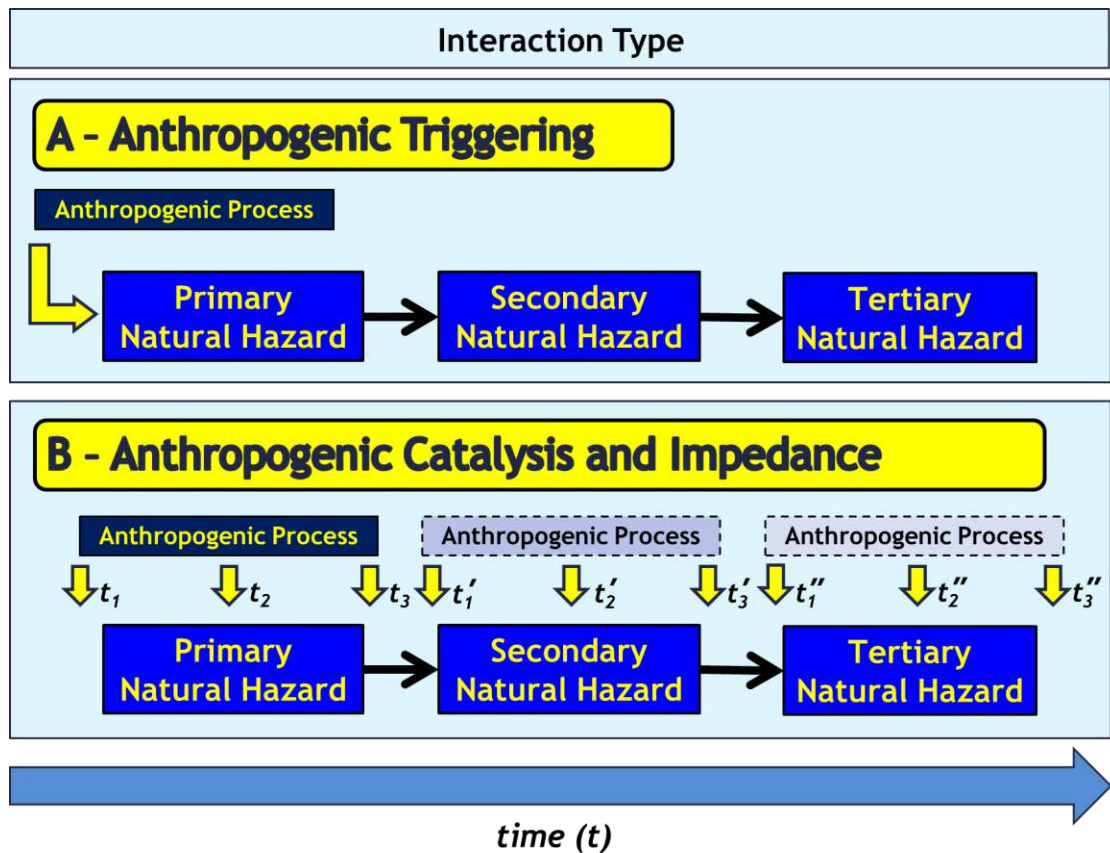
#### 4.2.6 Anthropogenic Processes and Natural Hazards

Having developed a classification scheme for anthropogenic processes (Task I, [Section 4.2.3](#)) and considered *anthropogenic process-anthropogenic process* interactions (Task II, [Section 4.2.5](#)), we now proceed to consider how these anthropogenic processes can influence natural hazards as background to Task III ([Section 4.3](#)) and Task IV ([Section 4.4](#)). Gill and Malamud (2016) described a range of interaction types that may be of relevance if integrating anthropogenic processes into multi-hazard approaches to manage natural hazards. Here we particularly focus on interactions where anthropogenic processes (i) trigger natural hazards and (ii) catalyse/impede natural hazard interactions. [Figure 4.4](#) summarises and visualises these two interaction types, which we proceed to discuss in turn.

*Anthropogenic Triggering* ([Figure 4.4A](#)). An anthropogenic process can trigger a (primary) natural hazard, which may or may not trigger secondary natural hazards to form a network of interactions (cascade). For example, the unloading of slopes, through poorly engineered roads, may trigger a landslide (e.g., Alexander, 1992; Sidle and Ochiai, 2006), which could then trigger further natural hazards, such as flooding due to the formation of a landslide dam (e.g., Costa and Schuster, 1988; Korup, 2002). Anthropogenic triggering is further discussed in [Section 4.3](#).

*Anthropogenic catalysis/impedance* ([Figure 4.4B](#)). Anthropogenic activity can also catalyse a particular natural hazard interaction (i.e., the triggering or increased likelihood of a secondary natural hazard through the action of a primary natural hazard). For example, vegetation removal on Mount Elgon (Uganda) is suggested to have reduced slope stability and likely catalysed the initiation of rain-triggered landslides (Knapen *et al.*, 2006; Claessens *et al.*, 2013). As shown in [Figure 4.4B](#), anthropogenic catalysts can act before ( $t_1$ ), during ( $t_2$ ), or (in the case of slow-onset secondary hazards) after ( $t_3$ ) the primary natural hazard occurs, to catalyse the interaction. We change notation here from **B** (before), **D** (during), **A** (after) used in [Figure 4.1](#), to  $t_1$  (before),  $t_2$

(during),  $t_3$  (after) as it is a more intuitive notation in this diagram, where time is shown to progress from left to right.



**Figure 4.4. Mechanisms relating anthropogenic process types to natural hazards and natural hazard interactions.** Two mechanisms are presented by which anthropogenic processes, such as those outlined in Table 4.2, may relate to natural hazards, such as those outlined in Table 4.4. The first mechanism (A) is anthropogenic triggering, where an anthropogenic process may trigger a primary natural hazard. This in turn may trigger further natural hazards to form a network of interactions (cascade). The second mechanism (B) is anthropogenic catalysis and impedance, where an anthropogenic process may catalyse or impede a defined primary natural hazard triggering a secondary natural hazard interaction. The anthropogenic process could occur before ( $t_1$ ), during ( $t_2$ ) or after ( $t_3$ ) the primary natural hazard, and at any point in a cascade system ( $t'$  and  $t''$ ).

Three examples of catalysing relationships include:

- i. *Catalyst occurs before primary natural hazard ( $t_1$ ).* Vegetation removal could catalyse the triggering of landslides (secondary natural hazard) by a storm (primary natural hazard) if removal occurs before ( $t_1$ ) the storm.
- ii. *Catalyst occurs simultaneously with primary natural hazard ( $t_2$ ).* Poor drainage can catalyse the triggering of floods (secondary natural hazard) by a storm (primary natural hazard) if it occurs simultaneously ( $t_2$ ) with the storm.

- iii. *Catalyst occurs after primary natural hazard ( $t_3$ )*. Infrastructure construction (unloading) can catalyse the triggering of ground heave (secondary natural hazard) by a storm (primary natural hazard) if it occurs after ( $t_3$ ) the storm. In this example the catalyst would also have the same influence if it occurred before or during the primary natural hazard.

In many cases the anthropogenic catalyst may occur at multiple time intervals ( $t_1$ ,  $t_2$  and/or  $t_3$ ). Anthropogenic activity can also impede or prevent a particular natural hazard. For example, vegetation removal may impede the triggering of wildfires by a lightning strike, due to a lack of available fuel. This is analogous to the deliberate action of prescribed burning, as seen in Wagle and Eakle (1979) and Fernandes and Botelho (2003). Again, as shown in **Figure 4.4B**, anthropogenic processes can act before ( $t_1$ ), during ( $t_2$ ), or after ( $t_3$ ) a primary natural hazard occurs so as to have an impedance effect. In both anthropogenic catalysis and impedance relationships, the anthropogenic process could act at any point in a cascade of natural hazards ( $t'$  and  $t''$ ). Anthropogenic catalysis and impedance are further discussed in **Section 4.4**.

### 4.3 Anthropogenic Triggering of Natural Hazards (Task III)

Using the classification of anthropogenic processes developed in **Section 4.2.3**, we now consider in Task III, which of these 18 anthropogenic processes can trigger different natural hazards. This section begins by introducing the 21 natural hazards that we consider in this study and a hazard classification scheme (**Section 4.3.1**), before proceeding to describe our overview, characterisation and visualisation of *anthropogenic process-natural hazard* triggering interaction relationships (**Section 4.3.2**), and analysing *anthropogenic process-natural hazard* type linkages (**Section 4.3.3**).

#### 4.3.1 Natural Hazards and Hazard Classification Schemes

In Gill and Malamud (2014) we considered the interactions between 21 natural hazards, with the hazards initially organised in that paper into six natural hazard groups based on the physical mechanism by which the hazard occurs (**Table 4.4**), *geophysical* (green), *hydrological* (blue), *shallow Earth processes* (orange), *atmospheric* (red), *biophysical* (purple) and *space hazards* (grey). Detailed descriptions of each of the 21 natural hazard types and limitations of this classification system, such as the exclusion of certain hazards and hazard groups, or the resolution used for their inclusion, are also noted in Gill and Malamud (2014). Here we extend this framework by addressing the important role of anthropogenic processes on triggering the same natural hazards and natural hazard groups. The classification of natural hazards presented in

**Table 4.4** has been made to account for different kinds of hazards globally, despite finer scales being locally of interest. For example, we use a broad classification of landslides, instead of more specific sub-classes, such as mudslide, debris flow, and rotational slides. The classification of natural hazards used is relevant in whole or part to many regions of the world. It includes most major natural hazard types and is easily scalable for use in specific case study locations.

**Table 4.4. Natural hazard groups and natural hazard types used in this chapter (reproduction of Table 2.2).** An outline of six hazard groups, containing 21 different natural hazard types, with the codes used in this chapter and component hazards noted.

Natural Hazard		Code	Component Hazards ( <i>where applicable</i> )
Group	Type		
<b>Geophysical</b>	Earthquake	EQ	Ground Shaking, Ground Rupture and Liquefaction.
	Tsunami	TS	
	Volcanic Eruption	VO	Gas and Aerosol Emission, Ash and Tephra Ejection, Pyroclastic and Lava Flows.
	Landslide	LA	Rockfall, Rotational and Translational Slide, Debris Flow, Lahar and Soil-Creep.
	Snow Avalanche	AV	
<b>Hydrological</b>	Flood	FL	Flash Flood, Fluvial Flood, Rural Ponding, Urban Flood, Coastal Flooding, Storm Surge, Jökulhlaups, Glacial Lake Bursts
	Drought	DR	Meteorological Drought, Agricultural Drought, Hydrological Drought
<b>Shallow Earth Processes (adapted from Hunt, 2005)</b>	Regional Subsidence	RS	Tectonic Subsidence.
	Ground Collapse	GC	Karst and Evaporite Collapse, Piping, Metastable Soils.
	Soil (Local) Subsidence	SS	Soil Shrinkage, Natural Consolidation and Settlement.
	Ground Heave	GH	Tectonic Uplift, Expansion (Swelling) of Soils and Rocks.
<b>Atmospheric</b>	Storm	ST	Tropical Cyclone, Hurricane, Typhoon, Mid-Latitude Storm.
	Tornado	TO	
	Hailstorm	HA	
	Snowstorm	SN	
	Lightning	LN	
	Extreme Temperature (Heat)	ET (H)	Heat Waves, Climatic Change
	Extreme Temperature (Cold)	ET (C)	Cold Waves, Climatic Change
<b>Biophysical</b>	Wildfire	WF	
<b>Space/Celestial</b>	Geomagnetic Storm	GS	
	Impact Event	IM	Asteroid, Meteorite.

### 4.3.2 Anthropogenic Process-Natural Hazard Triggering Interactions

In [Section 4.2.2](#) we introduced a review procedure used within our study, based on the guiding principles of Boaz *et al.* (2002) and described in [Table 4.1](#). This review procedure was used to examine potential triggering interactions between the 18 anthropogenic process types (described in [Table 4.2](#)) and the 21 natural hazard types (described in [Table 4.4](#)). This review of triggering interactions was iterative and pragmatic, with the development of a classification scheme for the 18 anthropogenic process types done simultaneously. An output of this review was a database of more than 120 references, listed in [Appendix B](#), with some of these also cited in this chapter.

In our methodology, each of the possible 378 *anthropogenic process-natural hazard* triggering interactions were considered using large literature databases (Google Scholar, Web of Science) to search for case studies and other relevant literature. This review procedure did not attempt to identify every reference or case study relating to each possible interaction, rather it used an iterative and pragmatic approach to ascertain whether the inclusion of the interaction in a characterisation of possible interactions can be supported by the available evidence. A Boolean search approach was used to identify articles where keywords relating to both the anthropogenic process and natural hazard appear in the same article. Different search terms were used for each anthropogenic process and each natural hazard. For example, in addition to ‘earthquake’, other search terms included ‘tremor’, ‘seismic activity’, and ‘seismic shaking’. Articles returned were briefly reviewed to determine their relevance, and whether it supported the existence of a particular interaction. Articles mentioning a natural hazard and an anthropogenic process but not considering the relationship between these were rejected. Those articles that did discuss a relationship between an anthropogenic process and a natural hazard were then critically examined to assess their veracity (e.g., considering the age of the publication and nature of the interaction). Where literature was identified to support the conclusion that a particular *anthropogenic process–natural hazard* triggering interaction occurs, this was noted through the interaction being classified as ‘possible’. Where literature was not identified, or literature appeared to reject a particular *anthropogenic process–natural hazard* triggering interaction, this was also noted through the interaction being classified as ‘not possible’. Before determining that an interaction was not possible, a diverse array of keywords was used in our Boolean search, and other grey literature considered. If this review was being adapted for use in a defined spatial region, it may be advantageous to integrate into this review process a stakeholder gathering to discuss and refine the results. Meyer *et al.*, (2013) successfully integrated this form of engagement into their cross-hazard review study of the costs of natural hazards.

In [Figure 4.5](#), we give an 18×21 interaction matrix, with 18 anthropogenic process types on the vertical axis and 21 natural hazard types on the horizontal axis. Through the assessment of

available literature outlined above, we identified 57 (out of  $18 \times 21 = 378$  possible) *anthropogenic process–natural hazard* triggering interaction relationships where an anthropogenic process type may trigger a natural hazard. The anthropogenic processes in **Figure 4.5** are arranged into three groups and further divided into eight sub-groups, as described in **Section 4.2.3** and **Table 4.2**. Natural hazards are organised into six hazard groups and coded, as introduced in **Section 4.3.1** and **Table 4.4** and explained in the interaction matrix key. Where a triggering relationship exists between an anthropogenic process and a natural hazard, the interaction matrix cell is shaded grey.

For 52 of the 57 identified *anthropogenic process–natural hazard* triggering interactions in **Figure 4.5**, a case study (with spatial and temporal limits) was found in the examined literature. This collection of case studies is noted in **Appendix B**, along with other relevant literature for each identified interaction. For example, a nuclear explosion may trigger a landslide or rock avalanche (**Figure 4.5**, cell 7.2–D) which we identified case-study examples (Adushkin, 2000; Pratt, 2005, Adushkin, 2006). For 5 of the 57 identified *anthropogenic process–natural hazard* triggering interactions, no specific case study was found (identified by \* in the grey box in **Figure 4.5**), but a relationship is described or conjectured in the literature. For example, a nuclear explosion may trigger a snow avalanche (**Figure 4.5**, cell 7.2–E), but a clearly defined case study was not identified in the literature, so while this is included in the interaction matrix it is marked with an asterisk (\*). While we note specific case studies for 52 of the 57 *anthropogenic process–natural hazard* triggering interactions in **Appendix B**, in our discussions we are considering probabilistic viewpoints, where the probabilistic behaviour of a relationship is often inferred from many individual events. This approach is used to consider *in general* how one hazard will influence another, rather than specific case examples.

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**Figure 4.5 [on following page]. Identification of anthropogenic process–natural hazard triggering interactions.** An  $18 \times 21$  interaction matrix with selected anthropogenic processes on the vertical axis and selected natural hazards on the horizontal axis. Anthropogenic processes (described in **Table 4.2**) are organised into three groups and further classified into eight general sub-groups of anthropogenic processes. Natural hazard types (described in **Table 4.4**) are divided into six broader natural hazard groups and coded, as explained in the key. This interaction matrix is populated using a database included in **Appendix B**. The interaction matrix shows 57 cases (out of 378 possible) where an anthropogenic process could trigger a natural hazard (cell shaded). Of these, there were five interactions where no case studies were identified in the literature (cell shaded with an asterisk, \*), but the relationship itself is inferred. Footnotes give further information about some of the relationships.

		TRIGGERED NATURAL HAZARD																				KEY				
		(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(O)	(P)	(Q)	(R)	(S)	(T)	(U)	GROUP	NATURAL HAZARD TYPE	CODE	
I. Subsurface Process	(1.1) GA	Groundwater Abstraction																					EQ	Earthquake	EQ	
	(1.2) OGE	Oil/Gas Extraction																					TS	Tsunami	TS	
	(1.3) SC	Subsurface Infrastructure Construction																					VO	Volcanic Eruption	VO	
	(1.4) SM	Subsurface Mining																					LA	Landslide	LA	
	(2.1) MFI	Material (Fluid) Injection																					AV	Snow Avalanche	AV	
	(3.1) VR	Vegetation Removal																					FL	Flood	FL	
	(3.2) AC	Agricultural Practice Change																					DR	Drought	DR	
	(3.3) UR	Urbanisation																					RS	Regional Subsidence	RS	
	(4.1) IC	Infrastructure Construction (Unloading)																					GC	Ground Collapse	GC	
	(4.2) QSM	Quarrying/Surface Mining (Unloading)																					SS	Soil (Local) Subsidence	SS	
II. Surface Process	(5.1) IN	Infrastructure (Loading)																					GH	Ground Heave	GH	
	(5.2) IMG	Infilled (Made) Ground																					ST	Storm	ST	
	(5.3) RD	Reservoir and Dam Construction																					TO	Tornado	TO	
	(6.1) DD	Drainage and Dewatering																					HA	Hailstorm	HA	
	(6.2) WA	Water Addition																					SN	Snowstorm	SN	
	(7.1) CE	Chemical Explosion																					LN	Lightning	LN	
	(7.2) NE	Nuclear Explosion																					ET (H)	Extreme Temperature (Hot)	ET (H)	
	(8.1) FR	Fire																					ET (C)	Extreme Temperature (Cold)	ET (C)	
	III. Subsurface & Surface Process	(9.1) RD	Reservoir and Dam Construction																					WF	Wildfire	WF
		(9.2) DD	Drainage and Dewatering																					GS	Geomagnetic Storm	GS
(9.3) WA		Water Addition																					IM	Impact Event	IM	
(10.1) CE		Chemical Explosion																					Description			
(10.2) NE		Nuclear Explosion																					Anthropogenic Process Triggers Natural Hazard.			
(10.3) FR		Fire																					* Triggering relationship inferred in the literature, but no case study has been identified.			
(11.1) RD		Reservoir and Dam Construction																					<b>Footnotes</b>			
(11.2) DD		Drainage and Dewatering																					[General #1] – Please note that these relationships do not include the impact of anthropogenic factors on long-term climate change, but do include impacts on localised changes to climate.			
(11.3) WA		Water Addition																					[General #2] – Where earthquakes are noted to be triggered, these may be low magnitude, low intensity events (colloquially referred to as ‘earth tremors’).			
(12.1) CE		Chemical Explosion																					[1.3M/L4M] – Primarily through rock-bursts, as lateral pressures are removed.			
(12.2) NE	Nuclear Explosion																					[3.1J] – Vegetation removal is both noted to increase and decrease precipitation/rainfall, through changes in evaporation and cloud formation. Differences relate to altitude and topography.				
(12.3) FR	Fire																					[5.3J] – Some studies suggest both increases and decreases in frequency of rain (or duffing events of this kind). There is disagreement in the literature about the nature of this relationship.				
(13.1) CE	Chemical Explosion																					[5.3B] – No case study identified, but some discussion in literature of localised cooling effect. There is disagreement in the literature about the nature of this relationship.				
(13.2) NE	Nuclear Explosion																					[7.1B] – No case study identified in literature, but some literature to support the existence of this relationship.				
(13.3) FR	Fire																					[7.1D] – Blasting increases the likelihood of slope failure through a deterioration of rock mass quality.				
(13.4) FR	Fire																					[7A5] – Case study infers blasting as a possible initiation of forest fire, but cause is unclear.				
(13.5) FR	Fire																					[7.2B, E.5] – No case studies identified in literature, due to relatively few nuclear explosions. Literature to support these relationships does exist.				

Figure 4.5 [full caption on previous page]. Anthropogenic process–natural hazard triggering interactions.

**Figure 4.5** gives an overview, in matrix form, of what *anthropogenic process–natural hazard* triggering interactions relationships exist and whether case studies have been identified; however, it does not indicate the following three factors:

- i. *Intensity of triggered natural hazard.* The intensity of a triggered natural hazard may vary depending on the type and intensity of the anthropogenic trigger, including but not limited to its spatial extent and its temporal extent. Here we discuss three aspects:
  - a. Anthropogenic process type. In **Figure 4.5** nine different types of anthropogenic processes are noted to have the potential to trigger earthquakes. Depending on the specific anthropogenic process, the resultant intensities of triggered earthquakes may range from low-magnitude, low intensity earthquakes (colloquially known as earth tremors in some regions) to high-magnitude, high intensity earthquakes. For example, when considering the population of earthquakes associated with subsurface infrastructure construction and subsurface mining, these are principally the release of stress in the form of low magnitude, low intensity earthquakes (Li *et al.*, 2007; Hagedorn *et al.*, 2008; Bischoff *et al.*, 2010).
  - b. Spatial area affected. The intensity of a triggered natural hazard may also relate to the spatial area affected. For example, two anthropogenic processes (*reservoir and dam construction, water addition*) are noted in **Figure 4.5** to trigger flooding, but these floods may be localised and impact tens to hundreds of square metres (e.g., some forms of water addition, such as opening an overflow pipe), or widespread and impact many square kilometres (e.g., poor drainage across an urban area, or the construction of a reservoir or dam).
  - c. Temporal extent. The temporal extent of anthropogenic processes may also result in different intensities of natural hazards. For example, sustained groundwater abstraction is likely to result in greater regional subsidence than short periods of groundwater abstraction.
- ii. *Timing of interaction relationship.* Significant differences exist in aspects of the timing of the different anthropogenic process triggering natural hazard relationships shown in **Figure 4.5**. Anthropogenic process types may be discrete (e.g., chemical explosions) or more continuous in their nature (e.g., groundwater abstraction). For many continuous anthropogenic process types, they may need to be sustained over a long period of time before a given natural hazard is triggered. Lag times may also exist between the occurrence of an anthropogenic process and the subsequent triggering of a natural hazard. For example, a short lag time often exists between a chemical explosion and the

triggering of a wildfire; whereas, a short or long lag time may exist between chemical explosions (blasting) and the triggering of a landslide.

- iii. *Likelihood of interaction relationship.* The probability for each of the triggering relationships in **Figure 4.5** is not indicated. These can relate to two aspects of likelihood:
  - a. The probability of the anthropogenic process occurring in a given spatial/temporal extent. For example, in a given spatial/temporal regime, there is a low likelihood of a nuclear explosion, but there is a high likelihood of infrastructure loading.
  - b. The probability that a natural hazard is triggered given that the anthropogenic process has occurred. For example, if groundwater abstraction occurs, there is a low likelihood of earthquakes; if reckless burning occurs, there is a high likelihood of wildfires.

The assessment of these three factors for each *anthropogenic process–natural hazard* triggering interactions may be possible to determine for specific locations, given additional place-specific data. The likelihood of any given *anthropogenic process–natural hazard* triggering interaction is likely to have some relationship to location-specific geology, hydrology, human practice and policy frameworks. Different regions or countries may have a different capacity to manage the relationship between anthropogenic activity and natural hazards, generating differential triggering likelihoods. For example, Morris *et al.* (2003) discuss the importance of holistic management strategies for groundwater abstraction. Excessive groundwater abstraction can trigger regional subsidence (Hunt, 2005). Management of this is challenging, with Morris *et al.* (2003) noting management frameworks being required for both public sector and private sector users. The ability to establish, monitor and enforce such frameworks will differ between countries.

### **4.3.3 Anthropogenic Process-Natural Hazard Type Linkages**

Using the 57 *anthropogenic process–natural hazard* triggering interactions presented in **Figure 4.5**, we apply the same ranking method used previously in **Section 4.2.5b** and **Figure 4.3**, to analyse the relative severity of each *triggering anthropogenic process* and *triggered natural hazard* in the context of this study. In **Figure 4.6** we visualise this relative severity by quantifying and ranking:

- i. *Triggering anthropogenic process (AP).* The extent to which each anthropogenic process triggers natural hazards (in **Figure 4.6** we use the term *anthropogenic process to natural hazard* links). Each single anthropogenic process can trigger a maximum possible 21 natural hazards.

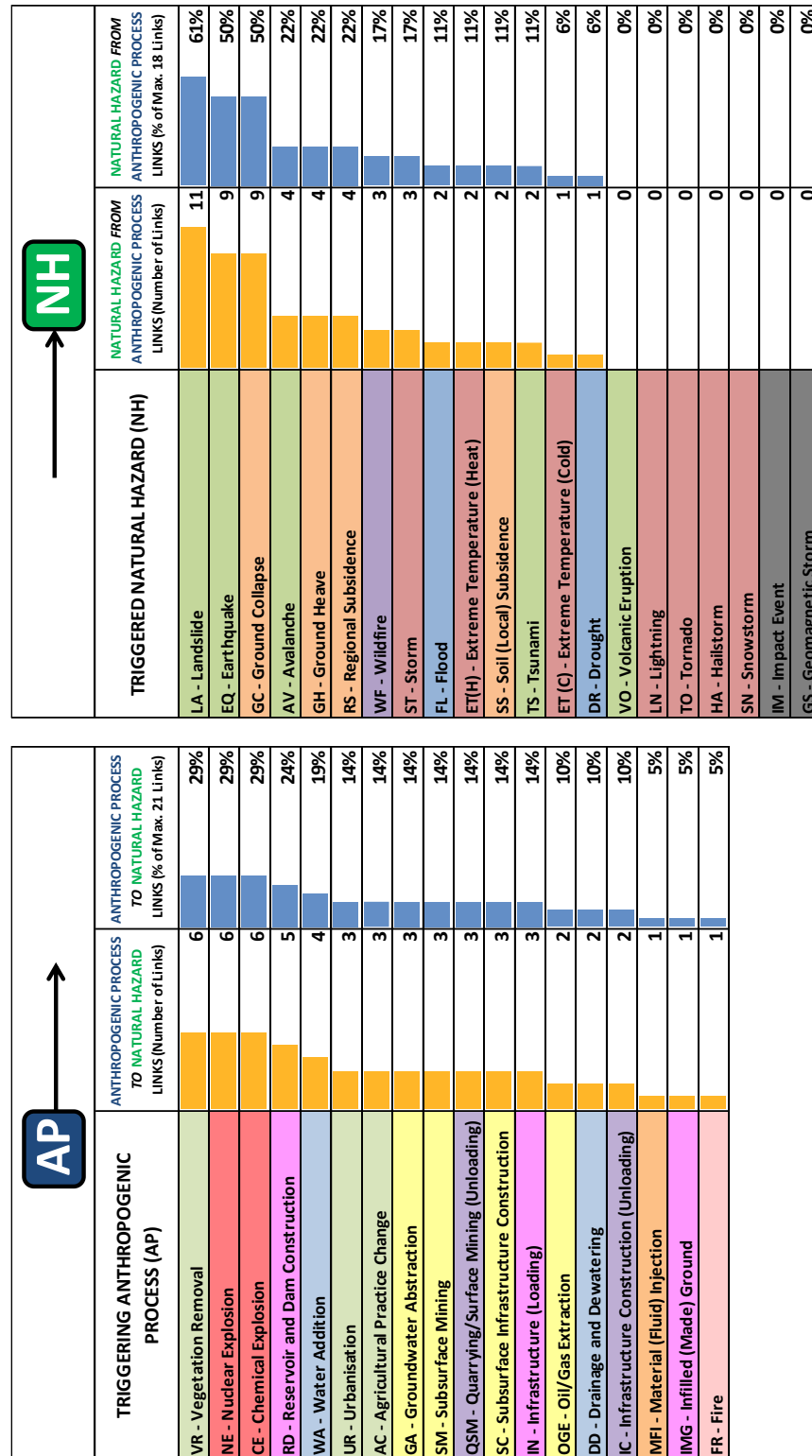
- 
- ii. *Triggered natural hazard (NH)*. The extent to which each natural hazard is triggered by anthropogenic processes (in **Figure 4.6** we use the term *natural hazard from anthropogenic process* links). Each single natural hazard can trigger a maximum possible 18 anthropogenic processes.

For each triggering anthropogenic process (AP) and triggered natural hazard (NH) in **Figure 4.6**, we sum the total number of relevant linkages from **Figure 4.5**, ranking them from highest to lowest number of links, and present the information in **Figure 4.6**. We also present the numbers of *anthropogenic process to natural hazard* links and *natural hazard from anthropogenic process* links as percentages of the maximum possible. From the rankings in **Figure 4.6** we see that:

- i. The three highest ranked anthropogenic processes, with the most *anthropogenic process to natural hazard* links (each with 6 links out of 21 potential links), are vegetation removal (**VR**), nuclear explosions (**NE**) and chemical explosions (**CE**). These three anthropogenic processes together account for 18 (32%) of the 57 *anthropogenic process to natural hazard* links.
- ii. The three highest ranked natural hazards, with the most *natural hazard from anthropogenic process* links, are landslides (**LA**, 11 links out of 18 potential links), earthquakes (**EQ**, 9 links) and ground collapse (**GC**, 9 links). These three natural hazards account for 29 (51%) of the 57 *natural hazard from anthropogenic process* links.

When considering each type of link as a percentage of the maximum possible for any one anthropogenic process and any one natural hazard, we note that:

- i. The three highest ranked percentages of *anthropogenic process to natural hazard* links are each 29% (each 6 of 21 possible links). This compares to the highest three ranked percentages of *natural hazard from anthropogenic process* links being 61%, 50%, and 50% (11, 9 and 9 of 18 possible links).
  - ii. The three lowest ranked percentages of *anthropogenic process to natural hazard* links are each 5% (each 1 of 21 possible links). This compares to the lowest three ranked percentages of *natural hazard from anthropogenic process* links being each 0% (each 0 of 18 possible links).
  - iii. Overall, there is a smaller spread of values (as represented by the standard deviation of the values) when considering *anthropogenic process to natural hazard* links (mean = 15%; median = 14%; standard deviation = 8%) compared to *natural hazard from anthropogenic process* links (mean = 15%; median = 11%; standard deviation = 18%). The latter is skewed by three large ( $\geq 50\%$ ) percentages, relating to landslides, earthquakes and ground collapse.
-



**Figure 4.6.** Ranking of individual anthropogenic processes (AP) and natural hazards (NH) based on the total number and percentage of the maximum possible (left) AP to NH links and (right) NH from AP links. Using the interaction matrix (Figure 4.5), the number of anthropogenic process natural hazard links is summed for each anthropogenic process in this study, and then ranked (left). This was then repeated for each natural hazard, summing and ranking triggered natural hazard from anthropogenic process links (right). For both we also present the results as a percentage of the maximum possible number of links (21 anthropogenic process to triggering natural hazard links; 18 natural hazards triggered by anthropogenic process links). Figure compiled using information from Figure 4.5.

The information and rankings in **Figure 4.6** do not reflect the overall likelihood of any particular anthropogenic process or triggering relationship. Certain anthropogenic processes ranking high (left hand side of **Figure 4.6**) may have a very low likelihood of occurring. Nuclear explosions (**NE**), for example, rarely occur, whereas the remaining 17 anthropogenic processes occur with much higher frequencies and are relatively widespread, although they themselves cover a range of likelihoods (e.g., vegetation removal, **VR**, is much more frequent than reservoir and dam construction, **RD**). Natural hazards that rank high (right hand side of **Figure 4.6**) may also have received that ranking through the inclusion of many low likelihood anthropogenic process and natural hazard interaction pairings. For example, earthquakes (**EQ**) are ranked second highest (9 links), but some of the *natural hazard from anthropogenic process* links contributing to this total are low likelihood interaction pairings (e.g., groundwater abstraction triggering earthquakes). Furthermore, as information about the expected intensity or range of intensities of the triggered natural hazards is not reflected in **Figure 4.5**, differential intensities are also not reflected in the rankings of **Figure 4.6**. Given these caveats, it is possible that a high likelihood-high intensity interaction pairing may be found outside of the top ranked *natural hazard from anthropogenic process links*. Location-specific likelihood, intensity and impact data could refine the rankings within **Figure 4.6** to better support planning and mitigation activities.

## 4.4 Anthropogenic Catalysing and Impedance of Natural Hazard Interactions (Task IV)

Anthropogenic processes can catalyse or impede natural hazard interactions, as introduced in **Section 4.2.6**. Here in Task IV, we explore ways to consider anthropogenic process types catalysing and impeding natural hazard interactions, using the example of vegetation removal. We begin by introducing an example of a systematic classification of natural hazard interactions (**Section 4.1**), and then consider visualisation techniques that can be used to represent the catalysis or impedance of natural hazard interactions by anthropogenic processes, using the example of vegetation removal (**Section 4.2**).

### 4.4.1 Natural Hazard Interactions

Natural hazard interactions can be either unidirectional or bidirectional, and include a primary natural hazard triggering a secondary natural and a primary natural hazard increasing the probability of a secondary natural hazard. In Gill and Malamud (2014) we used the 21 diverse natural hazard types introduced in **Table 4.4** and using a  $21 \times 21$  interaction matrix identified 90

possible triggering and increased probability interactions (out of  $21 \times 21 = 441$  possible interactions). This interaction matrix was previously presented in [Figure 2.2](#) with the 21 primary natural hazards on the vertical axis and the same 21 natural hazards as secondary natural hazards on the horizontal axis. Interactions and their characteristics were identified by examining more than 200 references from peer-reviewed and grey literature. Interactions include both triggering and increased probability relationships, with identified natural hazard interactions differing in terms of likelihood and the frequency of observed case studies in the literature. We define these two types of interactions between natural hazards as follows:

- i. *Triggering interactions.* One primary natural hazard triggers a secondary natural hazard. For example, an earthquake triggers a landslide, a storm triggers a flood, lightning triggers a wildfire.
- ii. *Increased probability interactions.* One primary natural hazard increases the likelihood of a secondary natural hazard. For example, a wildfire increases the probability of a landslide, ground subsidence increases the probability of a flood, a drought increases the probability of a wildfire.

Here we distinguish between triggering relationships and increased probability relationships as two different types of interactions, but we recognise that similarities exist between them. Both interaction types represent a change in probability of a secondary hazard (e.g., landslide), given a primary hazard (e.g., earthquake). They can be considered to be two end-member types, with a continuum between them:

- i. *Triggering:* A probability associated with a threshold being reached or passed.
- ii. *Increased Probability:* A probability associated with a change in environmental parameters, so as to move towards, but not reach a particular threshold.

Further discussion of the justification for, and benefits of, distinguishing between triggering and increased probability relationships as separate interaction types are noted in Gill and Malamud (2016). Understanding the influence of anthropogenic processes on natural hazard interactions allows us to constrain an additional contribution to the hazardousness of a given area (Regmi *et al.*, 2013).

#### **4.4.2 Visualising Anthropogenic Process Types Catalysing or Impeding Natural Hazard Interactions**

As previously illustrated in [Figure 4.4B](#) and discussed in [Section 4.2.6](#), anthropogenic processes have the potential to both catalyse and impede the interactions between natural hazards. A

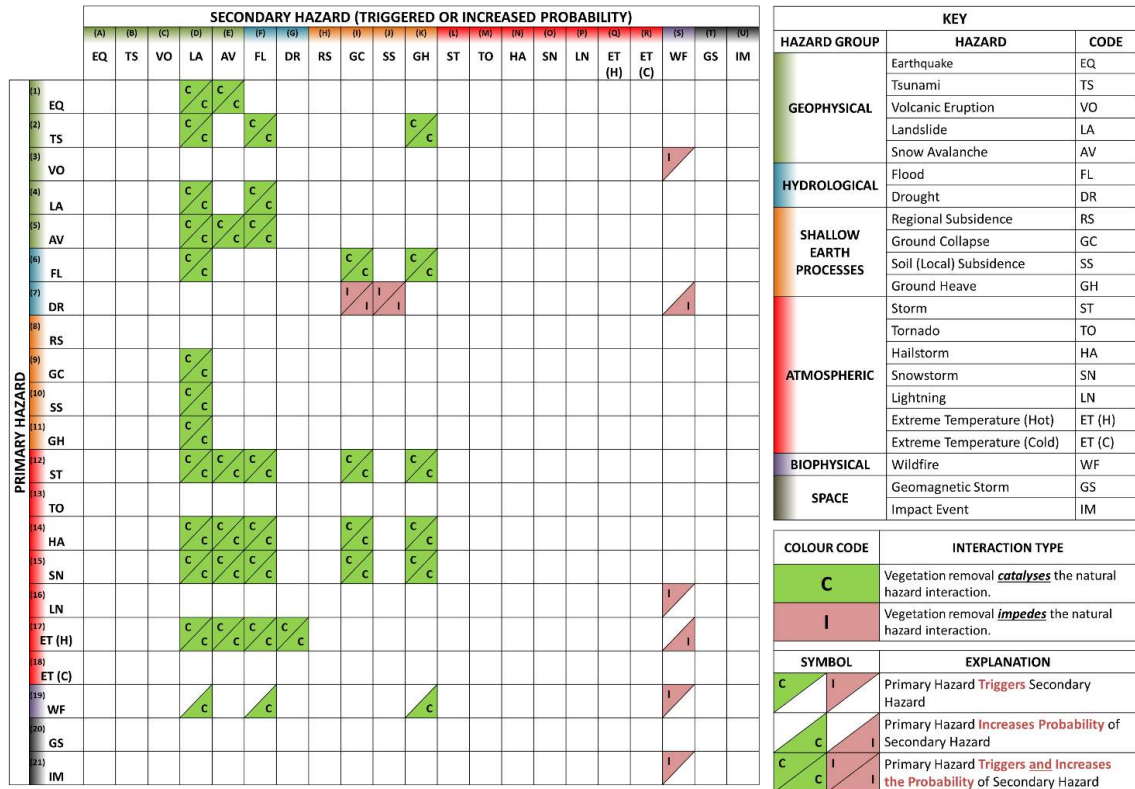
potential relationship therefore exists between each of the 18 anthropogenic process types in **Table 4.2** and the 90 natural hazard interactions shown in **Figure 2.2**, giving  $18 \times 90 = 1620$  possible catalysis/impedance relationships of anthropogenic processes on natural hazard interaction pairs. To represent potential catalysing and impedance effects, we must first select a suitable visualisation framework such as an interaction matrix like that used in **Figure 4.5** (**Section 4.3**). This interaction matrix would have to allow for three principal parameters to be represented: (i) primary natural hazard, (ii) secondary natural hazard, (iii) anthropogenic processes (as catalyst or impeder). While it would be possible to merge parameters (i) and (ii) into ‘hazard interaction pairings’, giving the 90 possible hazard interactions described in **Section 4.2**, this would generate a highly asymmetrical interaction matrix ( $18 \times 90$ ). The interaction matrix would have 18 anthropogenic process types on the vertical axis and 90 interaction pairings on the horizontal axis, with a total of 1620 cells representing possible relationships. Such a large and asymmetrical interaction matrix would likely lose its clarity and ease of utility for end-users. Where this framework is being applied in a region of limited spatial extent (e.g., a city, or region of a country) it is possible that relevant hazard interactions total less than 90 and relevant anthropogenic process types less than 18. In this case a smaller, more symmetrical interaction matrix could be developed, which may be an appropriate visualisation framework.

For a global overview with multiple interactions, we suggest that a series of 18 different interaction matrices (one for each anthropogenic process type considered) would be a better alternative to one large, asymmetrical interaction matrix. This form of visualisation adapts the natural hazard interaction matrix presented in **Figure 2.2** to include an additional parameter of information (the anthropogenic process considered). We demonstrate this methodology and visualisation framework to assess the influence of anthropogenic processes on natural hazard interactions using the example of vegetation removal. Vegetation removal is a common anthropogenic process of relevance to most inhabited regions of the world. Vegetation removal may occur over a small spatial extent (e.g., a 4000 m<sup>2</sup> field for agriculture) or over a larger spatial extent (e.g., a 100 km<sup>2</sup> area of rainforest that is removed for wood). The temporal extent over which vegetation removal occurs could be several days or several years, with likely positive correlation to the total spatial extent of removal. Vegetation removal may potentially catalyse or impede the natural hazard interactions presented in **Figure 2.2**.

To construct an interaction matrix that considers the influence of vegetation removal on natural hazard interactions, we first started with the matrix of 90 natural hazard interactions shown in **Figure 2.2**. We then examined the processes by which the primary natural hazard triggers or increases the probability of the secondary natural hazard for each of the 90 interactions. A table describing these mechanisms in Gill and Malamud (2014, Supplementary Material) was used to

support this process. A combination of expert judgement and relevant literature was used to determine if vegetation removal could catalyse or impede each mechanism (and therefore the interaction). The literature used to support this process included some of the references included in the database introduced in [Section 4.2.2](#) (and included in the [Appendix B](#)), particularly those relating to vegetation removal. Additional supporting literature, particularly comprehensive texts such as Goudie (2013) were also used. This additional literature was identified using a Boolean search of the anthropogenic process type, primary natural hazard and secondary natural hazard to determine if a catalysis or impedance relationship occurs or not. In this review, we were again not seeking to identify every reference on an interaction, rather identify enough information to populate an interaction framework by determining whether an interaction is feasible or not. For example, the interaction between a storm (ST, [Figure 2.2](#), row 12) and a flood (FL, [Figure 2.2](#), column F) is well understood and documented. Our background knowledge of the mechanism by which this interaction occurs suggests that vegetation removal will increase overland flow, and therefore catalyse the interaction. This is supported by literature (e.g., Clark, 1987; Bradshaw *et al.*, 2007) identified using a Boolean search of the anthropogenic process type, primary natural hazard and secondary natural hazard

Through this review process we identified 46 instances (out of 90 interactions possible) where natural hazard interactions are catalysed or impeded by vegetation removal. In [Figure 4.7](#) we present these interactions using an adapted interaction matrix. As in [Figure 2.2](#), the primary natural hazards are shown on the vertical axis and the secondary natural hazards on the horizontal axis, and both triggering and increased probability interactions between primary and secondary natural hazards are considered. Where the anthropogenic process of interest within [Figure 4.7](#) is suggested to catalyse a particular natural hazard interaction (triggering or increased probability), the relevant part of the cell is shaded green and labelled with a ‘C’ (for **catalyst**). Where the named anthropogenic process is suggested to impede a particular natural hazard interaction, the relevant part of the cell is shaded pink and labelled with an ‘I’ (for **impeder**). Although differential rates of catalysis or impedance are highly likely to exist, these are strongly affected by local conditions and so not represented within this visualisation.



**Figure 4.7. Influence of vegetation removal on natural hazard interactions.** A 21 × 21 interaction matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded and classified as explained in the key and Table 4.4. This interaction 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. Where vegetation removal is noted to catalyse the given hazard interaction the cell is shaded green and labelled with a ‘C’. Where vegetation removal is noted to impede the given hazard interaction the cell is shaded pink and labelled with an ‘I’.

In Figure 4.7, 38 cells are identified where vegetation removal could catalyse a natural hazard interaction, shown using green shading and labelled ‘C’. Examples include vegetation removal catalysing:

- i. Earthquakes triggering and/or increasing the probability of landslides, through a reduction in slope strength.
- ii. Storms triggering and/or increasing the probability of floods, through an increase in overland flow and saturation of the ground.
- iii. Wildfires increasing the probability of landslides, through concurrent removal of slope strength.

Eight further cells are identified where vegetation removal could impede a natural hazard interaction. These are also visualised in **Figure 4.7**, shown using pink shading and labelled ‘I’. Examples include vegetation removal impeding:

- i. Drought triggering or increasing the probability of soil (local) subsidence, through a reduction in the take-up of water, limiting the influence of the drought on shrink-swell soils.
- ii. Droughts increasing the probability of wildfires, through the removal of available fuel for fires.

In this section, we have given an example of one anthropogenic process (vegetation removal) selected from **Section 4.2.3** to assess its role in catalysing and impeding the natural hazard interactions described in **Section 4.2**. This example (which could be extended to the other 17 anthropogenic processes) illustrates our method for constraining and visualising catalysing/impeding interaction processes. This method can also be further adapted for use in local and regional case studies.

## 4.5 Discussion

Within this study we have assessed, classified, and visualised the potential of 18 anthropogenic processes to trigger other anthropogenic processes (**Section 4.2**), and 21 natural hazards (**Section 4.3**). We have also considered the ability of anthropogenic processes to catalyse/impede natural hazard interactions, using the example of vegetation removal to demonstrate a viable methodology and visualisation framework (**Section 4.4**). The collection of visualisations developed and discussed in **Sections 2 to 4**, and the multiple case studies that motivate this work, help illustrate the importance of considering anthropogenic processes within holistic multi-hazard assessments of hazard potential. Case studies are described throughout **Sections 1 to 4**, with many additional examples given in **Appendix B**.

In this discussion section we begin by describing some of the limitations and uncertainties associated with our analysis and visualisations (**Section 4.5.1**), then discuss the integration of this research into multi-hazard frameworks, including a description of ways that visualisations from **Sections 4.2 to 4.4** can be combined and used to strengthen multi-hazard frameworks (**Section 4.5.2**), and finish by discussing how interaction frameworks incorporating anthropogenic processes can be used within DRR (**Section 4.5.3**).

### 4.5.1 Limitations and Uncertainties

We now give five limitations and factors that contribute to uncertainty within our analysis of anthropogenic processes and their influence on natural hazards and natural hazard interactions:

- i. *Sub-Classifications of Selected Natural Hazards and Anthropogenic Processes.* Both the natural hazard types and anthropogenic process types used in this chapter could be sub-divided into further classes. An example relating to natural hazards, is the classification of landslides that could be sub-divided into the more specific type classifications of, for example, mudslides, debris flows, translational landslides and rockfalls. An example relating to anthropogenic processes is the classification of agricultural practice that could be sub-divided into type of change and relationship to crops, livestock or irrigation. In some applications of natural hazard interactions, such as the development of local/regional multi-hazard frameworks, some sub-classes would be better suited to informing policy makers or civil protection. For example, in London, rather than just having ‘floods’ as a class, it could be sub-divided into inland flooding, local/urban flooding (fluvial or surface run-off), coastal and tidal flooding, fluvial flooding, hazardous flash flooding or major reservoir/dam failure or collapse (London Resilience Partnership, 2014).
- ii. *Exclusion of Other Anthropogenic Processes.* The list of selected anthropogenic process types introduced in [Table 4.2](#) may exclude some other anthropogenic processes (e.g., fishing, aviation). The three anthropogenic process groups, eight sub-groups based on location near the Earth’s surface and 18 anthropogenic process types described in [Table 4.2](#) offers a relatively coarse scale but comprehensive overview of human influences on many aspects of the Earth system. The anthropogenic processes that we have selected for use within this study are based on an examination of multiple case studies. Anthropogenic processes were selected that were commonly associated with the triggering of natural hazards. Certain anthropogenic processes (e.g., fishing, aviation) may therefore be missing from this list as a result of them having minimal influence on the natural hazard types being examined in this study ([Table 4.4](#)), although we recognise they may influence other forms of environmental degradation.
- iii. *Scale of Interest.* We introduced in [Section 4.2.3](#) the importance of spatial and temporal scale of anthropogenic processes. Most of the processes included within [Table 4.2](#) could occur over many orders of magnitude in time and space, with their influence on natural hazards also differing. For example, quarrying and surface mining could be a small quarrying project (e.g., 0.1 km<sup>2</sup>) such as the marble quarries discussed by Mouflis *et al.*

(2008), or a large opencast mine, such as Chiquicamata, Chile (copper) two orders of magnitude larger, with area of 12.1 km<sup>2</sup> in 2000 (Flores and Karzulovic, 2000). Chiquicamata and other large opencast mining projects, may trigger natural hazards, or catalyse/impede natural hazard interactions, that are likely to be of a different scale to those associated with smaller quarries and surface mining operations. This is likely to be the same for almost all of the anthropogenic processes discussed within this study. Consequently, the application of the generalised, global assessments presented within **Sections 4.2 to 4.4** may benefit from further location-specific information on the scale and magnitude of relevant processes. Thresholds at which natural hazards are triggered, or natural hazard interactions are catalysed or impeded, could also be determined.

- iv. *Regulatory, Technical and Financial Capacity.* As introduced in **Sections 4.2.2** and **4.3.3**, different regions or countries may have different capacities to manage the relationships between anthropogenic activity and natural hazards. The likelihood of an anthropogenic process resulting in the triggering of a natural hazard, or catalysing/impeding natural hazard interactions may, therefore, be a function of this regulatory capacity. In **Section 4.3.2** we use the example of road construction, and suggest that the likelihood of associated infrastructure construction (unloading) triggering landslides will be affected by policies, technical knowledge and financial capability to undertake effective surveys, slope reinforcement and regular maintenance. Smaller unregulated projects may be more likely to result in the triggering of a serious natural hazard than a large, well-regulated project. The influence of anthropogenic processes on the natural environment may, therefore, be strongly associated with the ability of governments to adhere to and enforce standards of national and international quality.
- v. *Climate Change.* This chapter has not included the important influence of increased anthropogenic greenhouse gas emissions on natural hazards. Such gases are associated with increasing temperatures, which itself can trigger other natural hazards. The relevance and range of ways by which climate forces natural hazards is noted elsewhere, with McGuire and Maslin (2012) giving a comprehensive overview of the topic.

In addition to these aspects of uncertainty, in Gill and Malamud (2014) we describe in detail limitations and uncertainties associated with the hazard interactions data, classifications and visualisations. These include the following:

- i. knowledge bias,
- ii. exclusion and resolution of hazards,
- iii. use of older and grey literature,

- iv. contrasts between slow and rapid onset secondary natural hazards, and
- v. parameter uncertainties and networks of hazard interactions (cascades).

Given that we are using similar review guidelines, analysis techniques, classifications and visualisations within this study of anthropogenic processes, many of these limitations and uncertainties persist.

#### **4.5.2 Integration of Anthropogenic Processes into Multi-Hazard Frameworks**

In this chapter we have suggested that anthropogenic processes have a significant influence on the triggering of natural hazards ([Section 4.3](#)) and catalysing/impeding natural hazard interactions ([Section 4.4](#)). We recommend, therefore, that anthropogenic processes are carefully considered when trying to assess the potential of natural hazards in any given area and develop an enhanced multi-hazard assessment. In [Section 4.1](#) the term multi-hazard was defined as meaning “all possible and relevant hazards and their interactions, in a given spatial region and/or temporal period”. An enhanced multi-hazard framework, presented in Gill and Malamud (2016), emphasised the importance of also considering information on anthropogenic processes and technological hazards.

Many environments are shaped by anthropogenic activity, including the 18 anthropogenic process types detailed in [Table 4.2](#). Urban areas, for example, are an environment in which two or more of these anthropogenic processes may typically be found spatially and temporally overlapping. [Section 4.2.5](#) identified many examples where one anthropogenic process can result in other anthropogenic processes either before, during or after itself. Identifying and characterising principal anthropogenic processes and their influence on the natural environment, therefore, can help to build an understanding of what natural hazards may be triggered and which natural hazard interactions may be influenced by these processes, in a given region. Whereas the identification of relevant natural hazards is unlikely to change over significant time periods (in contrast with the likelihood of any given natural hazard, which may change), the relevance of anthropogenic processes is more likely to change. Over the course of months, years or decades new anthropogenic processes may start and existing processes stop or change in their spatial extent. This dynamic nature of anthropogenic processes should be recognised within multi-hazard frameworks, recognising that their distribution is not static and that continued monitoring of relevant anthropogenic processes may be required.

Interaction matrices such as [Figures 4.1, 4.5 and 4.7](#) are globally applicable, which can be adapted and scaled for use in specific locations. They can be used individually to inform policy, practice and research, but they can also be combined to allow an analysis of anthropogenic processes and

their influence on networks of natural hazard interactions (cascades). Combining the different anthropogenic process and natural hazard interaction matrix types presented in this chapter facilitates a more enhanced and comprehensive assessment of potential interactions for multi-hazard frameworks. **Figure 4.8** shows how a combination of **Figures 4.5** and **4.7** can be used to support a visualisation of networks of hazard interactions (cascades). **Figure 4.8** combines the  $18 \times 21$  interaction matrix of *anthropogenic process types triggering natural hazards* (**Figure 4.5**) with the  $21 \times 21$  interaction matrix of *natural hazards triggering natural hazards* (**Figure 2.2**), and gives an example of a network of hazard interactions (cascade). In this example: (i) (underlying matrix) vegetation removal (**VR**) is shown to trigger a landslide (**LA**), (ii) (overlying matrix) the landslide (**LA**) then triggers a flood (**FL**), then the flood (**FL**) could subsequently trigger or increase the probability of ground collapse (**GC**). Such networks of hazard interactions (cascades) are potentially widespread, with variation in terms of spatial and temporal influence, frequency and impact.

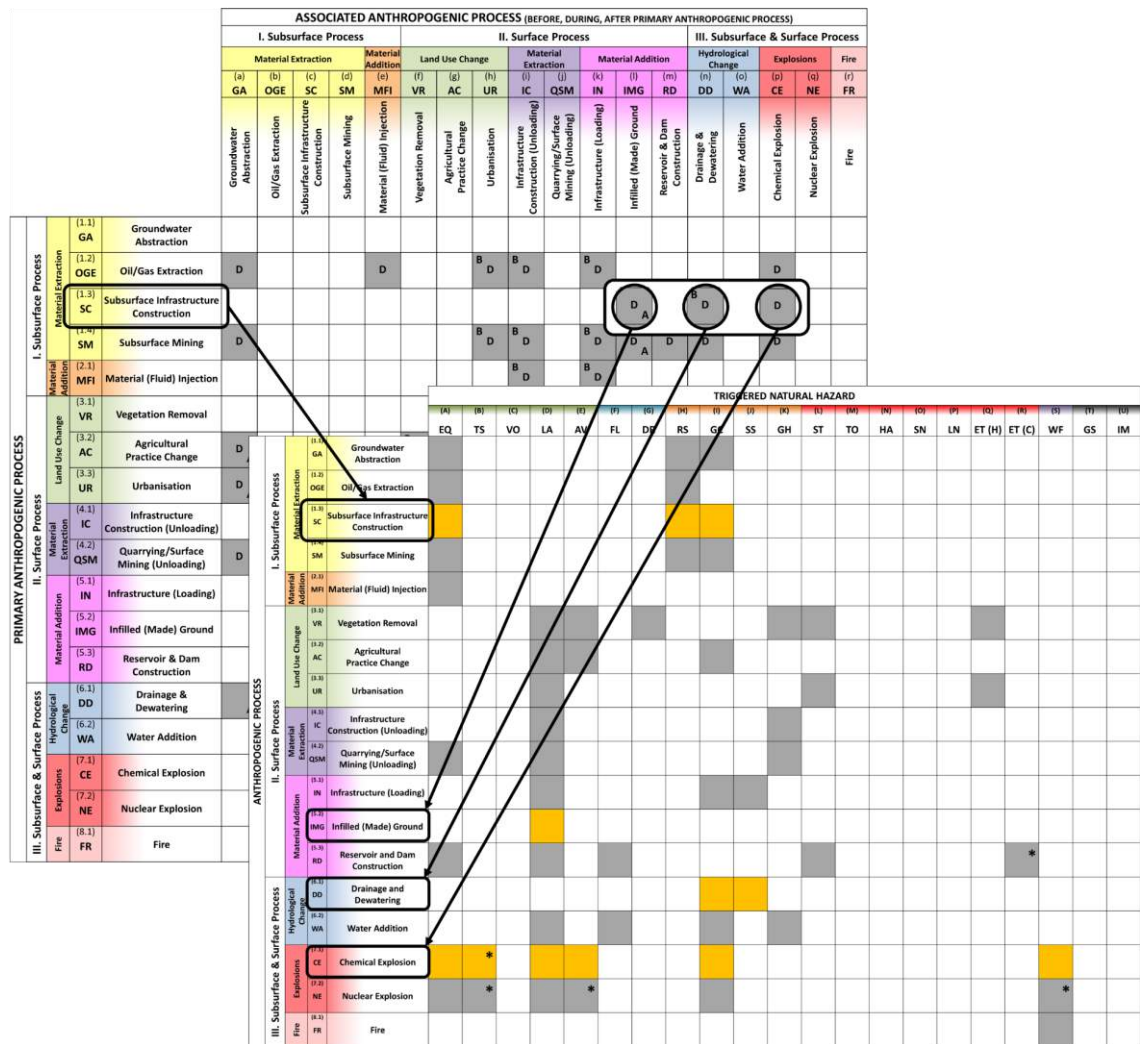


**Figure 4.8.** Initiation of network of interactions (cascade) visualised by combining Figures 4.5 and 2.2. A figure combining the 18 × 21 interaction matrix of anthropogenic process types triggering natural hazards (Figure 4.5) with the 21 × 21 interaction matrix of natural hazards triggering natural hazards (Figure 2.2). Full details of each interaction matrix can be found in the respective figures. An example of a network of interactions (cascade) is visualised. In this example, vegetation removal (VR) is shown to trigger a landslide (LA), which then triggers a flood (FL), which then triggers ground collapse (GC).

In a further example, **Figure 4.9** combines the  $18 \times 18$  interaction matrix of *anthropogenic interactions* (**Figure 4.1**) with the  $18 \times 21$  interaction matrix of *anthropogenic process types triggering natural hazards* (**Figure 4.5**) to demonstrate how the identification of ensembles of different anthropogenic processes can be used to consider the triggering of natural hazards. In this example:

- i. (underlying matrix) A *primary* anthropogenic process type, subsurface infrastructure construction (**SC**), is noted to trigger three *associated secondary* anthropogenic process types: infilled (made) ground (**IMG**), drainage and dewatering (**DD**) and chemical explosions (**CE**).
- ii. (overlying matrix) The one *primary* and three *associated secondary* anthropogenic process types could individually trigger one or more natural hazards, with **Figure 4.9** suggesting potential triggering mechanisms exist for eight different natural hazard types (earthquakes, tsunamis, landslides, snow avalanches, regional subsidence, ground collapse, soil subsidence, wildfires).

While it is unlikely that process-specific and location-specific factors would align so as to trigger all eight natural hazards, it is possible that the ensemble of anthropogenic process types could trigger one or more of these natural hazards. It is also possible that the original *primary* and each of the three *associated* anthropogenic process types could trigger further anthropogenic process types, which could in turn trigger other natural hazards. We observe in **Figure 4.9**, for example, that three of the four anthropogenic process types could independently trigger ground collapse (**GC**). The concurrent or simultaneous occurrence of these three anthropogenic processes could result in greater susceptibility to ground collapse.



**Figure 4.9. Triggering of natural hazards by an ensemble of anthropogenic processes, visualised by combining Figures 4.1 and 4.5.** A figure combining the  $18 \times 18$  interaction matrix of anthropogenic process type interactions, with interactions indicated using grey cell shading (Figure 4.1) with the  $18 \times 21$  interaction matrix of anthropogenic process types triggering natural hazards, with interactions indicated using grey and orange cell shading (Figure 4.5). Full details of each interaction matrix can be found in the respective figures. (i) (underlying matrix) An example of a *primary* anthropogenic process, subsurface infrastructure construction (SC), that may trigger three *associated secondary* anthropogenic processes (shaded in grey and circled): infilled (made) ground (IMG), drainage and dewatering (DD) and chemical explosions (CE). (ii) (overlying matrix) Together this ensemble of four anthropogenic processes could trigger up to eight different natural hazards (shaded in orange): earthquakes (EQ), tsunamis (TS), landslides (LA), avalanches (AV), regional subsidence (RS), ground collapse (GC), soil subsidence (SS) and wildfires (WF). Other anthropogenic process-natural hazard interactions are shown in grey. The natural hazards triggered in any given region will depend on many process-specific and location-specific factors. For example, the detonation of chemical explosives for blasting, used in subsurface infrastructure construction, is unlikely to be connected to the triggering of tsunamis.

Multi-hazard frameworks require the use of information from multiple, diverse disciplines (e.g., geology, meteorology, hydrology and engineering). Effectively visualising this information to enable the successful communication of complex, diverse information is challenging (Kappes *et al.*, 2012). Past studies have been made using descriptive narratives and classifications (e.g., Han

*et al.*, 2007), matrices (e.g., Tarvainen *et al.*, 2006; De Pippo *et al.*, 2008; Kappes *et al.*, 2010; Gill and Malamud, 2014) and event trees (e.g., Neri *et al.*, 2008; Neri *et al.*, 2013). In this study we use:

- i. *Interaction matrices.* The scalable interaction matrix framework synthesises and presents a large amount of information in an accessible manner. The matrices presented within this study (**Figures 4.1, 4.5, 4.7, 4.8**) can also be overlain as described previously (**Figures 4.9 and 4.10**).
- ii. *Network linkage diagrams.* This visualisation format (used in **Figure 4.2**), although not designed for rapid extraction of information, synthesises and communicates the diverse range of interactions in a visually striking manner to reinforce the importance of considering interactions.

Both types of visualisation draw upon examples of good practice guidelines for effective visualisations (e.g., Bostrom *et al.*, 2008; Telea, 2014). These include the careful consideration of factors such as figure type, structure and colours. It is anticipated that the visualisations developed within this study offer relevant information to a variety of end users, including those working on hazard assessment, DRR, and disaster management. The use of interaction matrix visualisations, for example, allows rapid access to information and easy modification or scaling if they are to be applied in specific regions. Interaction matrices also facilitate the addition of further information (e.g., additional anthropogenic processes, shading to indicate likelihood) should it be necessary.

### **4.5.3 Multi-Hazard Frameworks for Disaster Risk Reduction (DRR)**

Principal user communities for the visualisations derived within this chapter include disaster management and DRR practitioners and policy makers. Together with others, such as spatial and urban planners and the engineering sector, they help contribute to sustainable and resilient cities and communities. Within the targets for Goal 11 (*sustainable cities and communities*) of the United Nations' Sustainable Development Goals, is a call for a substantial increase in the "number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, [and] resilience to disasters" (United Nations, 2015). Goal 11 proceeds to encourage the development and implementation of "holistic disaster risk management" (United Nations, 2015) as described within the Sendai Framework for DRR 2015–2030 (UNISDR, 2015a). We suggest that the different types of interaction matrix visualisations that we have developed (**Figures 4.1, 4.5, 4.7,**

4.8, 4.9 and 4.10) can help to support the development of integrated policies towards DRR and holistic disaster risk management:

- i. *Anthropogenic process interactions (Figure 4.1)*. Here we identified 64 interactions between 18 anthropogenic processes, with 9 of 18 (50%) of anthropogenic process types having the potential to trigger three or more *associated secondary* anthropogenic process types. The concurrent or successive occurrence of multiple anthropogenic process types, discussed in [Section 4.2.5](#), may have an influence on the triggering of natural hazards through either (a) multiple natural hazards being triggered concurrently or sequentially, or (b) a given natural hazard type being exacerbated by two or more anthropogenic process types occurring concurrently. Through visualising interactions between anthropogenic process types, user communities will potentially be able to rapidly assess how different anthropogenic process types may group together, for use in holistic disaster risk management ([Figure 4.9](#)).
- ii. *Anthropogenic process–natural hazard triggering interaction relationships (Figure 4.5)*. Here we identified 57 cases whereby an anthropogenic process type may trigger a natural hazard. We believe that the potential triggering of natural hazards by anthropogenic processes is an important consideration for managing and reducing disaster risk. In [Figure 4.5](#) we synthesise a large amount of complex information from across multiple natural science and engineering disciplines to facilitate an effective analysis by user communities.
- iii. *Catalysing/impedance of natural hazard interactions (Figure 4.7)*. Anthropogenic process types can influence natural hazard interactions in addition to triggering individual natural hazard types. Therefore, we suggest that integrated policies to support DRR should consider how anthropogenic process types can influence natural hazard interactions. In [Figure 4.7](#) we use the example of vegetation removal, to demonstrate a replicable methodology for the coarse-scale analysis of such influences.
- iv. *Integration of anthropogenic processes and natural hazards interaction matrices (Figures 4.9 and 4.10)*. In [Figures 4.9](#) and [4.10](#) we use combinations of [Figures 4.1](#), [4.5](#) and [4.7](#) to better characterise and visualise networks of hazard interactions (cascades). The first example ([Figure 4.8](#)) used [Figures 4.5](#) and [4.7](#) to show how an anthropogenic process type can initiate a network of interacting hazards (cascades). The second example ([Figure 4.9](#)) used [Figures 4.1](#) and [4.5](#) to show how an ensemble of concurrent anthropogenic processes could trigger multiple natural hazards. Bringing the

visualisations together in this way allows for possible spatially and temporally relevant interactions to be identified and integrated into policy and planning.

We suggest that the visualisations and descriptions within this study can be used alongside existing multi-hazard tools and methodologies (e.g., Tarvainen *et al.*, 2006; De Pippo *et al.*, 2008; Kappes *et al.*, 2010; Kappes *et al.*, 2012; Neri *et al.*, 2013; Marzocchi *et al.*, 2012; Gill and Malamud, 2014; Liu *et al.*, 2016; Gallina *et al.*, 2016; Gill and Malamud, 2016) to support a more holistic and informed approach to DRR and disaster risk management.

## 4.6 Conclusions

In this study we have characterised anthropogenic processes and presented a detailed overview of their ability to trigger natural hazards and influence natural hazard interactions. This study has developed a three-level classification of 18 anthropogenic processes, and identified 64 interactions between these anthropogenic processes. We used more than 120 references ([Appendix B](#)) to identify 57 triggering relationships between the 18 anthropogenic process types and 21 diverse natural hazards included within this study. For these *anthropogenic process-natural hazard* triggering interaction relationships, example case study was identified for 91% of these relationships, with the other 9% of relationships being conjectured through an examination of possible physical mechanisms. We have also described and characterised relationships where anthropogenic processes influence natural hazard interactions through both catalysis and/or impedance mechanisms. An example showing the role of vegetation removal in catalysing and impeding 46 (out of a possible 90) natural hazard interactions was presented, demonstrating a possible framework for analyses of further anthropogenic processes.

The characterisations and visualisation interaction frameworks presented throughout [Sections 4.2](#) to [4.5](#) do the following:

- i. Supports the development of holistic multi-hazard methodologies, integrating information about anthropogenic processes to allow for more comprehensive interaction frameworks to be constructed and therefore more comprehensive analysis of natural hazards.
- ii. Simplifies a diverse array of cross-sectoral information to facilitate an effective analysis of possible interactions by those working on integrated disaster risk management, within both policy and practitioner communities.

**Part II: Adapting and  
Applying Global Interaction  
Frameworks for Use in  
Regional Settings  
(Guatemala)**

# Chapter 5. From Global to Regional Perspectives on Natural Hazard Interactions: Challenges and Opportunities

## Summary

This chapter identifies, characterises and makes suggestions as to how to address the principal challenges of adapting global natural hazard interaction frameworks for use in regional settings. These aims are addressed through (i) a synthesis of existing regional applications of interaction frameworks (or *regional interaction frameworks*) to identify possible challenges in this process, and (ii) a set of 19 semi-structured interviews and a 3-hour workshop with hazard and civil protection professionals operating in the multi-hazard environment of Guatemala. The adaptation of global interaction frameworks for regional settings is a helpful step in the development of comprehensive multi-hazard methodologies to support disaster risk reduction (DRR) and management. In the context of this thesis, a *regional interaction framework* is defined to be a usable visualisation that aids the identification and characterisation of relevant interactions in a given, defined region, such as a national or sub-national scale. This chapter first provides a comparative synthesis of seven existing regional interaction frameworks. From this comparative synthesis, seven challenges are identified that we believe should be considered when adapting global interaction frameworks to regional settings: (i) spatial extent, (ii) temporal extent, (iii) likelihood-magnitude relationships, (iv) selection and classifications of hazards and processes, (v) stakeholder perceptions and consensus on hazard interactions, (vi) language and visual style, and (vii) limitations and uncertainties. These challenges are examined in turn, using evidence from both literature and perspectives from hazard professionals operating in the multi-hazard environment of Guatemala. The latter is done through 19 semi-structured interviews and one workshop with 16 participants. General considerations to support the development of regional interaction frameworks are proposed, aiming to facilitate the construction of clear, comprehensive and systematic frameworks that can be used in applied contexts.

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# Chapter 6. Regional Perspectives on Natural Hazard Interaction Frameworks (Application to Guatemala)

## Summary

Here we develop regional interaction frameworks for both national and sub-national (Southern Highlands) spatial extents in Guatemala. Frameworks are organised and populated using five principal sources of evidence: (i) Internationally-accessible literature (total of 93 peer-review and 76 grey literature); (ii) Civil protection bulletins (267 bulletins from 11 June 2010 to 15 October 2010); (iii) Field observations (eight locations, with four examples discussed in the text); (iv) Stakeholder interviews (19 semi-structured interviews conducted from 28 February 2014 to 14 March 2014); (v) Stakeholder workshop results (16 participants, 06 March 2014). In the latter two, stakeholders consisted of hazard and civil protection professionals. These five sources of evidence were synthesised to determine an appropriate classification scheme for relevant natural hazards in Guatemala. This classification includes 6 hazard groups, 19 natural hazard types, and 37 natural hazard sub-types. For a national spatial extent in Guatemala, we proceed to construct and populate a 21×21 hazard interaction matrix, identifying 49 possible interactions between 21 (19 of which are relevant in Guatemala) natural hazard types. For a sub-national spatial extent (Southern Highlands of Guatemala), we construct and populate a 33×33 hazard interaction matrix, identifying 112 possible interactions between 33 natural hazard sub-types. This information is presented in a series of accessible hazard interaction visualisations. Evidence sources are also used to explore possible networks of hazard interactions and anthropogenic processes. Interactions identified in the 21×21 hazard interaction matrix (national extent) are contrasted with interactions identified by workshop participants. We use *Matthews' Correlation Coefficient (MCC)* to compare agreement between (i) individuals and the national interaction framework, and (ii) the group collective knowledge and the national interaction framework. While both suggest a need for further consideration of natural hazard interactions, the collective knowledge of the group is suggested by *MCC* values to show better agreement with the national interaction framework than any one individual. In this chapter, we develop a systematic assessment of possible natural hazards and natural hazard interactions, integrating five different sources of internationally and locally-accessible evidence to support the better understanding of natural hazard interactions in the multi-hazard environment of Guatemala.

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# Chapter 7. Summary, Conclusions and Future Research Directions

## 7.1 Introduction

In this final chapter we consider the results and conclusions of **Chapters 2 to 6** in the context of our original research questions (**Section 1.3**). We begin with an abbreviated summary of Parts I (global) and II (regional) of this thesis. Detailed **Chapters 2 to 6** summaries have already been provided at each chapter's start.

*Part I (Chapters 2 to 4):* These three chapters developed the following: *global interaction frameworks*, characterising interactions associated with 21 natural hazards and 18 anthropogenic processes; a series of visualisation frameworks to synthesise and communicate this information. Our global interaction frameworks were discussed in the context of multi-hazard methodologies, helping to develop 'cross-hazard approaches' to understand the 'hazardousness' of a given location (Hewitt and Burton, 1971).

*Part II (Chapters 5 and 6):* These two chapters adapted the global interaction frameworks, developed in previous chapters, for use in *regional (multi-national, national, and sub-national) settings*. Regional interaction frameworks are defined as usable visualisations that aid the identification and characterisation of relevant interactions in a given, defined regional setting. Such frameworks are an important step in the development of comprehensive and applied multi-hazard methodologies to support disaster risk reduction and management. These two chapters included (i) identifying and discussing principal challenges associated with developing regional interaction frameworks, (ii) constructing and populating examples of regional interaction frameworks for Guatemala, and (iii) contrasting hazard interaction networks developed from data and understandings, thus populating contrasting knowledge worlds.

The remainder of this chapter is organised as follows: **Section 7.2** refers to our original research questions (which cut across chapters), synthesising the conclusions of **Chapters 2 to 6** to discuss each question in turn. **Section 7.3** discusses examples of current research and knowledge transfer impact, potential use of this research in the future, the identification of interacting hazards and their integration into multi-hazard assessments, and three additional multi-hazard research gaps. **Section 7.4** provides some short concluding remarks.

## 7.2 Relationship of Thesis to Original Research Questions

In [Chapter 1](#) we set out the aim of this thesis' research: "to increase the understanding and characterisation of natural hazard interactions and interaction networks at both global and regional (multi-national to sub-national, depending on context) scales". In addressing this research aim, we identified two objectives:

- O1. [Global scale]** To undertake a comprehensive review, and develop broad based classifications, of interactions across a diverse range of hazard and process types.
- O2. [Regional Scales]** To adapt the global interactions frameworks (developed in objective 'O1') for use in regional settings (Guatemala); exploring, quantifying and contrasting hazard interaction networks developed from data and understandings populating contrasting knowledge worlds (specifically, the international scientific literature, and hazard/civil protection professionals operating in the region).

These two objectives were addressed through five research questions (**Q1 to Q5**), cutting across [Chapters 2 to 6](#) of this thesis.

Here we synthesise conclusions from across [Chapters 2 to 6](#) to address each research question in turn. Given the use of figures to synthesise information through this thesis, we also note examples of key figures relating to the research questions. Limitations were extensively discussed in the context of each chapter. Rather than repeating these here, we note that our conclusions are affected by research limitations and sources of uncertainty, and refer the reader back to appropriate sections of each chapter. We now address **Q1 to Q5**:

- Q1. What broad types of interaction can be identified in the literature, and how do these interactions join together to form networks of hazard interactions (cascades)?**

We addressed **Q1** through [Chapters 2 to 4](#). [Chapter 2](#) identifies four ways natural hazards can interact with other natural hazards:

- (i) *triggering* relationships
- (ii) *increased probability* relationships
- (iii) *decreased probability* relationship
- (iv) *spatial-temporal coincidence* of natural hazards

Examples were given of each interaction type, with *triggered* and *increased probability* relationships explored in depth through a series of hazard interaction matrices. [Chapter 3](#) explores additional interaction types, introducing the importance of anthropogenic processes and

technological hazards. **Figure 3.2** illustrated nine different triggering relationships between natural hazards, anthropogenic processes and technological hazards. *Catalysing and impedance* interaction types were also identified, whereby one hazard/process catalyses or impedes a triggering relationship between two hazards/processes. In **Figure 3.3** we illustrated 12 possible catalysis/impedance interaction types, in addition to the previously mentioned nine triggering interaction types. The prevalence of triggering and catalysis interactions types involving anthropogenic processes was demonstrated in **Chapter 4**, with many examples from the literature. **Chapters 2 to 4** also address Q1 by illustrating networks of interactions (cascades). These networks can be single or multi-branched, involve one type of hazard/process (e.g., just natural hazards) or multiple hazard/process types (e.g., natural hazards and anthropogenic processes).

**Q2. What examples of a hazard/process triggering a natural hazard can be identified in the literature?**

**Example sub-questions included:**

- a. **What examples exist of natural hazards triggering other natural hazards, and can these interactions be further characterised, in terms of (i) relative forecasting ability, (ii) relative likelihood, and (iii) simplified relationships to model the relationship between the intensity of primary and secondary hazards?**
- b. **What examples exist of anthropogenic processes and technological hazards triggering natural hazards?**

We addressed **Q2** (and associated sub-questions) in **Chapter 2** (natural hazards) and **Chapter 4** (anthropogenic processes), with additional discussion and examples in **Chapter 3**.

[**Q2a**] **Chapter 2** used more than 200 peer-review and grey references to identify 90 examples of interactions between 21 diverse natural hazards. These interactions consisted of a primary natural hazard triggering and/or increasing the probability of a secondary natural hazard (**Figure 2.2**). *Natural hazard-natural hazard* interactions were characterised in **Chapter 2** in terms of their (i) relative forecasting ability (**Figure 2.6**), (ii) relative likelihood (**Figure 2.7**), and (iii) simplified relationships modelling the relationship between the intensity of primary and secondary hazards (**Figures 2.11** and **2.12**).

[**Q2b**] **Chapter 4** used more than 120 peer-review and grey references to identify 57 examples of anthropogenic processes triggering natural hazards (**Figure 4.5**), when considering 18 anthropogenic processes and 21 natural hazards. Using these 18 anthropogenic processes, this chapter also identified 64 examples of anthropogenic processes triggering (or influencing the

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occurrence of) associated anthropogenic processes (**Figure 4.1**). These 64 *anthropogenic process-anthropogenic process* interactions were characterised, based on whether the associated anthropogenic process occurs before, during and/or after the primary anthropogenic process.

**Q3. What visualisations can be developed to better understand and communicate these interactions and networks of hazard interactions (cascades)?**

We addressed Q3 throughout **Chapters 2 to 6**, developing a series of accessible visualisations to synthesise and communicate large amounts of diverse information from many scientific disciplines. Examples include:

- i. *Hazard interaction matrices*. Matrices were developed in **Chapters 2, 4 and 6** to synthesise large amounts of diverse evidence (e.g., **Figures 2.2, 2.6, 4.5, 6.10**). *Hazard interaction matrices* were discussed with hazard and civil protection professionals in Guatemala, with feedback recorded in **Chapter 5** and used to shape hazard interaction matrices development in **Chapter 6**. Matrices were used to represent networks of interactions in **Chapters 2, 3, 4 and 6** (e.g., **Figures 2.3, 3.5, 4.8, 6.13**).
- ii. *Network linkage diagrams*. **Chapter 2** introduced a hazard network linkage diagram for 21 natural hazards (**Figure 2.4**). This visualisation style was also used in **Chapter 4**, to visualise interactions between 18 anthropogenic process types (**Figure 4.2**). This visualisation style is less accessible in terms of extracting specific interaction information, but it effectively demonstrates a wide diversity of interactions. It challenges the assumption of independence of hazards, supporting multi-hazard methodologies that seek to integrate hazard interactions. This visualisation style was also used in **Chapter 5** to elicit information from stakeholders on relevant natural hazard interactions in Guatemala (**Figure 5.5**). This approach not only generates data, but also facilitates discussion by stakeholders on relevant interactions.
- iii. *Hazard/process flow diagrams*. This visualisation style was used in **Chapter 3** to help visualise and communicate interactions between multiple hazard and process types (e.g., **Figures 3.2, 3.3**). Hazard/process flow diagrams can also be used to show networks of interactions (cascades), connecting multiple triggering and catalysing interactions to show a single or multi-branch chain of interactions (e.g., **Figures 3.6, 3.7**).

These visualisations have been developed with careful consideration to visual style and language, in order to communicate important aspects of hazard interactions. The visualisation styles set out above can help to facilitate an effective analysis by those working on reducing and managing disaster risk within both policy and practitioner communities.

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**Q4. At a national spatial extent, and for one sub-national spatial extent in Guatemala, what potential hazard interactions can be identified, and how can we characterise them?**

**Example sub-questions include:**

- a. **What are the principal challenges in constructing regional interaction frameworks and populating them with interaction information?**
- b. **What methods exist to address these challenges, or communicate the uncertainties associated with them in the regional interaction framework?**
- c. **What interactions are relevant in different regions of Guatemala?**
- d. **How do interactions documented in the literature contrast with the knowledge of hazard/civil protection professionals operating in the region?**

We addressed **Q4** (and associated sub-questions) in **Chapters 5** and **6**, which focused on the adaptation of global interaction frameworks for use in regional settings.

**[Q4a, 4b]** **Chapter 5** identified *seven principal challenges* in constructing regional interaction frameworks, through a comparative synthesis of seven existing regional interaction frameworks. Challenges identified and discussed were:

- (i) spatial extent (including resolution),
- (ii) temporal extent (including resolution),
- (iii) likelihood-magnitude relationships,
- (iv) selection and classifications of hazards and processes,
- (v) stakeholder perceptions and consensus on hazard interactions,
- (vi) language and visual style,
- (vii) limitations and uncertainties.

Ways to address these seven challenges were discussed in **Chapter 5**, using both literature and engagement with hazard and civil protection stakeholders in Guatemala. We recognised in **Chapter 5** the difficulty in addressing all seven of these challenges in a comprehensive manner in any one regional interaction framework.

**[Q4c]** **Chapter 6** used a multi-method approach, drawing on five evidence sources (literature, civil protection bulletins, field observations, stakeholder interviews, stakeholder workshop), to characterise relevant hazard interactions in the following spatial extents:

- i. National spatial extent of Guatemala (49 possible interactions between 19 natural hazard types, **Figure 6.10**).

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- ii. Sub-national spatial extent of the Southern Highlands of Guatemala (112 possible interactions between 33 natural hazard sub types, **Figure 6.12**).

The evidence sources described above were also used to identify 17 anthropogenic processes relevant in Guatemala, each of which could trigger a range of natural hazards or catalyse natural hazard interactions as outlined in **Chapter 4**.

[Q4d] This sub-question was addressed using the results of a workshop with 16 hazard and civil protection professionals in Guatemala, the methodology and results of which were outlined in **Chapters 5 and 6**. These workshop results were contrasted with the national hazard interaction matrix (**Chapter 6, Figure 6.10**), compiled using five evidence sources (literature, civil protection bulletins, field observations, stakeholder interviews, stakeholder workshop). This comparison was quantified in **Chapter 6** using Matthews' Correlation Coefficient (*MCC*), with  $MCC = -1.0$  a 'zero' overlap in congruence and  $MCC = +1.0$  'perfect' overlap. For the 16 individual participants we found  $0.21 \leq MCC \leq 0.45$ , and for the collective knowledge of participants (using the national hazard interaction matrix in **Chapter 6, Figure 6.10**), those interactions identified by  $\geq 3$  workshop participants gave  $MCC = 0.51$ . In this context we recognised that for this knowledge to be truly collective, there needs to be the institutional and informal mechanisms to promote the communication required for this knowledge to be accessed in its collective form.

**Q5. What are the implications of our global and regional interaction frameworks for multi-hazard methodologies to support DRR, management, and response?**

We addressed Q5 through **Chapters 2 to 6**, connecting each chapter's conclusions to the broader context of multi-hazard methodologies to support DRR, management, and response. **Chapters 2 and 3** discussed different interpretations of 'multi-hazard', falling on a spectrum from those that examine 'more than one hazard' (hazards treated independently) to the integration of interactions between hazards (dependence recognised). The implications of excluding interactions are discussed, including the distorting of management priorities. **Chapters 2 to 4** demonstrated the prevalence of natural hazard interactions on a global scale, and in **Chapter 6** the prevalence of natural hazard interactions in Guatemala. In characterising these diverse interactions in a more systematic and comprehensive way than previously done, we have helped to reinforce the importance of multi-hazard approaches integrating natural hazard interactions. **Chapters 2 to 4** describe how our global interaction frameworks, and the ability to map out possible networks of hazard interactions (cascades) can help (i) better model the observed reality of disaster events, (ii) constrain potential changes in physical and social vulnerability between successive hazards, and (iii) prioritise resource allocation for mitigation and DRR.

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The development of global interaction frameworks (e.g., [Figures 2.2, 4.8](#)), and the use of effective visualisations to synthesise data, seeks to support end users in diverse geographic regions. The development of regional interaction frameworks (e.g., [Figures 6.10, 6.12](#)) demonstrates a multi-method comprehensive approach to systematically characterise relevant interactions in a defined spatial extent. The design and population of regional interaction frameworks was informed by stakeholder consultation, and it is hoped that the resulting frameworks can support hazard and civil protection professionals to consider hazard interactions. A method was also developed ([Chapters 5 and 6](#)) which contrasts final regional interaction frameworks with the individual and collective knowledge of participants. This method is designed to help evaluate whether the introduction of regional interaction frameworks into hazard monitoring and management institutions helps to strengthen individual and collective understanding of hazard interactions.

### **Q1-5. General Comments**

Together our responses to **Q1–Q5** have addressed the broader aim of this research, to increase the understanding and characterisation of natural hazard interactions and interaction networks at both global and regional (multi-national to sub-national, depending on context) scales. In doing this we have also contributed to the development and improvement of multi-hazard approaches to assess hazard potential.

## **7.3 Research and Knowledge Transfer Impact**

In this section we describe examples of ways in which information in this thesis has already been used by others ([Section 7.3.1](#)), ways in which the research may be used in the future ([Section 7.3.2](#)), the identification of hazard interactions and their integration into multi-hazard assessments as a research gap ([Section 7.3.3](#)), and three additional research gaps ([Section 7.3.4](#)).

### **7.3.1 Examples of Current Research and Knowledge Transfer Impact**

Two peer-review journal articles have been published on this research ([Chapter 2](#) in *Reviews of Geophysics* 2014; [Chapter 3](#) in *Earth System Dynamics* 2016). Here we briefly discuss how these publications have been used in knowledge transfer (teaching) and influenced other research and policy publications. We also note opportunities, that this work has generated, to introduce this work into research and operational settings.

**Knowledge Transfer.** Through discussions at international conferences, we are aware of the publication from [Chapter 2](#) currently being used in undergraduate and/or postgraduate teaching

in the UK, Romania and China. An invited seminar was given based on [Chapter 2](#) (and its relevance to Guatemala), to a Masters course in Risk Management hosted by CONRED in Guatemala.

**Research and policy publications.** Research articles citing publications from this thesis include those building more quantitative multi-hazard and multi-risk assessments (e.g., Mignan *et al.*, 2014; Liu *et al.*, 2015; Liu *et al.*, 2016; Mignan *et al.*, 2016), and those with a particular focus on a type of natural hazard or environmental process (e.g., Jacobs *et al.*, 2015, landslides; Eppelbaum and Isakov, 2015, tornadoes and hurricanes; Forzieri *et al.*, 2016, climate change; Billi *et al.*, 2016; sinkholes and karst). The publications resulting from this thesis are also helping to shape policy debates and discussion in the natural hazards community. For example, Aitsi-Selmi *et al.* (2016, pp. 8, 11) write about a science and technology agenda to support DRR in the 21<sup>st</sup> Century, and include the following comments regarding our publications:

*“However, disaster risk is increasingly understood to be complex and multifaceted (involving hazard, exposure, vulnerability, and capacity), with interdependencies that may be overlooked and cause cascading effects over time and space (Gill and Malamud 2014, 2016).” [Chapters 2 and 3]*

*“Methods are largely confined to a single hazard, with little or no ability to aggregate risks from different threats/hazards. A multi-hazard approach will require data and methods to assess, model, and plan for both multiple hazards in the same location and cascading hazards across all disciplines (Gill and Malamud 2014)” [Chapter 2]*

Aitsi-Selmi *et al.* (2016) reflect on outcomes and discussions at a meeting of scientists involved in DRR, facilitated by UNISDR who are mandated with overseeing implementation, monitoring and evaluation of the Sendai Framework for DRR (UNISDR, 2015a).

**Workshops.** In February 2013 we co-organised a workshop at University College London on the *dynamics and impact of interacting natural hazards*. This was attended by 16 people from 9 organisations, including academia, the public sector (e.g., British Geological Survey, British Antarctic Survey) and private sector. Then, in 2015 we delivered a workshop on hazard interactions at the British Geological Survey, for the UK Natural Hazards Partnership’s Hazard Impact Modelling Group. This workshop used the exercises outlined in [Chapter 5](#) to encourage participants from six organisations to consider relevant interactions in the United Kingdom. Participants said that the workshop was very relevant and interesting, and that the exercise identifying linked and triggered hazards had captured their imagination. In 2015 we were also invited to present work based on [Chapters 2](#) and [5](#) to the ‘*Increasing Resilience to Natural Hazards in Earthquake-prone and Volcanic Regions*’ consortium (NERC, 2016).

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### 7.3.2 Potential Use of this Research in the Future

In this section, we discuss ways in which the results and conclusions of **Chapters 2 to 6** could be used for future research impact. The research presented through **Chapters 2 to 6** has shown early evidence of impact, as outlined in **Section 7.3.1**. It also has potential impact in the future, with thesis material being used and developed to support natural hazards research, disaster risk reduction, and disaster risk management. Here we propose three examples of ways in which this research could be used by others.

*[Research Use 1] Transitioning from single to multi-hazard approaches.* Visualisations developed in this thesis help to place single hazard research into the context of a dynamic, multi-hazard environment. As hazard interactions often involve more than one system (e.g., atmosphere, lithosphere, hydrosphere), it is helpful for the scientific community to visualise and understand these interactions. We believe the global interaction frameworks in **Chapters 2 to 4** could help to foster improved communication between researchers in different hazard communities, and encourage a more interdisciplinary approach.

*[Research Use 2] Rapid response applications.* **Chapter 2** noted how global interaction frameworks could be transposed 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 or application that relates our visualisations to other information and data (key references, equations, case studies, empirical relationships). Such a tool would allow interested academic, policy and practitioner communities to rapidly access relevant information that helps them to better understand possible hazard interaction in the event of a major natural hazard, or when planning mitigation strategies. Regional versions of this application could be run in an open ‘wiki’ style format, where expert communities can edit and update information relating to their field of expertise. In the context of anthropogenic processes (**Chapter 4**), transposing this information into a publicly-accessible application may help decision making by groups such as spatial planners.

*[Research Use 3] Disaster risk reduction and management in Guatemala.* The introduction of the regional interaction frameworks developed in **Chapter 6** into an operational setting in Guatemala could help to strengthen disaster risk reduction and management. In the interviews described in **Chapter 5**, participants commented that regional interaction frameworks for Guatemala would be beneficial. Participant C4 (CONRED) stated that ‘*it is the dream of Guatemala to have visualisations like these*’. In **Table 5.8** we summarised the range of user groups in Guatemala identified by interview and workshop participants that could use this information. These included: risk managers, educators, economists, planners, development

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practitioners, academics, agricultural practitioners, hazard scientists, civil protection communities, local authorities and insurance. Working to introduce our regional interaction frameworks into operational settings such as CONRED and INSIVUMEH could help to support disaster risk reduction and management. As noted by Participant C2 (CONRED) interaction frameworks ‘*could be used by CONRED to help them understand this information. [and] CONRED can then take responsibility for putting them into a form suitable for communities*’.

### 7.3.3 Identifying Interacting Hazards and Integrating them into a Multi-Hazard Assessment (Research Gap)

One of the most pressing research gaps related to hazard interactions, which we outline here, is the improved integration of hazard interaction frameworks into multi-hazard assessments. Here we briefly describe a potential set of steps to develop interaction frameworks and integrate them into multi-hazard assessments. We refer to relevant sections of this thesis, and highlight gaps in research or methodologies that currently hinder this integration. We also offer some reflections on these gaps, noting why it would be particularly beneficial to address these to support disaster risk reduction and management.

One potential set of broad steps to identify hazard interactions, and then effectively integrate them into multi-hazard assessments, is as follows:

- 1. Identification and Characterisation of Single Hazards.** An analysis of what single hazards could occur in a given region can be done using the following: (a) theoretical understanding of hazard characteristics and environments in which they may occur; (b) evidence of past examples in this region; and (c) evidence of past examples in regions with similar natural environmental features and dynamics (e.g., similar topography, geology, tectonics). Existing methodologies exist which characterise each single hazard in terms of likelihood and or potential intensity over any given time-scale.
- 2. Identification of Hazard Interactions.** Given information about relevant single hazards in a given region, possible interactions between these can be identified. This can be done by using the following: (a) examples of interactions in this region, using diverse evidence sources (internationally- and locally-accessible) such as instrumental records, archival records, stakeholder interviews and field visits (we demonstrate this methodology in [Chapter 6](#) for national and sub-national scales in Guatemala); (b) examples of interactions in other regions with similar natural environmental features and dynamics can also be examined (e.g., a network of interacting hazards in El-Salvador may provide evidence of interacting hazards useful in Guatemala); (c) theoretical frameworks that

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outline possible interacting hazards, such as the global interaction frameworks presented in **Chapters 2** and **4** of this thesis. The output at this stage, regional interaction frameworks such as those presented in **Figures 6.10** and **6.12**, could help raise awareness of multi-hazard interactions, and support users in determining possible interactions.

**3. Characterisation of Hazard Interactions.** Hazard interactions can occur on different timescales, and have different intensities. Characterisation of interactions, in terms of likelihood and intensity, is therefore important additional information required to integrate interaction frameworks into multi-hazard assessments. Characterisation can be done at progressively increasing degrees of complexity (with examples given):

- a. [*Single vs. Population*] The Guatemalan national (**Figure 6.10**) and sub-national (**Figure 6.12**) interaction frameworks give an initial characterisation by distinguishing between the nature of secondary hazards. Those with the potential to have multiple occurrences (a large population) from one single triggering hazards are distinguished from those where there is a single occurrence of the secondary hazard.
- b. [*Spatial Overlap-Temporal Likelihood*] Interactions can be characterised in terms of their *spatial overlap-temporal likelihood* of interaction. This was done in **Section 2.5.2** for the global interaction framework. A similar analysis would be useful for the regional interaction frameworks in **Sections 6.5.3a** and **6.5.3b**.
- c. [*Quantitative Characterisation of Likelihood-Magnitude*] **Section 5.6** describes the addition of inclusion of information on likelihood-magnitude relationships within regional interaction frameworks. In **Section 5.6**, the data requirements to do this at a resolution greater than (a) and (b) above are described, and visualisation approaches such as that used in the UK National Risk Register (UK Cabinet Office, 2015) are outlined. This thesis does not quantitatively characterise each natural hazard interaction identified within Guatemala; however, the information on natural hazards included in **Appendix E** could help inform this characterisation. It is likely, however, that more data would need to be collected, or an expert elicitation approach (see **Section 5.8** where discussed) used. This additional quantitative characterisation of interactions would help improve the utility of this approach to those working in disaster risk reduction.
- d. [*Physical and Social Impact*] A further degree of complexity would be the addition of information on relative physical and social impact of each interaction. This requires additional data on location-specific physical and social vulnerability, an area which this thesis has not addressed, but of importance for analysing the relative impact of the identified interactions.

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Depending on the degree of complexity achieved, itself a function of data availability and the necessary resources to examine effectively that data, the output at this stage could help inform decision making about which interactions pose the greatest threat to a given region.

For further characterisation of interactions to be achieved, methods to represent spatial and temporal variability in interaction likelihood, intensity and physical/social impact would need to be considered. For example, the likelihood of a storm-triggered landslide could be low on some slopes and very high on other slopes. Information within this layer may therefore consist of a set of probability distributions for each interaction. It is also possible that the likelihood may change over time. For example, after an earthquake a slope may move from having a low likelihood of failure to a high likelihood of failure during a storm. The likelihood layer would therefore give a ‘snapshot’ of likelihood at a given time. The impact of an interaction may also vary spatially and temporally. For example, when considering impact in terms of the number of people affected, a storm-triggered-landslide will have different consequences depending on the landslide size, human exposure on the affected slope, and levels of physical and social vulnerability. If there are wide variations in likelihood, intensity and impact across a national or sub-national region, then generalisations (over space and time) may be of limited use. It would be more feasible to include this information for smaller case study regions, and more limited timeframes.

Together, the three broad steps outlined above would help to generate regional interaction frameworks that are comprehensive, evidenced, and of greatest use to those involved in disaster risk reduction and management. The information required to integrate hazard interactions frameworks into multi-hazard assessments will depend on the purpose of the assessment. Identification of possible hazard interactions helps to transition from single- to multi-hazard thinking, fostering improved communication between researchers in different hazard communities, and encouraging more interdisciplinary approaches. Characterisation of possible hazard interactions helps to improve decision making in DRR and civil protection agencies, by facilitating an understanding of which interactions are most likely to occur and which interactions could cause the greatest damage. These offer two different types of multi-hazard assessment, both of which could help to improve the consideration of natural hazard dynamics in a given region.

#### **7.3.4 Three Additional Multi-Hazard Research Gaps**

**Chapters 2 to 6** have also helped to identify other research gaps (in addition to the hazard integration research gap outlined in **Section 7.3.3**), where additional research could help to fully realise the impacts noted in **Section 7.3.2**. In this context, we briefly note three research gaps that

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would aid the development of more comprehensive multi-hazard approaches, and improve their integration into disaster risk reduction and management.

**(Research gap 1) *Technological hazards.*** Chapter 3 identified three groups of hazards and processes which may form part of a multi-hazard environment: natural hazards, anthropogenic processes and technological hazards/disasters. In this thesis, we have identified and characterised groups of interactions between natural hazards and anthropogenic processes. A similar systematic and classification of relationships involving natural hazards and technological hazards/disasters is currently a research gap which would provide a beneficial component for multi-hazard research.

**(Research gap 2) *Improved regional assessments.*** In this thesis, we have offered some general considerations for qualitative and semi-quantitative regional interaction frameworks (Chapter 5), and developed a systematic characterisation of hazard interactions in Guatemala (Chapter 6). The development of additional regional (multi-national, national and sub-national spatial extents) assessments of interactions, done in association with stakeholder communities, would help strengthen evidence on best practice for framework development in different geographic regions. Eventually, an atlas of interaction frameworks could be developed for different nations or continents.

**(Research gap 3) *Perception of multi-hazard environments and disasters.*** Chapters 5 and 6 have discussed an approach that contrasts stakeholder perceptions of natural hazard interactions with (i) other stakeholder perceptions of natural hazard interactions, and (ii) a national interaction matrix developed using multiple evidence sources. This workshop methodology could be developed and repeated in different locations to answer further research questions. Examples include:

- Does introducing a regional interaction framework into an organisation influence individual and collective understanding of interactions? How can this process of introducing a framework best help to promote cross-sectoral and cross-disciplinary discussion?
- To what extent does recognition of hazard interactions differ between different institutions, in different locations? Do organisations considering multiple hazards have a different perception of interactions to those organisations focused on one or a small number of hazards.

## 7.4 Concluding Remarks

Recent high profile multi-hazard disasters have given greater prominence to hazard and process interactions and networks of interactions (cascades). For example, following the 25 April 2015,  $M_w = 7.8$  Nepal earthquake and triggered hazards, the European Geosciences Union (EGU, 2015) issued a statement including the following paragraph:

*“This complicated hazard environment emphasises the pressing need for an integrated analysis and management of different natural hazards, since single-event analyses do not fully quantify the enhanced risk of these combined events. There is little agreement within the geoscience community on how earthquakes trigger a cascade of related events and how they should be modelled. A multidisciplinary study on the dynamics of the interaction between the different natural processes that produce risk situations is needed.”*

The work that we have presented in this thesis makes a contribution to the EGU’s requests. This thesis has built on existing multi-hazard and interaction literature to present syntheses of interactions greater in scope than previously existed. Our characterisations of natural hazards have included 21 natural hazard types, later expanded in Guatemala to 37 hazard sub-types. Our characterisations of anthropogenic processes have included 18 anthropogenic process types. The interaction frameworks that we have developed have the following characteristics:

- i. *Systematic and evidenced.* The hazard and process classifications used in this thesis’ global and regional interaction frameworks are developed in a systematic way. Interaction frameworks are populated with relevant interactions by critically examining evidence from diverse sources. Global interaction frameworks were constructed using large databases of peer-review and grey literature, and regional interaction frameworks brought together diverse strands of evidence, including stakeholder engagement.
- ii. *Integrated.* This thesis’ hazard frameworks support an integrated approach to the analysis and management of natural hazards. Global and regional frameworks have been developed by drawing on evidence sources from diverse disciplines including geology, hydrology, meteorology, engineering, and social science.
- iii. *Scalable.* This thesis’ hazard frameworks can be scaled and easily adapted to enable communities of practice in different geographic and disciplinary settings to understand and characterise relevant interactions. The number of variables (e.g., primary hazards/processes, secondary hazards/processes, interaction types) can be reduced or expanded to match the hazard environment of interest.

As noted in [Chapter 1](#), an *all-hazards-at-a-place* framework, encouraging a *cross-hazard approach* to understand the *hazardousness* of a given location, has been advocated for at least 45

years (Hewitt and Burton, 1971). Through this thesis we have built on existing progress towards the *cross-hazard* (or multi-hazard) approaches encouraged by Hewitt and Burton (1971), with the development of new systematic, comprehensive interaction frameworks at global and regional scales. The frameworks developed in this thesis cut across multiple scientific domains, unite diverse sources of evidence, and synthesise this using visualisation formats that promote a greater understanding and ability to characterise natural hazard interactions. When integrated into multi-hazard methodologies, interaction frameworks can contribute to an improved theoretical and practical understanding of hazards and disaster risk reduction.

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# APPENDICES

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# Appendix A. Natural Hazard Interactions

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<b>Table A.1.</b> Mechanisms, case studies and additional references for each hazard interaction identified in <b>Figure 2.2 (Chapter 2)</b> .....	362
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**Table A.1. Mechanisms, case studies and additional references for each hazard interaction identified in Figure 2.2 (Chapter 2).** Information is presented which describes the physical process by which each primary hazard triggers, or increases the probability, of secondary hazards. Where identified, relevant case studies are put forward for each hazard interaction, and additional references used to analyse and classify each hazard interaction are noted. Some of these references describe a process related to the interaction, and not the interaction itself (e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions).

PRIMARY HAZARD: EARTHQUAKE				
Secondary Hazard	Grid ID	Generic Mechanism Description	Example Case Study	Relevant Literature (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Earthquake	1A	A primary earthquake causes changes in lithospheric stresses, leading to aftershocks as the lithosphere responds to these changes.	<b>Tohoku, Japan, 2011</b> (Asano <i>et al.</i> , 2011)	Omori (1894); Gutenberg and Richter (1944); Utsu (1961); Bath (1965); Utsu (1995); Helmstetter and Sornette (2003); Das and Henry (2003); Scherbakov <i>et al.</i> (2004); Felzer and Brodsky (2006)
Tsunami	1B	A rupturing fault line causes the displacement of a large amount of water, triggering a tsunami.	<b>Chile, 2010</b> (Wilson <i>et al.</i> , 2010)	Tsuchiya and Shuto (1995); Tibballs (2005); Bryant (2008)
Volcanic Eruption	1C	Changes in lithospheric stress either (i) reduces confining pressure or (ii) increases pressure within the magma chamber.	<b>Chile, 1906 &amp; 1960</b> (Watt <i>et al.</i> , 2009)	Linde and Sacks (1998); Hill <i>et al.</i> (2002); Feuillet <i>et al.</i> (2006); Harris and Ripepe (2007); Manga and Brodsky (2006); Eggert and Walter (2009)
Landslide	1D	Seismic shaking results in changes in shear stresses and strength causing the movement of rock and soil material under gravitational forces.	<b>Northridge, USA, 1994</b> (Harp & Jibson, 1995)	Keefer (1994); Alexander (1993); Stark and Hovius (2001); Keefer (2002); Malamud <i>et al.</i> (2004a); Malamud <i>et al.</i> (2004b); Nadim <i>et al.</i> (2006); Meunier <i>et al.</i> (2007); Smith and Petley (2009); Clague and Stead (2012)

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<b>PRIMARY HAZARD: EARTHQUAKE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Snow Avalanche	1E	Seismic shaking results in changes in shear stresses and strength causing the movement of snow and ice material under gravitational forces.	<b>Huascarán, Peru, 1970</b> (Podolskiy <i>et al.</i> , 2010a)	Nadim <i>et al.</i> (2006); Podolskiy <i>et al.</i> (2010b)
Flood	1F	Intersection of faults and rivers can result in localised vertical or horizontal displacement of ground and waterways, making land more susceptible to flooding.	<b>Mississippi, USA</b> (Holbrook <i>et al.</i> , 2006)	
Regional Subsidence	1H	Vertical displacement caused by faulting results in subsidence on a regional scale.	<b>Alaska, USA, 1964</b> (Hays, 1981)	Seed and Idriss (1982); Atwater <i>et al.</i> (2003); Hunt (2005); Shennan and Hamilton (2006)
Ground Collapse	1I	Seismic shaking results in vibrocompaction of metastable deposits, resulting in localised ground collapse.	<b>Haiyuan, China, 1920</b> (Zhang and Wang, 2007)	Seed and Idriss (1982); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Yuan and Wang (2009); Jehring (2007)
Ground Heave	1K	Vertical displacement caused by faulting results in uplift on a regional scale.	<b>Chi-Chi, Taiwan, 1999</b> (RMS, 2000)	Seed and Idriss (1982); Hunt (2005)

<b>PRIMARY HAZARD: TSUNAMI</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	2C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism.		Lorenz (1987); Zimanowski and Wohletz (2000); Newhall <i>et al.</i> (2001); Ritchie and Gates (2001); Join <i>et al.</i> (2005); Hamilton <i>et al.</i> (2010a); Hamilton <i>et al.</i> (2010b)

<b>PRIMARY HAZARD: TSUNAMI</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	2D	Incoming water can (i) increase groundwater levels and therefore pore water pressures, decreasing effective stress, and (ii) increase erosion of the slope toe.	<b>Port of Nice, France, 1979</b> (Wright and Rathje, 2003)	Wyllie and Mah (2004); Nadim <i>et al.</i> (2006); Clague and Stead (2012)
Flood	2F	A tsunami will trigger coastal flooding and possible fluvial flooding through increased groundwater levels and surface run off.	<b>Japan, 2011</b> (SEA, 2011)	Tibballs (2005); Bryant and Haslett (2007); Bryant (2008)
Ground Collapse	2I	Hydrocompaction of metastable soils or dissolution of karst results in ground collapse.		Alexander (1993); Bell (1999); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Yuan and Wang (2009); Kehew (2006); Jehring (2007); Gutierrez <i>et al.</i> (2008)
Ground Heave	2K	Increased water results in swelling of clay minerals and thus ground heave.		Johnson and De Graff (1988); Alexander (1993); Bell (1999); Sridharan and Prakash (2000); Hunt (2005); Kehew (2006); Booth (2011)
<b>PRIMARY HAZARD: VOLCANIC ERUPTION</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Earthquake	3A	Injections of magma result in changes in lithospheric stresses, triggering volcano-tectonic earthquakes.	<b>Unzen, Japan, 1985-1999</b> (Umakoshi <i>et al.</i> , 2001)	Lahr <i>et al.</i> (1994); Sparks (2003)

<b>PRIMARY HAZARD: VOLCANIC ERUPTION</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Tsunami	3B	Tsunamis can be as a result of (i) ejection of pyroclastic material displacing large volumes of water, (ii) underwater explosions, (iii) underwater caldera collapses.	<b>Krakatoa, Indonesia, 1883</b> (Ritchie and Gates, 2001; Bryant, 2008)	Mastin and Witter (2000); Choi <i>et al.</i> (2002); Tinti <i>et al.</i> (2003a); Tinti <i>et al.</i> (2003b)
Landslide	3D	Volcanic activity can either (i) increase shear stress or (ii) decrease shear strength, resulting in landslides (flank instability).	<b>Unzen and Mayuyama, Japan, 1792</b> (Nagai and Goto, 2011)	McGuire (1996); Voight and Elsworth (1997); Nadim <i>et al.</i> (2006); Clague and Stead (2012)
Snow Avalanche	3E	Volcanic activity can either (i) increase shear stress or (ii) decrease shear strength, resulting in snow avalanches.	<b>Lassen Peak, USA, 1915</b> (Clynne, 1999)	Major and Newhall (1989); Pierson and Janda (1994); Nadim <i>et al.</i> (2006)
Flood	3F	Lava, ash and pyroclastic material can (i) dam waterways, (ii) block drainage, (iii) melt snow/ice, and thus result in flooding.	<b>Gjálp, Iceland, 1996</b> (Guðmundsson <i>et al.</i> , 1997)	Major and Newhall (1989); Kataoka <i>et al.</i> (2008)
Ground Collapse	3I	Volcanism can increase the acidity of rain and groundwater - thus promoting dissolution. The removal of magma can also result in large void space and ground collapse.	<b>Galapagos Islands, 1968</b> (Filson <i>et al.</i> , 1973)	Hunt (2005); Cole <i>et al.</i> (2005)
Lightning	3P	The collision of ash particles can result in electric discharge in the form of lightning.	<b>Mt. St. Augustine, Alaska, USA, 2006</b> (Thomas <i>et al.</i> , 2007)	Pounder (1980); Rakov and Uman (2003); James <i>et al.</i> (2008); McNutt and Williams (2010)
Extreme Temperature (Heat)	3Q	The ejection of sulphur into the stratosphere can result in both net heating and net cooling.	<b>Pinatubo, Philippines, 1991</b> (Wilson <i>et al.</i> , 1993)	Robock and Free (1995); Robock (2000); Ritchie and Gates (2001); Self <i>et al.</i> (2004); Francis and Oppenheimer (2004)
Extreme Temperature (Cold)	3R	The ejection of sulphur into the stratosphere can result in both net heating and net cooling.	<b>Pinatubo, Philippines, 1991</b> (Wilson <i>et al.</i> , 1993)	

<b>PRIMARY HAZARD: VOLCANIC ERUPTION</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Wildfire	3S	High temperature lava, ash and pyroclastic material can directly trigger wildfires when it comes in contact with flammable material.	<b>Soufriere Hills, Montserrat, 1997</b> (Loughlin <i>et al.</i> , 2002)	
<b>PRIMARY HAZARD: LANDSLIDE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Tsunami	4B	Landslides impacting upon or within water result in the displacement of water, thus triggering a tsunami. These landslides can be either subaerial or submarine.	<b>Mayuyama, Japan, 1792</b> (Nagai and Goto, 2011)	Ward (2001); Bardet <i>et al.</i> (2003); Bryant (2008); Di Risio <i>et al.</i> (2011); Clague and Stead (2012)
Volcanic Eruption	4C	Unloading of a volcano by landslides and flank collapse reduces confining pressures, changing lithospheric stress and strength conditions. Material input into lava has also been shown to trigger the nucleation of bubbles, triggering an eruption (Carey <i>et al.</i> , 2012)	<b>Hawaii, USA</b> (Lipman <i>et al.</i> , 1990)	McGuire (1996); Pinel and Jaupart (2005); Manconi <i>et al.</i> (2009); Clague and Stead (2012)

<b>PRIMARY HAZARD: LANDSLIDE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	4D	A landslide can result in the mobilisation and deposition of material in another location, increasing the weight on the head of a slope and promoting instability. The mobilisation of sediment by landslides can also increase the likelihood of debris flows in the event of a rainstorm.	<b>East Cucaracha, Panama, 1986</b> (Bhandari, 1995)	Ter-Stephanian (1977); Tang <i>et al.</i> (2009); Clague and Stead (2012)
Flood	4F	Material from landslides can (i) dam waterways, and (ii) increase sedimentation in rivers, to promote flooding.	<b>Chi-Chi, Taiwan, 1999</b> (RMS, 2000)	Costa and Schuster (1998); Dunning <i>et al.</i> (2007); Clague and Stead (2012)

<b>PRIMARY HAZARD: SNOW AVALANCHE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	5C	Unloading of a volcano by snow avalanches reduces confining pressures, changing lithospheric stress and strength conditions.		
Landslide	5D	Snow avalanches can result in the mobilisation and deposition of material in another location, increasing the weight on the head of a slope - promoting instability.	<b>Huascarán, Peru, 1962</b> (Morales, 1966)	Pierson and Janda (1994); Clague and Stead (2012)

<b>PRIMARY HAZARD: SNOW AVALANCHE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Snow Avalanche	5E	Snow avalanches can result in the mobilisation and deposition of material in another location, increasing the weight on the head of a slope - promoting instability.		
Flood	5F	Material from snow avalanches can (i) dam waterways, and (ii) melt, to promote flooding.	<b>Montana, USA, 1980s</b> (Butler, 1989)	King (1934)
<b>PRIMARY HAZARD: FLOOD</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	6C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism.		Lorenz (1987); Zimanowski and Wohletz (2000); Newhall <i>et al.</i> (2001); Ritchie and Gates (2001); Join <i>et al.</i> (2005); Hamilton <i>et al.</i> (2010a), Hamilton <i>et al.</i> (2010b)
Landslide	6D	Flood waters can (i) increase groundwater levels and therefore pore water pressures, decreasing effective stress, and (ii) increasing erosion of the slope toe.	<b>Himalayas, India, 2000-2005</b> (Gupta and Sah, 2008)	Wyllie and Mah (2004); Nadim <i>et al.</i> (2006); Clague and Stead (2012)
Ground Collapse	6I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.	<b>Saudia Arabia, 1992-1999</b> (Al-Harthi and Bankher, 1999)	Alexander (1993); Bell (1999); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Yuan and Wang (2009); Kehew (2006); Jehring (2007); Gutierrez <i>et al.</i> (2008)

<b>PRIMARY HAZARD: FLOOD</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Ground Heave	6K	Increased water results in the swelling of clay minerals.		Johnson and De Graff (1988); Alexander (1993); Nelson and Miller (1997); Bell (1999); Sridhavan and Prakash (2000); Hunt (2005); Kehew (2006); Booth (2011)
<b>PRIMARY HAZARD: DROUGHT</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Ground Collapse	7I	Drought results in the removal of hydraulic support promoting ground collapse.	<b>Alabama, USA, 1950s</b> (Newton, 1984)	Hunt (2005)
Soil (Local) Subsidence	7J	Reduced water results in the shrinking of clay minerals and thus local subsidence.	<b>France, 1976 + 1989</b> (Corti <i>et al.</i> , 2011)	Johnson and De Graff (1988); Hunt (2005)
Wildfire	7S	Drought results in dry and dead vegetation which increases the probability of wildfires.	<b>Mexico, 1998</b> (Uppgren and Stock, 2000)	Balling <i>et al.</i> (1992); Westerling and Swetnam (2003); Bachelet <i>et al.</i> (2003); Lenihan <i>et al.</i> (2003); Smith and Petley (2009)
<b>PRIMARY HAZARD: REGIONAL SUBSIDENCE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Flood	8F	Regional subsidence increases vulnerability to flooding.	<b>Alaska, USA, 1964</b> (Hays, 1981)	Yong <i>et al.</i> (1991); Peterson <i>et al.</i> (2000); Burkett <i>et al.</i> (2001); Hunt (2005)

<b>PRIMARY HAZARD: GROUND COLLAPSE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	9D	Collapse of metastable soils and dissolution of rock can change the stress conditions within slopes.	<b>Haiyuan, China, 1920</b> (Zhang and Wang, 2007)	Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Nadim <i>et al.</i> (2006); Jehring (2007)
<b>PRIMARY HAZARD: SOIL (LOCAL) SUBSIDENCE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	10D	Local/soil subsidence changes the stress conditions within slopes.	<b>New Orleans, USA</b> (Sewer, 2006)	Hunt (2005); Nadim <i>et al.</i> (2006)
<b>PRIMARY HAZARD: GROUND HEAVE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	11D	Ground heave changes the stress conditions within slopes.	<b>Mt. Elgon, Uganda</b> (Mugagga <i>et al.</i> , 2012)	Popescu (2002); Hunt (2005); Nadim <i>et al.</i> (2006); Wu and Huang (2006); Zeng <i>et al.</i> (2011)

<b>PRIMARY HAZARD: STORM</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Earthquake	12A	Earthquakes triggered by (i) Reductions in atmospheric pressure reducing the sea-floor confining stress (ii) increased precipitation increasing pore pressure.	<b>Taiwan, 2002-2007</b> (Liu <i>et al.</i> , 2009)	Hainzl <i>et al.</i> (2006); McGuire (2010)
Tsunami	12B	Perturbations in air pressure over the ocean can generate large amplitude standing waves.	<b>Balearic Islands, 2006</b> (Montserrat <i>et al.</i> , 2006)	Belušić and Strelec Mahović (2009); Tappin <i>et al.</i> (2013)
Volcanic Eruption	12C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism, forming small steam explosions or more intense activity.	<b>Merapi Volcano, Indonesia, 1930-31</b> (Voight <i>et al.</i> , 2000)	Lorenz (1987); Mastin (1997); Zimanowski and Wohletz (2000); Newhall <i>et al.</i> (2001); Ritchie and Gates (2001); Join <i>et al.</i> (2005); Hamilton <i>et al.</i> (2010a); Hamilton <i>et al.</i> (2010b)
Landslide	12D	Rainwater increases groundwater levels and therefore pore water pressures, decreasing effective stress.	<b>Guatemala, 1998</b> (Bucknam <i>et al.</i> , 2001)	Wyllie and Mah (2004); Nadim <i>et al.</i> (2006); Clague and Stead (2012)
Snow Avalanche	12E	The addition of water to snow and ice can result in rapid melting, and downward movement of material.	<b>Swiss-Austrian Alps, 1950-51</b> (Latenser and Pfister, 1997)	Morales (1966); McClung and Schaerer (1993); Nadim <i>et al.</i> (2006)
Flood	12F	Heavy rainfall can increase groundwater and surface water levels - causing flash, fluvial and urban flooding.	<b>Guatemala, 2010</b> (Miles <i>et al.</i> , 2012)	Alexander (1993); Smith and Petley (2009); Zevenbergen <i>et al.</i> (2010)
Ground Collapse	12I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.	<b>Guatemala, 2010</b> (Stewart, 2011)	Alexander (1993); Bell (1999); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Kehew (2006); Jehring (2007); Gutierrez <i>et al.</i> (2008); Yuan and Wang (2009)
Ground Heave	12K	Increased water results in swelling of clay minerals.	<b>Front Range, Colorado</b> (Noe, 1997)	Johnson and De Graff (1988); Alexander (1993); Bell (1999); Sridhavan and Prakash (2000); Hunt (2005); Kehew (2006)

<b>PRIMARY HAZARD: STORM</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Tornado	12M	Tornadoes are produced in hurricanes or tropical storms as a result of vertical shear profiles within the outer bands of the storm (NOAA, 2012a)	<b>Hurricane Andrew, Eastern USA, 1992</b> (NOAA, 2013b)	Vescio <i>et al.</i> (1996); Marks and Shay (1998); Curtis (2004); Schultz and Cecil (2009)
Lightning	12P	Collisions between solid precipitation in clouds act as a charging mechanism for a tornado, resulting in a differential charge across the cloud, and between the cloud and the ground. As this charge differential increases, a channel of air that acts as a conductor develops between the cloud and the ground. A small amount of charge starts moving toward the ground and is met by an upward leader of opposite charge. As they meet a powerful electrical discharge occurs (NOAA, 2013c).	<b>Hurricane Andrew, Eastern USA, 1992</b> (Molinari <i>et al.</i> , 1994)	Carey <i>et al.</i> (2002); Lang and Rutledge (2002); Rakov and Uman (2003); NOAA (2013c)
<b>PRIMARY HAZARD: TORNADO</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Lightning	13P	See Storm → Lightning	<b>USA, 1989-1992</b> (Perez <i>et al.</i> , 1997)	Carey <i>et al.</i> (2002); Rakov and Uman (2003)

<b>PRIMARY HAZARD: HAILSTORM</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	14C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism.		Lorenz (1987); Zimanowski and Wohletz (2000); Newhall <i>et al.</i> (2001); Ritchie and Gates (2001); Join <i>et al.</i> (2005); Hamilton <i>et al.</i> (2010a); Hamilton <i>et al.</i> (2010b)
Landslide	14D	Water from hailstorms can increase groundwater levels and therefore pore water pressures, decreasing effective stress.	<b>Bududa, Uganda, 2013</b> (Wanzusi and Watala, 2013)	Wyllie and Mah (2004); Nadim <i>et al.</i> (2006); Alcántara-Ayala <i>et al.</i> (2011); Clague and Stead (2012)
Snow Avalanche	14E	Additional weight from hailstones and the wetting of snow can trigger snow avalanches.		Nadim <i>et al.</i> (2006)
Flood	14F	Water from hailstorms can increase both surface and groundwater, promoting flooding.	<b>Southern England, UK, 2008</b> (BBC, 2008)	Alexander (1993); Smith and Petley (2009); Zevenbergen <i>et al.</i> (2010)
Ground Collapse	14I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.		Alexander (1993); Bell (1999); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Kehew (2006); Jehring (2007); Gutierrez <i>et al.</i> (2008); Yuan and Wang (2009)
Ground Heave	14K	Increased water results in swelling of clay minerals.		Alexander (1993); Bell (1999); Hunt (2005); Kehew (2006)
Lightning	14P	See Storm → Lightning	<b>Sydney, Australia, 1999</b> (Buckley <i>et al.</i> , 2001)	Carey <i>et al.</i> (2002); Rakov and Uman (2003); NOAA (2013c)

<b>PRIMARY HAZARD: SNOWSTORM</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	15C	Water from snowmelt can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism.	<b>Lassen Peak, USA, 1915</b> (Clyne <i>et al.</i> , 1999)	Lorenz (1987); Zimanowski and Wohletz (2000); Newhall <i>et al.</i> (2001); Ritchie and Gates (2001); Join <i>et al.</i> (2005); Hamilton <i>et al.</i> (2010a); Hamilton <i>et al.</i> (2010b)
Landslide	15D	Water from snowstorms can increase groundwater levels and therefore pore water pressures, decreasing effective stress.	<b>Umbria, Italy, 1996/7</b> (Cardinali <i>et al.</i> , 2000)	Wyllie and Mah (2004); Nadim <i>et al.</i> (2006); Clague and Stead (2012)
Snow Avalanche	15E	Additional weight from snow and the wetting of snow can trigger snow avalanches.	<b>Swiss-Austrian Alps, 1950-51</b> (Latenser and Pfister, 1997)	McClung and Schaerer (1993); Nadim <i>et al.</i> (2006); Singh <i>et al.</i> (2011)
Flood	15F	Water from snowstorms can increase both surface and groundwater, promoting flooding.	<b>Red River, North America, 1996-7</b> (Kunkel, 2003)	Alexander (1993); Smith and Petley (2009); Zevenbergen <i>et al.</i> (2010)
Ground Collapse	15I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.	<b>Sivas, Turkey</b> (Waltham, 2008)	Alexander (1993); Bell (1999); Derbyshire (2001); Jefferson <i>et al.</i> (2003); Jefferson <i>et al.</i> (2004); Hunt (2005); Kehew (2006); Jehring (2007); Gutierrez <i>et al.</i> (2008); Yuan and Wang (2009)
Ground Heave	15K	Increased water from snowmelt results in the swelling of clay minerals.	<b>Western Canada, 1962-1964</b> (Hamilton, 1980)	Alexander (1993); Bell (1999); Hunt (2005); Kehew (2006)
<b>PRIMARY HAZARD: LIGHTNING</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Wildfire	16S	Lightning discharge can spark fires.	<b>Ontario, Canada, 1980s</b> (Flannigan and Wotton, 1990)	Alexander (1993); Rakov and Uman (2003); Smith and Petley (2009); NOAA (2013c)

<b>PRIMARY HAZARD: EXTREME TEMPERATURE (HOT)</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Earthquake	17A	Glacial unloading reduces confining pressures and therefore triggers earthquakes.	<b>Southern Alaska, USA</b> (Sauber and Molnia, 2004)	McNutt and Beavan (1987); McNutt (1999); Wilcock (2001); McGuire (2010a); Hampel <i>et al.</i> (2010); Guillas <i>et al.</i> (2010)
Volcanic Eruption	17C	Melting of snow and ice on the summit and flanks of volcanoes reduces confining stress, and promotes hydromagmatic interactions.	<b>Iceland, 12ka</b> (MacLennan <i>et al.</i> , 2002)	Jull and Mackenzie (1996); Huybers <i>et al.</i> (2009); McGuire (2010); Deeming <i>et al.</i> (2010); Sigmundsson <i>et al.</i> (2010); Tuffen <i>et al.</i> (2010)
Landslide	17D	High temperatures can result in the melting of snow and ice, increasing groundwater levels and thus reducing effective stress.	<b>Umbria, Italy, 1996/7</b> (Cardinali <i>et al.</i> , 2000)	Nadim <i>et al.</i> (2006); McGuire (2010); Deeming <i>et al.</i> (2010); Huggel <i>et al.</i> (2010); Keiler <i>et al.</i> (2010); Tuffen (2010)
Snow Avalanche	17E	High temperatures can result in the melting of snow and ice. This wetting promotes snow avalanche activity.	<b>Mt. Cook, New Zealand, 1991</b> (Huggel <i>et al.</i> , 2010)	Nadim <i>et al.</i> (2006)
Flood	17F	Melting of snow and ice can result in flooding.	<b>Red River, USA, 1997</b> (NOAA, 2013d)	McGuire (2010); Keiler <i>et al.</i> (2010); Tuffen (2010)
Drought	17G	High temperatures result in an increase in evapotranspiration - thus promoting drought conditions.	<b>Bulgaria, 1992</b> (Estrela <i>et al.</i> , 2001)	Le Houérou (1996)
Storm	17L	Increased ocean temperatures promote the formation of tropical storms.	<b>North Atlantic, 2005</b> (Trenberth and Shea, 2006)	Webster <i>et al.</i> (2005); Knutson <i>et al.</i> (2010)
Wildfire	17S	The drying of vegetation by extreme temperatures can result in an increased probability of wildfires.	<b>Montana, USA, 2007</b> (Geotimes, 2007)	Bailing <i>et al.</i> (1992); Westerling <i>et al.</i> (2003); Krawchuk <i>et al.</i> (2009)

<b>PRIMARY HAZARD: EXTREME TEMPERATURE (COLD)</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Volcanic Eruption	18C	Formation of ice sheets results in the lowering of sea-levels and thus reduction of confining pressure on magma chambers.		Huybers <i>et al.</i> (2009)
Drought	18G	Extreme cold conditions can lead to a winter drought when precipitation is in solid rather than liquid form.	<b>Laki, Iceland, 1783-1784</b> (Thordarson and Self, 2003)	
Hailstorm	18N	Extreme cold conditions can increase the probability of hailstorms, by making freezing conditions more likely.	<b>Southern England, UK, 2008</b> (BBC, 2008)	Singh <i>et al.</i> (2011)
Snowstorm	18O	Extreme cold conditions can increase the probability of snowstorms, by making freezing conditions more likely.	<b>Southern England, UK, 2008</b> (BBC, 2008)	Singh <i>et al.</i> (2011)
<b>PRIMARY HAZARD: WILDFIRE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Landslide	19D	Wildfires remove vegetation which acts as a major water sink and adds shear strength through anchorage, thus increasing the probability of landslides.	<b>California, USA, 2003</b> (Cannon <i>et al.</i> , 2004)	Spittler (1995); Cannon <i>et al.</i> (2001); Spittler (2005); Nadim <i>et al.</i> (2006); Moody <i>et al.</i> (2008); Santi <i>et al.</i> (2008)
Flood	19F	The removal of vegetation by wildfires (i) removes a major sink for water, (ii) promotes surface run-off, and thus promoting flooding.	<b>Colorado, USA, 1996</b> (Moody and Martin, 2001)	Spittler (1995); Spittler (2005)

<b>PRIMARY HAZARD: WILDFIRE</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Ground Heave	19K	The removal of vegetation exposes clay soils, thus increasing the probability of ground heave in the event of increased moisture.		Hunt (2005); Jones and Jefferson (2012)
Extreme Temperature (Heat)	19Q	Wildfires can result in large amounts of carbon dioxide being released into the atmosphere, increasing the greenhouse effect.		
Wildfire	19S	Spotting from wildfires can trigger further wildfires.	<b>Portugal, 1999</b> (Botelho <i>et al.</i> , 2002)	Alexander (1993); Smith and Petley (2009); Albini <i>et al.</i> (2012)

<b>PRIMARY HAZARD: IMPACT EVENT</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
Earthquake	21A	Impact events can cause major lithospheric disturbance, including the release of stress as earthquakes.	<b>Chicxulub Impact, ~65myr</b> (Schulte <i>et al.</i> , 2010)	Toon <i>et al.</i> (1997); Pierazzo and Artemieva (2012)
Tsunami	21B	Impact events in water can cause large scale displacement of water, thus triggering a tsunami.	<b>Chicxulub Impact, ~65myr</b> (Schulte <i>et al.</i> , 2010)	Toon <i>et al.</i> (1997); Paine (1999); Ward and Asphaug (2000); Pierazzo and Artemieva (2012)
Volcanic Eruption	21C	Impact events can cause major lithospheric disturbance, triggering volcanic eruptions.		
Extreme Temperature (Cold)	21R	Impact events can cause large-scale injections of dust and other particles into the atmosphere -	<b>Chicxulub Impact, ~65myr</b> (Kring, 2007)	Toon <i>et al.</i> (1997); Pierazzo and Artemieva (2012)

<b>PRIMARY HAZARD: IMPACT EVENT</b>				
<b>Secondary Hazard</b>	<b>Grid ID</b>	<b>Generic Mechanism Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. some of these references describe a process related to the interaction, and not the interaction itself, e.g., phreatomagmatism, but not the interaction of flooding and volcanic eruptions)
		causing widespread cooling effects.		
Wildfire	21S	Impact events can cause wildfires as super-heated material touches flammable materials.	<b>Tunguska, Russia, 1908</b> (Kresak, 1978)	Toon <i>et al.</i> (1997); Pierazzo and Artemieva (2012)

**Table A.2. Ability to characterize triggered and increased probability secondary hazards given information from the primary hazard.** A table to outline the forecasting potential of the location, timing and magnitude of each secondary hazard, given information about the primary hazard. Each forecasting factor is given a classification from N (value 0) to H (value 3) depending on what information is available to help constrain the factor. These three values are totalled to give a rating from 0-9, and colour coded in terms of the ability to characterise the secondary hazard, with poor (0-3, light shading), semi (4-6, medium shading) or excellent (7-9, dark shading).

<b>Primary Hazard</b>	<b>Secondary Hazard</b>	<b>Forecasting Factors</b>			<b>Overall Rating</b>
		<b>Location</b>	<b>Time</b>	<b>Magnitude</b>	
<b>Earthquake</b>	Earthquake	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Tsunami	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Regional Subsidence	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	<b>Tsunami</b>	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H
Landslide		N-L-M-H	N-L-M-H	N-L-M-H	5/9
Flood		N-L-M-H	N-L-M-H	N-L-M-H	8/9
Ground Collapse		N-L-M-H	N-L-M-H	N-L-M-H	3/9
Ground Heave		N-L-M-H	N-L-M-H	N-L-M-H	6/9
<b>Volcanic Eruption</b>	Earthquake	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Tsunami	N-L-M-H	N-L-M-H	N-L-M-H	8/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	8/9

Primary Hazard	Secondary Hazard	Forecasting Factors			Overall Rating
		Location	Time	Magnitude	
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Lightning	N-L-M-H	N-L-M-H	N-L-M-H	4/9
	Extreme Temp. (Heat)	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Extreme Temp. (Cold)	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Wildfire	N-L-M-H	N-L-M-H	N-L-M-H	5/9
Landslide	Tsunami	N-L-M-H	N-L-M-H	N-L-M-H	8/9
	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	6/9
Snow Avalanche	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	5/9
Flood	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	4/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	6/9
Drought	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Soil (Local) Subsidence	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Wildfire	N-L-M-H	N-L-M-H	N-L-M-H	3/9
Regional Subsidence	Flood	N-L-M-H	N-L-M-H	N-L-M-H	5/9
Ground Collapse	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	6/9
Soil (Local) Subsidence	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	5/9
Ground Heave	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	5/9
Storms	Earthquake	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Tsunami	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Tornado	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Lightning	N-L-M-H	N-L-M-H	N-L-M-H	4/9

Primary Hazard	Secondary Hazard	Forecasting Factors			Overall Rating
		Location	Time	Magnitude	
<b>Tornadoes</b>	Lightning	N-L-M-H	N-L-M-H	N-L-M-H	4/9
<b>Hailstorm</b>	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Lightning	N-L-M-H	N-L-M-H	N-L-M-H	4/9
<b>Snowstorm</b>	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Ground Collapse	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	6/9
<b>Lightning</b>	Wildfire	N-L-M-H	N-L-M-H	N-L-M-H	6/9
<b>Extreme Temperature (Heat)</b>	Earthquake	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	4/9
	Snow Avalanche	N-L-M-H	N-L-M-H	N-L-M-H	4/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Drought	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Storm	N-L-M-H	N-L-M-H	N-L-M-H	2/9
	Wildfire	N-L-M-H	N-L-M-H	N-L-M-H	3/9
<b>Extreme Temperature (Cold)</b>	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	2/9
	Drought	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Hailstorm	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Snowstorm	N-L-M-H	N-L-M-H	N-L-M-H	6/9
<b>Wildfires</b>	Landslide	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Flood	N-L-M-H	N-L-M-H	N-L-M-H	5/9
	Ground Heave	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Wildfire	N-L-M-H	N-L-M-H	N-L-M-H	6/9
	Extreme Temp. (Heat)	N-L-M-H	N-L-M-H	N-L-M-H	6/9
<b>Impact Event</b>	Earthquake	N-L-M-H	N-L-M-H	N-L-M-H	7/9
	Tsunami	N-L-M-H	N-L-M-H	N-L-M-H	8/9
	Volcanic Eruption	N-L-M-H	N-L-M-H	N-L-M-H	3/9
	Extreme Temp. (Cold)	N-L-M-H	N-L-M-H	N-L-M-H	6/9

Primary Hazard	Secondary Hazard	Forecasting Factors			Overall Rating
		Location	Time	Magnitude	
	Wildfires	N – L – M – H	N – L – M – H	N – L – M – H	5/9

**Table A.3. Global Hazard Distribution Maps.** A series of maps used to evaluate the global distribution of natural hazards. These can be used to determine the global *spatial overlap* of multiple hazards at a coarse resolution.

Natural Hazard	Map Reference
Earthquake	Giardini <i>et al.</i> (2013)
Tsunami	A3M AG (2007)
Volcanic Eruption	Prentis (2013)
Landslide	NASA (2007)
Avalanche	Kramer (1992)
Flood	Dilley <i>et al.</i> (2005)
Drought	Dilley <i>et al.</i> (2005)
Loess	Rodbell (2012)
Karst	Ford and Williams (2007)
Soil (Local) Subsidence and Clay Swelling	USDA (2005)
Tornado	NOAA (2013e)
Storm & Hailstorm	Barry and Chorley (1998)
Lightning	NASA (2006)
Snowstorm	Assumed widespread potential
Extreme Heat	Assumed global potential
Extreme Cold	Assumed global potential
Wildfire	Krawchuk <i>et al.</i> (2009)
Geomagnetic Storm	Assumed global Potential
Impact Event	Assumed global Potential

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# Appendix B. Anthropogenic Processes

## Triggering Natural Hazards

**Table B.1.** Mechanisms, case studies and additional references for each of the identified anthropogenic process and natural hazard interactions in Figure 4.5 (Chapter 4). Information is presented which describes the physical process by which each anthropogenic process triggers a natural hazard. Where identified, relevant case studies and additional references used to analyse and classify each interaction are noted. Some of these references describe a process related to the interaction, and not the interaction itself. *All references are included in full at the end of this appendix.*

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SUBSURFACE MATERIAL EXTRACTION				
ANTHROPOGENIC PROCESS TYPE: GROUNDWATER ABSTRACTION				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	1.1A	Changes in sub-surface stress conditions due to the removal of groundwater, eventually leading to the rapid release of stored energy.	<b>Lorca, Spain, 2011</b> (Gonzalez <i>et al.</i> , 2012)	Donnelly (2009)
Regional Subsidence	1.1H	Removal of groundwater reduces pore pressures and induces consolidation of a confined aquifer. This results in the lowering of the ground surface.	<b>Mexico, 1900s-Present</b> (González-Morán <i>et al.</i> , 1999)	Alexander (1993); Galloway <i>et al.</i> (1999); Waltham (2002); Chai <i>et al.</i> (2004); Hunt (2005); Holzer and Galloway (2005); Hu <i>et al.</i> (2006); Chen <i>et al.</i> (2007a); Galloway and Burbey (2011)
Ground Collapse	1.1I	Removal of hydraulic support can induce the collapse of underground voids.	<b>Texas, USA</b> (Holzer, 1984)	Newton (1984); Lamoreaux and Newton (1986); Daoxian (1988); Pando <i>et al.</i> (2013)

<b>ANTHROPOGENIC PROCESS GROUP: SUBSURFACE PROCESSES</b>				
<b>ANTHROPOGENIC PROCESS SUB-GROUP: SUBSURFACE MATERIAL EXTRACTION</b>				
<b>ANTHROPOGENIC PROCESS TYPE: OIL/GAS EXTRACTION</b>				
<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	1.2A	Changes in sub-surface stress conditions due to the removal of fluids, eventually leading to the rapid release of stored energy.	<b>Texas, USA, 1920s</b> (Segall, 1989)	Teng <i>et al.</i> (1973); Suckale (2009)
Regional Subsidence	1.2H	Removal of hydrocarbon fluids reduces pore pressures and induces consolidation of a confined aquifer. This results in the lowering of the ground surface.	<b>Lacq, France, 1957-1967</b> (Maury <i>et al.</i> , 1992)	Martin and Serdengecti, (1984); Alexander (1993); Hunt (2005); Suckale, (2009)

<b>ANTHROPOGENIC PROCESS GROUP: SUBSURFACE PROCESSES</b>				
<b>ANTHROPOGENIC PROCESS SUB-GROUP: SUBSURFACE MATERIAL EXTRACTION</b>				
<b>ANTHROPOGENIC PROCESS TYPE: SUBSURFACE INFRASTRUCTURE CONSTRUCTION</b>				
<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake (*Rock Bursts)	1.3A	The removal of lateral support, changing ground stress conditions. This can facilitate the release of stored energy in the form of earth tremors (including rock bursts).	<b>Gotthard Base Tunnel, Switzerland, 2005</b> (Hagedorn <i>et al.</i> , 2008)	
Regional Subsidence	1.3H	Large-scale removal of subterranean material can result in the lowering of the ground surface.	<b>Gotthard Highway Tunnel, Switzerland</b> (Zangerl <i>et al.</i> , 2008)	De Graff and Romesburg (1981); Attewell and Woodman (1982); Lee <i>et al.</i> (1992); Rowe and Lee (1992); Alexander, (1993); Hunt (2005)
Ground Collapse	1.3I	Subsurface removal of material through infrastructure construction can create voids which then collapse.	<b>Kurtkulagi Irrigation Tunnel, Turkey, 1994</b> (Türkmen and Ozguzel, 2003)	Ege (1984); Chen (1988); Alexander (1993); Hunt (2005); Wang <i>et al.</i> (2008)

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SUBSURFACE MATERIAL EXTRACTION				
ANTHROPOGENIC PROCESS TYPE: <b>SUBSURFACE MINING</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquakes (*rock bursts and fault reactivation)	1.4A	Mining involves the removal of lateral support, changing ground stress conditions which can reactivate faults. Changing stress conditions can facilitate the release of stored energy in the form of earth tremors.	<b>China (Various) Li et al., 2007</b>	Donnelly (2009)
Regional Subsidence	1.4H	Mining involves the removal of lateral support, changing ground stress conditions which can reactivate faults. Changing stress conditions can facilitate the release of stored energy in the form of earth tremors.	<b>Eastern USA (Gray and Bruhn, 1984)</b>	De Graff and Romesburg (1981); Dunrud (1984); Alexander (1993); Hunt (2005)
Ground Collapse	1.4I	Subsurface removal of material through mining can create voids which then collapse.	<b>Reading, UK, 2000 (Edmonds, 2008)</b>	Ege, (1984); Chen (1988); Alexander (1993); Hunt (2005); Wang <i>et al.</i> (2008)

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SUBSURFACE MATERIAL ADDITION				
ANTHROPOGENIC PROCESS TYPE: <b>MATERIAL (FLUID) INJECTION</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	2.1A	Addition of fluids increases pore pressures, changing the sub-surface stress conditions. This can eventually lead to the rapid release of stored energy.	<b>Denver, USA, 1962-1966 (Healy et al., 1968)</b>	Teng <i>et al.</i> (1973); Raleigh <i>et al.</i> (1976); Simpson (1986); Donnelly (2009); Suckale (2009); Keranen <i>et al.</i> (2013); Hough and Page (2015)

**ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES**  
**ANTHROPOGENIC PROCESS SUB-GROUP: LAND USE CHANGE**

**ANTHROPOGENIC PROCESS TYPE: VEGETATION REMOVAL**

<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	3.1D	The removal of vegetation can reduce the shear strength of slopes, thus promoting failure.	<b>Nilgiris District, India</b> (Kumar and Bhagavanulu, 2007)	Varnes (1984); Alexander (1992); Alexander (1993); Glade (2003); Knapen <i>et al.</i> (2006); Claessens <i>et al.</i> (2013)
Snow Avalanche	3.1E	Vegetation can help to prevent large avalanches and slow their velocity. Colonisation and subsequent deforestation can therefore increase avalanche likelihood.	<b>Tyrol, Austria, 1800-</b> (Alexander, 1993)	McClung (2001)
Drought (Reduction in Precipitation)	3.1G	Deforestation is both noted to decrease and increase (see Storms) precipitation/rainfall through changes in evaporation and cloud formation.	<b>Nilgiris District, India, 1944-1961+</b> (Meher-Homji, 1991) (*Case study examines the relationship between deforestation and rainfall).	Nobre <i>et al.</i> (1991); Wang (2004); Garcia-Carreras and Parker (2011)
Ground Heave	3.1K	The removal of vegetation in expansive soils can result in heave as less water is taken up through root systems, and more resides in the soil.	<b>United Kingdom</b> (Driscoll, 1983)	
Storm	3.1L	Deforestation is both noted to increase and decrease (see drought) precipitation/rainfall through changes in evaporation and cloud formation.	<b>Southwest Brazil, 1978-</b> (Negri <i>et al.</i> , 2004)	Fairman <i>et al.</i> (2011)
Extreme Temperature (Heat)	3.1Q	Deforestation is noted to increase local temperatures through a reduction in evaporation.	<b>Southwest Brazil, 1978-</b> (Negri <i>et al.</i> , 2004)	Meher-Homji (1991); Nobre <i>et al.</i> (1991)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: LAND USE CHANGE				
ANTHROPOGENIC PROCESS TYPE: AGRICULTURAL PRACTICE CHANGE				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	3.2D	Changes in agricultural practice, including reducing slope management, can result in an increase in landslides through reducing the shear strength of the slope.	<b>New Zealand</b> (Glade, 2003)	Varnes (1984); Alexander (1993)
Snow Avalanche ( <i>Snow Gliding</i> )	3.2E	Changes in agricultural practice, including reducing slope management, can result in an increase in avalanches through reducing the shear strength of the slope.	<b>Alpine Ecosystems</b> (Newesely <i>et al.</i> , 2000)	
Ground Collapse	3.2I	Changes in agricultural practice can alter the hydrological system and promote ground collapse.	<b>Turkey</b> (Doğan and Yılmaz, 2011)	Wang <i>et al.</i> (2010); Coxon (2011)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: LAND USE CHANGE				
ANTHROPOGENIC PROCESS TYPE: URBANISATION				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	3.3D	An increase in urbanisation on marginally stable slopes can increase the stresses places on slopes, promoting failure.	<b>Caramanico, Italy</b> (Wasowski, 1998)	Varnes (1984)
Storm	3.3L	Urbanisation can trigger excessive precipitation due to the thermal effects and increased frictional convergence of built-up areas (Barry and Chorley, 1998)	<b>Atlanta, USA, 1996</b> (Bornstein and Lin, 2000)	Barry and Chorley, (1998); Chen <i>et al.</i> , (2007b)
Extreme Temperature (Heat)	3.3Q	Urbanisation leads to localised increases in temperatures, due to changes in the land surface materials to ones that retain heat, and waste energy from industry and residential areas.	<b>Phoenix, Arizona, USA, ~1945-Present</b> (Baker <i>et al.</i> , 2002)	Landsberg (1981); Barry and Chorley (1998); Chen <i>et al.</i> (2007b); Grimmond (2007)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SURFACE MATERIAL EXTRACTION				
ANTHROPOGENIC PROCESS TYPE: <b>INFRASTRUCTURE CONSTRUCTION (UNLOADING)</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	4.1D	The removal of lateral support can weaken slopes or exposures of rock, either triggering or increasing the likelihood of slope failure.	<b>Cuyocuyo, Peru, 1980s</b> (Alexander, 1993)	Varnes (1984); Alexander (1993); Montgomery (1994); Waltham (2002); Devkota <i>et al.</i> (2012); Brenning <i>et al.</i> , (2015)
Ground Heave	4.1K	Removal or excavation of material results in surface swelling and therefore localised uplift. Minor uplift can cause damage to infrastructure.	<b>Hauerstein, Switzerland</b> (Chiaverio and Thut, 2010)	Einstein (1996)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SURFACE MATERIAL EXTRACTION				
ANTHROPOGENIC PROCESS TYPE: <b>QUARRYING/SURFACE MINING (UNLOADING)</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	4.2A	A large-scale decrease in vertical stress can result in the activation of faults and triggering of earthquakes, notably in areas of thrust faulting.	<b>Belchatow, Poland, 1979-1980</b> (Gibowicz <i>et al.</i> , 1981)	Smith <i>et al.</i> (1974); Spottiswoode and McGarr (1975); Simpson (1986)
Landslide	4.2D	The removal of lateral support can weaken slopes, either triggering or increasing the likelihood of slope failure.	<b>Cortes de Pallas, Spain</b> (Alonso <i>et al.</i> , 1993)	Waltham (2002)
Ground Heave	4.2K	Removal or excavation of material results in surface swelling and therefore localised uplift. Minor uplift can cause damage to infrastructure.	<b>Zagreb, Croatia, 1963-1985</b> (Stanic and Nonveiller, 1995)	Hawkins (2014)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SURFACE MATERIAL ADDITION				
ANTHROPOGENIC PROCESS TYPE: <b>INFRASTRUCTURE (LOADING)</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	5.2D	Changes in stress conditions through the placing of an additional load onto a slope, thus promoting slope failure.	<b>Eskihisar, Turkey</b> (Sonmez and Ulusay, 1999)	Varnes (1984); Alexander (1992); Alexander (1993)
Ground Collapse	5.2J	Changes in infrastructure loading can alter the hydrological system and promote ground collapse.	<b>West-Central Florida</b> (Tihansky, 1999)	Newton (1976); Lamoreaux and Newton (1986); Newton (1987)
Soil (Local) Subsidence	5.2J	The placing of an additional load onto the ground can cause settlement, or local (soil) subsidence.	<b>London, UK, 1970s</b> (Cooke <i>et al.</i> , 1981)	Hunt (2005)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SURFACE MATERIAL ADDITION				
ANTHROPOGENIC PROCESS TYPE: <b>INFILLED (MADE) GROUND</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	5.3D	Large scale deposition of material can result in a landslide if the material is poorly compacted and fails.	<b>Aberfan, Wales, UK, 1966</b> (Siddle <i>et al.</i> , 1996)	Bishop (1973); Alexander (1993); Hungry <i>et al.</i> (2001)

ANTHROPOGENIC PROCESS GROUP: SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: SURFACE MATERIAL ADDITION				
ANTHROPOGENIC PROCESS TYPE: <b>RESERVOIRS AND DAM CONSTRUCTION</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	5.1A	Changes in stress conditions through the placing of an additional load can trigger earthquakes, notably in areas of extensive normal faulting. An increase in pore-water pressure is also suggested to reduce effective stress and allow movement on faults.	<b>Koyna, India, 1967</b> (Gupta and Rastogi, 1976)	Gupta and Combs (1976); Simpson (1986); Assumpção <i>et al.</i> (2002), McGarr <i>et al.</i> (2002)
Landslide	5.1D	The construction of a reservoir can result in landslides through (i) toe erosion, (ii) increased pore-water pressures in the base of slopes, (iii) removal of hydraulic support via rapid water drawdown.	<b>Three Gorges Dam, China, 2003</b> (Wang <i>et al.</i> , 2008)	Wang <i>et al.</i> (2004); Li <i>et al.</i> (2013)
Flood	5.1F	Reservoir construction leads to flooding of land upstream of the reservoir as flow or rivers is impeded.	<b>Three Gorges Dam, China, 2003</b> (Xu <i>et al.</i> , 2013)	
Storm (precipitation)	5.1L	Open pools of water result in greater evaporation and increases in rainfall.	<b>Chile</b> (Pizarro <i>et al.</i> , 2013)	Gonzales (1994); Degu <i>et al.</i> (2011)
Extreme Temperature (Cooling)	5.1R	Localised cooling effect, through an increase in evaporation.	<i>No Case Study Identified</i>	Gonzales (1994); Codrón (1994)

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: HYDROLOGICAL CHANGE				
ANTHROPOGENIC PROCESS TYPE: <b>DRAINAGE AND DEWATERING</b>				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Ground Collapse	6.1I	Removal of water results in the removal of hydraulic support, promoting the collapse of voids.	<b>Sidin Village, China, 1965</b> (Daoxian, 1988)	Stephens <i>et al.</i> (1984); Galloway <i>et al.</i> (1999)
Soil (Local) Subsidence	6.1J	Drainage and removal of water can result in consolidation of organic soils, and shrinkage of clay minerals.	<b>Nevada, USA, 1992-2000</b> (Katzenstein, 2000)	Hunt (2005)

<b>ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES</b>				
<b>ANTHROPOGENIC PROCESS SUB-GROUP: HYDROLOGICAL CHANGE</b>				
<b>ANTHROPOGENIC PROCESS TYPE: WATER ADDITION</b>				
<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Landslide	6.2D	Addition of water due to irrigation or poor drainage design increases pore pressures and reduces effective stress – thus promoting landsliding.	<b>Heifangtai, Gansu, China</b> (Xu <i>et al.</i> , 2012)	Varnes (1984); Alexander (1993)
Flood	6.2F	Addition of water due to irrigation or poor drainage design increases soil moisture saturation and thus promotes flooding.	<b>Kampala, Uganda, 1980s-</b> (Douglas <i>et al.</i> , 2008)	
Ground Collapse	6.2I	Addition of water due to irrigation or poor drainage design can result in dissolution of rock material or piping of sediment, and subsequent collapse of voids.	<b>Heifangtai, Gansu Province, China (1968-)</b> (Xu <i>et al.</i> , 2012)	Smalley and Marković (2014)
Ground Heave	6.2K	Addition of water due to irrigation or poor drainage design can result in the swelling of clay minerals and heave.	<b>Saskatchewan, Canada, 1961-</b> (Yoshida <i>et al.</i> , 1982)	Johnson and De Graff (1988)

<b>ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES</b>				
<b>ANTHROPOGENIC PROCESS SUB-GROUP: EXPLOSIONS</b>				
<b>ANTHROPOGENIC PROCESS TYPE: CHEMICAL EXPLOSION</b>				
<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	7.1A	Explosions (e.g., blasting) can change ground stress conditions, triggering the release of stored energy in the form of an earth tremor.	<b>Nigeria</b> (Aigbedion and Iyayi, 2007)	Cook (1976); Alexander (1993)
Tsunami	7.1B	Explosive energy results in the displacement of water and the generation of a tsunami.	<i>No Case Study Identified</i>	Le Méhauté and Wang (1996)
Landslide	7.1D	Explosions (e.g., blasting) increase the likelihood of slope failure through a deterioration of rock mass quality.	<b>Eskihisar, Turkey</b> (Sonmez and Ulusay, 1999) (Blasting noted to have weakened the rock mass)	Dvorák (1977); Davydov (1982); Alexander (1993)

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: EXPLOSIONS				
ANTHROPOGENIC PROCESS TYPE: CHEMICAL EXPLOSION				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Snow Avalanche	7.1E	Explosions (e.g., blasting) can cause ground vibrations, dynamically loading a snow pack and triggering an avalanche.	<b>Khibini Mountains, Russia, 1998</b> (Mokrov <i>et al.</i> , 2000)	Jamieson and Stethem (2002); Zarrini and Pralhad (2010)
Ground Collapse	7.1I	Explosions (e.g., blasting) can cause ground vibrations which lead to the collapse of underground voids.	<b>Guixian County, China, 1963</b> (Daoxian, 1988)	Tharp (1999)
Wildfire	7.1S	Release of thermal energy from explosions can trigger fires.	<b>Horsnell's Gully, Australia, 1957</b> (Cochrane <i>et al.</i> , 1962) (inferred)	

ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES				
ANTHROPOGENIC PROCESS SUB-GROUP: EXPLOSIONS				
ANTHROPOGENIC PROCESS TYPE: NUCLEAR EXPLOSION				
Natural Hazard	Grid ID	Description	Example Case Study	Relevant Literature (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Earthquake	7.2A	Explosions (particularly from underground nuclear tests) can change ground stress conditions, triggering the release of stored energy.	<b>USA, 1965</b> (Basham, 1969)	Teng <i>et al.</i> (1973); Alexander (1993); Pratt (2005)
Tsunami	7.2F	Explosive energy results in the displacement of water and the generation of a tsunami.	<i>No Case Study Identified</i>	Le Méhauté and Wang (1996)
Landslide	7.2D	Nuclear explosions can trigger slope failures through shaking, rapid changes to slope strength and deterioration of rock mass quality.	<b>Novaya Zemlya, Russia, 1973</b> (Adushkin, 2000)	Pratt (2005); Adushkin (2006)

**ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES****ANTHROPOGENIC PROCESS SUB-GROUP: EXPLOSIONS****ANTHROPOGENIC PROCESS TYPE: NUCLEAR EXPLOSION**

<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Snow Avalanche	7.2E	Nuclear explosions can trigger snow avalanches through shaking, temperature changes and deterioration of snow/ice pack quality.	<i>No Case Study Identified</i>	<i>Principle same as for rock avalanches: Adushkin (2000); Adushkin (2006)</i>
Ground Collapse	7.2I	Explosions (particularly from underground nuclear tests) can change ground stress conditions, triggering the collapse of underground voids.	<b>USA, 1958-</b> (Houser, 1969)	
Wildfire	7.2S	Significant thermal energy from a nuclear explosion can result in the triggering of wildfires.	<i>No Case Study Identified</i>	Ehrlich <i>et al.</i> (1983)

**ANTHROPOGENIC PROCESS GROUP: SUBSURFACE AND SURFACE PROCESSES****ANTHROPOGENIC PROCESS SUB-GROUP: COMBUSTION (FIRE)****ANTHROPOGENIC PROCESS TYPE: FIRE**

<b>Natural Hazard</b>	<b>Grid ID</b>	<b>Description</b>	<b>Example Case Study</b>	<b>Relevant Literature</b> (N.B. references describe further examples, processes related to the interaction, and mechanisms which support the inclusion of this interaction)
Wildfire	8.1S	Reckless lighting of fires or poor control/management of localised fires can result in wildfires being triggered.	<b>Ghana, Various</b> (Amissah <i>et al.</i> , 2010)	Nkomo and Sassi (2009)

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# Appendix C. Ethics Approval

Here we present confirmation by King's College London of ethics approval (issued on 18 April 2013) and an extension of this approval (issued on 8 May 2015).

18<sup>th</sup> April 2013

TO: **Joel Gill**  
SUBJECT: Full Approval of Ethics Application

Dear Joel,

**REP(GSSHM)/12/13-18: "Evaluating the multiple interactions between natural hazards"**

I am pleased to inform you that the above application has been reviewed by the GSSHM Research Ethics Panel that FULL APPROVAL is now granted.

Please ensure that you follow all relevant guidance as laid out in the King's College London Guidelines on Good Practice in Academic Research (<http://www.kcl.ac.uk/college/policyzone/index.php?id=247>).

For your information ethical approval is granted until 18/04/15. If you need approval beyond this point you will need to apply for an extension to approval at least two weeks prior to this explaining why the extension is needed, (please note however that a full re-application will not be necessary unless the protocol has changed). You should also note that if your approval is for one year, you will not be sent a reminder when it is due to lapse.

Ethical approval is required to cover the duration of the research study, up to the conclusion of the research. The conclusion of the research is defined as the final date or event detailed in the study description section of your approved application form (usually the end of data collection when all work with human participants will have been completed), not the completion of data analysis or publication of the results. For projects that only involve the further analysis of pre-existing data, approval must cover any period during which the researcher will be accessing or evaluating individual sensitive and/or un-anonymised records. Note that after the point at which ethical approval for your study is no longer required due to the study being complete (as per the above definitions), you will still need to ensure all research data/records management and storage procedures agreed to as part of your application are adhered to and carried out accordingly.

If you do not start the project within three months of this letter, please contact the Research Ethics Office.

Should you wish to make a modification to the project or request an extension to approval you will need approval for this and should follow the guidance relating to modifying approved applications:

<http://www.kcl.ac.uk/innovation/research/support/ethics/applications/modifications.aspx>

The circumstances where modification requests are required include the addition/removal of participant groups, additions/removal/changes to research methods, asking for additional data from participants, extensions to the ethical approval period. Any proposed modifications should only be carried out once full approval for the modification request has been granted.

Any unforeseen ethical problems arising during the course of the project should be reported to the approving committee/panel. In the event of an untoward event or an adverse reaction a full report must be made to the Chair of the approving committee/review panel within one week of the incident.

Please would you also note that we may, for the purposes of audit, contact you from time to time to ascertain the status of your research.

If you have any query about any aspect of this ethical approval, please contact your panel/committee administrator in the first instance (<http://www.kcl.ac.uk/innovation/research/support/ethics/contact.aspx>).

We wish you every success with this work.

Yours sincerely  
Research Support Assistant

**8 May 2015**

TO: Joel Gill

SUBJECT: Approval of Modification Request

Dear Joel,

**REP (GSSHM)/12/13-18 - Evaluating the multiple interactions between natural hazards**

Thank you for submitting a modification request for the above study. I am writing to confirm approval of this. The modification is summarised below:

1. The UK participant group will now include Hazard Professionals from all of the UK, not just the Merthyr Tydfil/Aberdare region.
2. An extension to the previous period of ethical approval. Approval is now granted until the **18<sup>th</sup> April 2016**.

If you have any questions regarding this application, please contact the Research Ethics Office.

Kind regards,

Research Support Assistant

**On behalf of**

GSSHM REP Reviewer

# Appendix D. Examples of Expanded Hazard Classifications

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## D1. Example: Volcanic Eruptions

Here we take the broad category of volcanic eruption, used in **Chapters 2 to 4**, and suggest one approach to adapt this into more specific sub-types. This enables to progress from considering ‘volcanic eruption’ to a broader classification of ‘volcanic activity’. There are existing classifications of volcanic activity and volcanic hazards, including those used in the regional interaction frameworks of Neri *et al.* (2008) and Neri *et al.* (2013), introduced in **Section 5.2**. The event tree presented by Neri *et al.* (2008) for Vesuvius (Italy) includes six stages: precursor, initiation, progression, dominant eruptive style, eruptive category, and generic hazards. Within each of these stages, there are different classifications. For example, generic hazards associated with explosive eruptions include fallout, pyroclastic density currents, ballistics, lahars/floods, landslides, tsunamis, and lava flow. Some of these we would consider, in the context of this thesis, to be triggered secondary hazards grouped under other classifications other than ‘volcanic activity’ (e.g., tsunamis, landslides). Others help to form the basis for an expanded classification of volcanic activity.

A specific classification of volcanic hazards, rather than the broader classification of volcanic eruption, facilitates the inclusion of different stages of the eruptive cycle. This would give decision makers enhanced information when assessing the spatial and temporal relevance of possible secondary hazards. For example, if we were to include subterranean magma movement as a hazard sub-type, this would enable the characterisation of seismic activity triggered by magma movement during quiescence, or through the movement of magma from one volcano interacting with water close to another volcano (Hutchison, 2014). Detailed classifications of volcanic hazards also help us to differentiate different types of volcano, and the hazards that they are associated with.

In the context of Central American stratovolcanoes (e.g., Fuego, Guatemala), Alvarado *et al.* (2007) notes the following possible hazard sub-types (i) magma movement (subterranean), (ii) volcanic gas emissions, (iii) lava flows, (iv) air-fall tephra, (v) pyroclastic density currents, and (vi) volcanic explosions (either vertical or lateral). Given that this classification relates to volcanoes in Central America, we take this example sub-classification, and use it in a hazard

interaction matrix, shown in **Figure D.1**. We show our original classification of ‘volcanic eruptions’, but now also include the six hazard sub-types identified above on the vertical axis of an interaction matrix. The same style and format as previous interaction matrices (e.g., **Figure 2.2**) is used. The horizontal axis contains the original 21 natural hazards described in **Table 2.2**, as secondary hazards. Footnotes, detailing each interaction, are also included. As with our initial classification of 21 natural hazards presented in **Table 2.2**, alternative approaches are possible and this is just one way to further classify volcanic eruptions.

Expanding the original classification of ‘volcanic eruptions’ to now include six hazard sub-types associated with volcanic activity gives a more comprehensive overview of possible interactions. We note from **Figure D.1** that these six sub-hazards collectively trigger and/or increase the probability of 12 different secondary hazards, with a total of 29 interactions. Our previous assessment of natural hazard interactions (**Figure 2.2**), using the classification ‘volcanic eruption’ indicated that volcanic eruptions could trigger and/or increase the probability of 10 different secondary hazards, with a total of 10 interactions. The inclusion of subterranean magma movement (during quiescence) allows the additional identification of volcano-volcano interactions, and ground heave (surface deformation). The six new sub-types of volcanic activity could also be integrated into the secondary hazards of the interaction matrix.

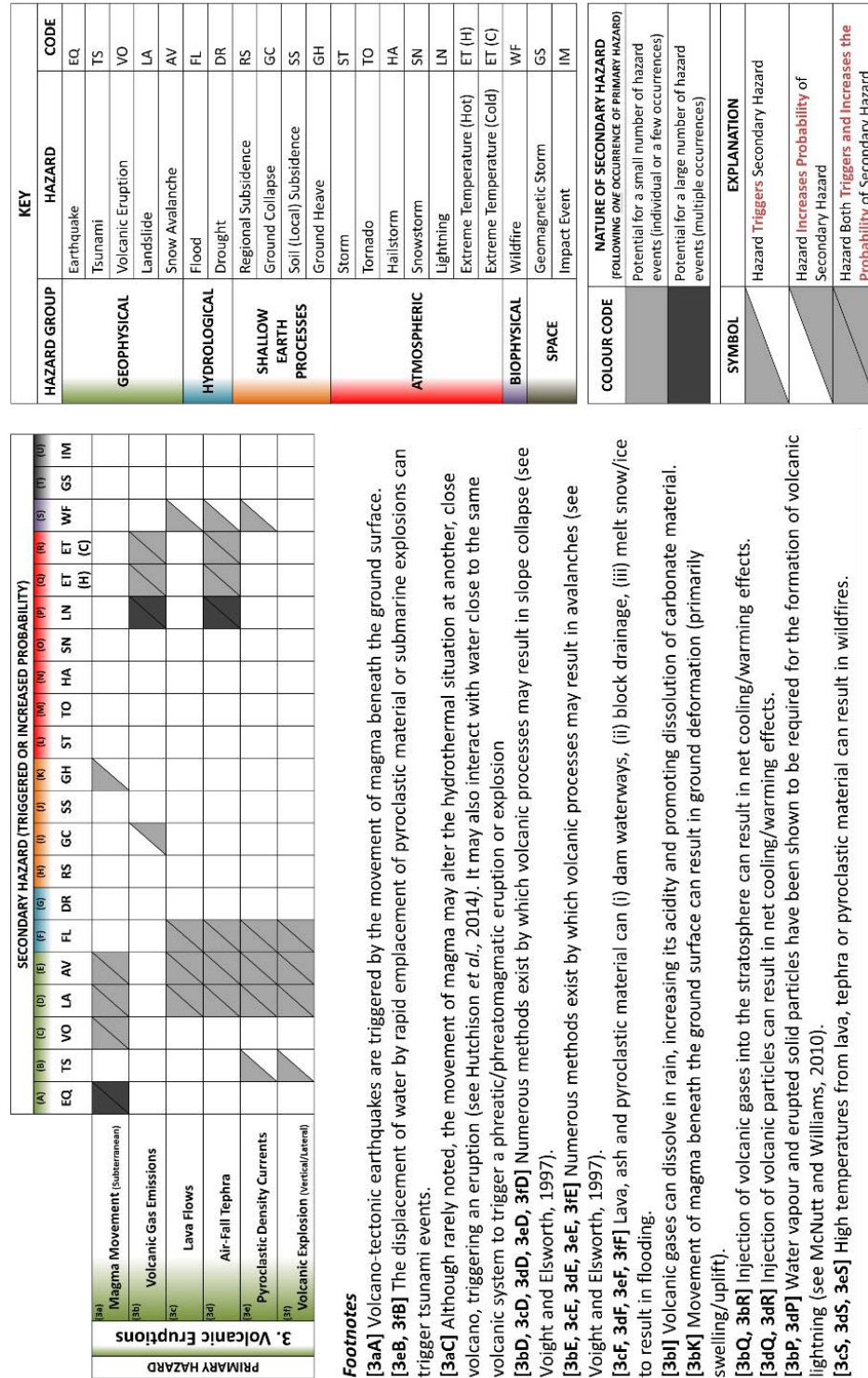
## **D2. Example: Landslides**

The broad classification of *landslide*, also used in previous global interaction frameworks (e.g., **Figure 2.2**) can also be sub-divided into specific sub-types. Selected landslide sub-types would likely depend on the geographical location, underlying geology and soil depth and type. In some volcanic regions, for example, the mobilisation of pyroclastic material as lahars will be a relevant and frequently observed type of mass movement. In other volcanic and non-volcanic areas, lahars will not be frequently observed or relevant. Landslide classification schemes have been described in the literature (Varnes, 1978; Cruden and Varnes, 1996; Hungr *et al.*, 2014), generally using a two-parameter classification that combines movement type with material type. These three classifications are widely cited, with recent examples of them being used by others. For example, Ciurleo *et al.* (2016) used Varnes (1978) to classify landslide types in the Calabria Region of Italy; and Jacobs *et al.* (2016) classify landslides in Uganda using both Cruden and Varnes (1996) and Hungr *et al.* (2014). Other classification schemes do exist, for example Gaprindashvili and Van Westen (2016) note a simple three type classification used in Georgia, grouping landslides into mudflows, slides and rockfalls

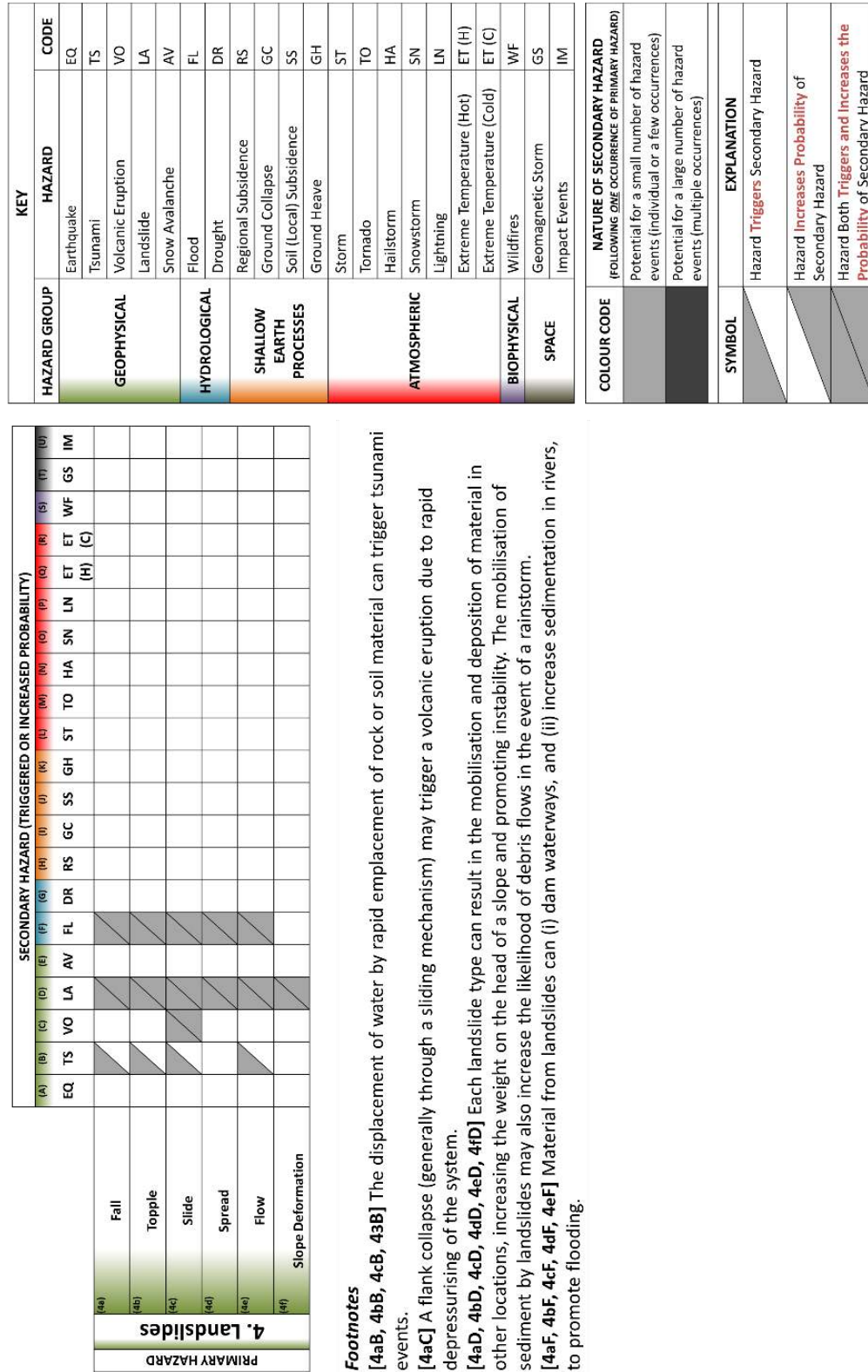
The most recent of these three landslide classifications (Hungr *et al.*, 2014) described 32 possible landslide-type keywords. Expanded classifications are beneficial, but there are also limitations associated with their use. The inclusion of 32 different landslide categories is likely to be too detailed for an interaction framework to retain its utility. Detailed classifications may result in a regional interaction framework struggling to effectively synthesise a large amount of information for ease of understanding and use by stakeholders. A further challenge with using large number of hazard sub-types is the generation of asymmetry within the interaction matrix. The interaction matrix would be highly asymmetrical if it included 32 landslide sub-types, and only six volcanic activity sub-types and one sub-type of wildfire for example. In some of the regional interaction frameworks described in [Section 5.2](#), asymmetry existed in the classifications of natural hazards. Extensive sub-classifications were used for some natural hazards, and broad classifications used for others. If asymmetry exists in the classifications used for different natural hazards, this should be taken into consideration when interpreting the interaction framework. A balance must be achieved between using detailed classifications of natural hazards and maintaining clarity and ease of use.

The assessment of key landslide types in the region of interest would be an initial helpful step in an improved landslide classification scheme, with these being collapsed into several landslide sub-types. In [Figure D.2](#) we take the broad classification ‘*landslide*’ and divide this into six hazard sub-types: (i) fall, (ii) topple, (iii) slide, (iv) spread, (v) flow, and (vi) slope deformation (e.g., creep). These are drawn from the principal landslide types in Varnes (1978), Cruden and Varnes (1996), and Hungr *et al.* (2014). This is again one example of an expanded classification, with other alternatives possible. The six hazard sub-types (i)–(vi) are placed as primary hazards on the vertical axis of [Figure D.2](#), an interaction matrix that uses the same style and format as previous interaction matrices (e.g., [Figure 2.2](#)). The horizontal axis contains the original 21 natural hazards described in [Table 2.2](#), as secondary hazards. Footnotes, detailing each interaction, are also included.

When using this expanded classification of landslides, we note from [Figure D.2](#) that the six hazard sub-types collectively trigger and/or increase the probability of 4 different natural hazards, with a total of 16 interactions. Our previous assessment of natural hazard interactions ([Figure 2.2](#)), using the classification ‘*landslide*’ indicated that landslides could trigger and/or increase the probability of 4 secondary hazards, with a total of 4 interactions. The six landslide sub-types could also be integrated into the secondary hazards of the interaction matrix.



**Figure D.1. Sub-classification of volcanic activity and identified hazard interactions.** A 6 × 21 matrix, with primary hazards on the vertical axis and secondary hazards on the horizontal axis. Primary hazards are limited to six sub-types, grouped under the broad category of ‘volcanic eruption’. Secondary 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).



**Footnotes**

[4aB, 4bB, 4cB, 4dB] The displacement of water by rapid emplacement of rock or soil material can trigger tsunami events.

[4aC] A flank collapse (generally through a sliding mechanism) may trigger a volcanic eruption due to rapid depressurising of the system.

[4aD, 4bD, 4cD, 4dD, 4eD, 4fD] Each landslide type can result in the mobilisation and deposition of material in other locations, increasing the weight on the head of a slope and promoting instability. The mobilisation of sediment by landslides may also increase the likelihood of debris flows in the event of a rainstorm.

[4aF, 4bF, 4cF, 4dF, 4eF] Material from landslides can (i) dam waterways, and (ii) increase sedimentation in rivers, to promote flooding.

**Figure D.2. Sub-classification of landslides and identified hazard interactions.** A 6 × 21 matrix, with primary hazards on the vertical axis and secondary hazards on the horizontal axis. Primary hazards are limited to six sub-types, grouped under the broad category of ‘landslides’. Secondary 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.

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# Appendix E. Guatemala Hazards Background

## Single Natural Hazards and Interactions of Guatemala

A description of 17 individual single natural hazards in Guatemala, including a characterisation of their origin and dynamics. This information is used in [Chapter 6](#).

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### [E1](#) Introduction and Summary of Appendix E

In [Appendix E](#) we use 169 references (93 peer-review and 76 grey-literature sources) to characterise the origin and dynamics of 17 natural hazards of relevance to Guatemala. [Appendix E](#) facilitates the identification of relevant natural hazards, appropriate classification schemes for these natural hazards, and relevant natural hazard interactions. This information is used in [Section 6.5](#) to construct regional hazard interaction frameworks for Guatemala.

This appendix is not presented as a full systematic review of all aspects of every Guatemala relevant natural hazard type. Rather we present a comprehensive and evidenced overview of 17 diverse natural hazards, with the purpose of being able to synthesise relevant interaction relationships. We also do not attempt to characterise the likelihood of each single natural hazard, or the likelihood of interaction pairings. Some information is included that gives a coarse resolution impression of how frequently different events occur, however we do not develop an interaction framework that includes likelihood information. For natural hazards which can impact a large spatial extent (multiple countries) we also include background context from Central America. The scope of this overview goes beyond existing reviews in the literature:

- i. Bundschuh and Alvarado (2007) presents a detailed overview of aspects of four (of our 17) natural hazards in Central America, with sections on earthquakes and volcanic eruptions, and earthquake triggered tsunamis and landslides.

- 
- ii. The GFDRR ThinkHazard! tool (GFDRR, 2016) describes the spatial relevance of seven (of our 17) natural hazards (river and coastal flood, earthquake, cyclone, volcano, landslide, and water scarcity)
  - iii. PreventionWeb (2015) synthesise the frequency of hazards (1990–2014), using data from the CRED EM-DAT database. This includes seven (of our 17) natural hazards (drought, earthquake, extreme temperature, flood, landslide, storm, and volcano).
  - iv. DesInventar (2016) gives loss detail for events that occurred from 1988–2013. Each loss event can be categorised under 30 different natural, biological and technological hazard types (e.g., landslides, epidemic and structural collapse). Of the natural hazards included in DesInventar (2016), 12 (of our 17) natural hazards are considered (with some of these 12 including more than one of the 30 original categories). We refer to the DesInventar (2016) database through this appendix, particularly to discuss natural hazards for which there is little other literature available (e.g., lightning, hailstorms). Where other literature is available to characterise the natural hazard, we generally do not refer to the DesInventar database as data from this is already incorporated into this literature. For example, in [Section E7](#) we discuss flooding in Guatemala, noting the example of Soto *et al.* (2015), which used information from DesInventar.

There are also helpful overviews in the literature of broad hazard types in Guatemala, and the history of hazards associated with one spatial location. For example, volcanic activity in Guatemala is outlined in Brown *et al.* (2015), and a detailed overview of activity at the volcano Santiaguito is presented in the relevant section of the Global Volcanism Program (2013). Finally, there exist many publications associated with specific case studies including one or more natural hazards. For example, Seed *et al.* (1981) discussed liquefaction near Lake Amatitlán, as a result of the 1976  $M_w = 7.5$  earthquake.

We begin by giving an overview of the natural environment associated with the study area, including the tectonic and climatic environment ([Section E2](#)). We then proceed to characterise each of the following individual natural hazards, and their associations with other natural hazards: earthquakes ([Section E3](#)), tsunamis ([Section E4](#)), volcanic eruptions ([Section E5](#)), landslides ([Section E6](#)), floods ([Section E7](#)), droughts ([Section E8](#)), shallow Earth processes, including ground collapse, subsidence and heave ([Section E9](#)), storms and tropical cyclones ([Section E10](#)), other meteorology phenomena (lightning, hailstorms, tornadoes and extreme temperatures) ([Section E11](#)), and wildfires ([Section E12](#)).

**Note to Reader:** Appendix E has been omitted from the e-thesis due to inclusion of third party copyright material for which permissions could not be granted. Please contact the author for further information on this Appendix. References used are noted below.

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# Appendix F. Guatemala Field Observations

## Field Observations

A description of 4 field visits made in Guatemala, and the natural hazards and interactions observed and discussed. This information is used in [Chapter 6](#).

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### F1 Lake Atitlán (San Pedro La Laguna)

Lake Atitlán was visited from 19–29 January and 13–15 February 2014, with most of this time in San Pedro La Laguna, Sololá Department. Lake Atitlán, with a surface area of 130 km<sup>2</sup>, (INSIVUMEH, 2016), is surrounded by steep topography, including the volcanoes of Atitlán, Tolimán and San Pedro. The town of San Pedro La Laguna sits at the foot of the volcano San Pedro and on the shores of Lake Atitlán. [Figure F.1 \(top left\)](#) shows the eastern flank of the volcano San Pedro, and [Figure F.1 \(top right\)](#) gives a birds-eye perspective of the town of San Pedro La Laguna, at the base of the northern flank of San Pedro and on the shore of Lake Atitlán. It is a popular tourist destination, with several Spanish schools in the town. There is also agriculture in the region, including coffee plantations. The town is expanding, with unregulated slope development, as shown in [Figure F.1 \(bottom left\)](#), including houses adding extra floors to expand upwards. It is unclear if foundations are initially designed to support this increased load. One issue faced by residents of San Pedro La Laguna is changing lake levels, with flooding observed due to recent rises in lake levels. [Figure F.1 \(bottom right\)](#) shows the level of Lake Atitlán, as of January 2014. Rising waters have impacted property at the edge of the lake.

This region is susceptible to rainfall triggered landslides (Burchfiel, 2012). For example, grey literature reports a landslide on the volcanic flanks of San Pedro associated with Tropical Storm Agatha (Lynch, 2010). Mass movements in the high-relief topography around the lake have the potential to trigger lake tsunamis (Luna, 2007). Sedimentation from debris flows and landslides may also exacerbate flooding due to rising lake levels. Water enters Lake Atitlán from the surrounding topography, and is primarily removed through drainage into groundwater aquifers through fractures (Newhall *et al.*, 1987). During periods of heavy rain, the lake level will typically rise by 1–1.5 m, with drainage into groundwater aquifers then resulting in the lake level to fall (Newhall *et al.*, 1987). Frequent landslides may result in sedimentation blocking these fractures. This theory is supported by a reported 2 m drop in the level of Lake Atitlán after the 4 February

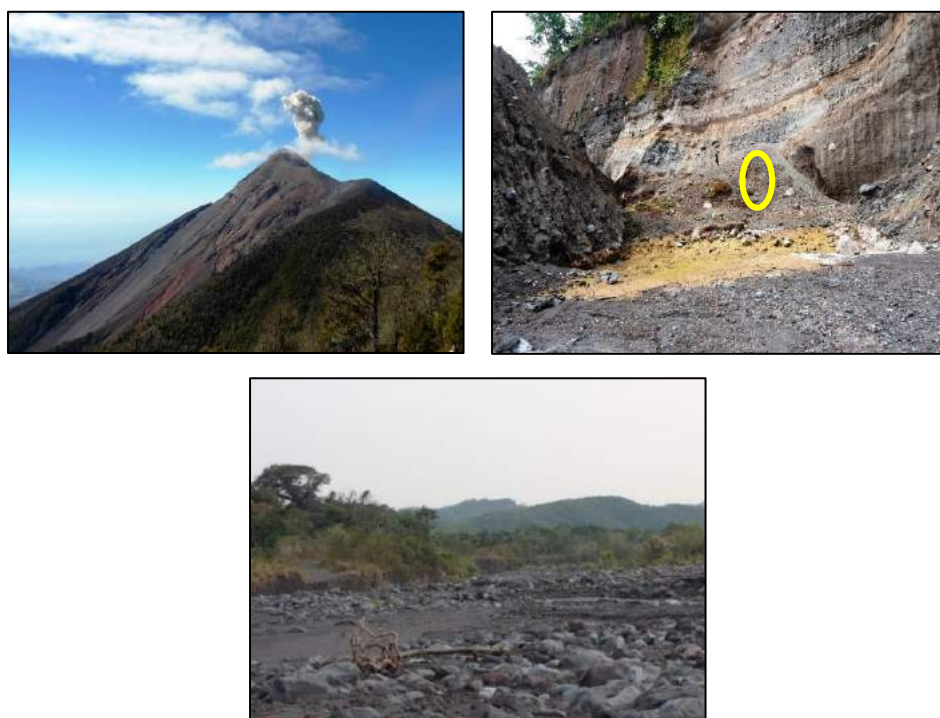
1976,  $M_w = 7.5$  earthquake (Newhall *et al.*, 1987), likely as a result of the opening of new fractures to facilitate drainage. Through this example, we therefore observe interactions that occur over a short, rapid timescale (i.e., the triggering of a landslide during Tropical Storm Agatha), and interactions that occur over a longer timeframe (i.e., the regular occurrence of heavy rain over one or more wet seasons resulting in rising lake levels and flooding).



**Figure F.1. San Pedro La Laguna, Lake Atitlán (Sololá Department).** The multi-hazard environment around San Pedro La Laguna. (**Top left**) the eastern flank of San Pedro bordering Lake Atitlán. (**Top right**) San Pedro La Laguna sitting between the northern flank of San Pedro and Lake Atitlán. (**Bottom left**) unregulated urban development in San Pedro. (**Bottom right**) the level of Lake Atitlán has risen in recent years, as evidenced by this flooded building. Author's photographs, taken in January to February 2014.

## F2 Eruption of Fuego, Lahars and Flooding

Fuego is an active volcano, located at the point where three Departments meet (Chimaltenango, Escuintla and Sacatepéquez Departments). Fuego was visited from 8–12 February 2014. During visits to Fuego and the surrounding area, several small eruptions were observed, each generating tephra. **Figure F.2 (top left)**, taken from the flanks of Acatenango (a neighbouring volcano), shows one small eruption. During large eruptions, significant pyroclastic density currents can be generated, producing large volumes of tephra. In **Figure F.2 (top right)** the extent of one pyroclastic density current from 2012 can be observed (note the person in the background, yellow circle, for scale). This deposit almost fills the steep-sided gully, termed a ‘barranca’ in Guatemala. During heavy rain, pyroclastic material can be mobilised as lahars, moving large distances away from the volcanic source. In **Figure F.2 (bottom)** we show the deposits of one lahar close to Fuego, which destroyed an important access road. Further mobilisation of this material will result in being transported further down the hydrological system, resulting in river sedimentation and triggering flooding.



**Figure F.2.** Fuego (Chimaltenango, Escuintla and Sacatepéquez Departments). The multi-hazard environment around the volcano Fuego. **(Top left)** The northern flank of Fuego, taken from Acatenango. **(Top right)** Pyroclastic density current deposits from a 2012 eruption of Fuego, in a barrancas, with a person circled in yellow for scale. **(Bottom)** Lahar deposits in *Barranca Ceniza*, mobilised from pyroclastic material and deposited in 2012. Author’s photographs, taken in February to March 2014.

### F3 Lake Atitlán: Tolimán and Panabaj

In addition to visiting San Pedro La Laguna on the shores of Lake Atitlán, a short visit to the flanks of the volcano Tolimán and the town of Panabaj was made between 13–15 February 2014. During this visit the volcano San Pedro was climbed to view the topography of the area around Tolimán. In **Figure F.3 (left)** we show the volcanoes of Tolimán (left of image) and Atitlán (right of image). The combination of steep topography, unconsolidated volcanic soils, and heavy rainfall in this region results in a high susceptibility to landslides. In **Figure F.3 (right)** we show one example of a landslide, which impacted the town of Panabaj. On 5 October 2005, heavy rains associated with Hurricane Stan mobilised soils on the slopes of volcano Tolimán (**Figure F.3, left**), generating a debris flow that buried the village of Panabaj (**Figure F.3, right**). This disaster resulted in more than 1000 fatalities Luna (2007). As noted previously, other debris flows in this region have resulted in the triggering of tsunamis (Luna, 2007).



**Figure F.3. Tolimán and Panabaj, Lake Atitlán (Sololá Department).** The multi-hazard environment around Lake Atitlán, that resulted in a disaster at Panabaj. (**Left**) the volcanoes Tolimán (left) and Atitlán (right). (**Right**) the town of Panabaj sits between these two volcanoes, with much of it buried during the debris flow of 2005. The image shows a house impacted by this debris flow, with the lahar deposits still visible on the exterior walls. Photographs taken in February 2014.

## F4 Eruption of Santiaguito and Erosive Lahars

The environment around the Santiaguito lava dome and Santa María (Quetzaltenango) was visited from 16–19 February 2014. This included visits to the INSIVUMEH observatory close to Santiaguito, a climb of Santa María to observe Santiaguito, and visits to sites affected by pyroclastic density currents, lahars and floods in Quetzaltenango and the neighbouring Retalhuleu Department. In **Figure F.4 (top left and right)** we show the Santiaguito lava dome, and the eruption of tephra. In **Figure F.4 (bottom left)** we show the erosive capacity of lahars originating from Santiaguito, resulting in the formation of a gorge. In **Figure F.4 (bottom right)** we show the impact of material mobilised during lahars on the Samalá river. Lahars can trigger flooding in this region and the coastal lowlands. Hazards associated with this region have also been well-documented in the literature (e.g., Flynn *et al.*, 2002; Cepero, 2003; Harris *et al.*, 2006; Soto, 2015).



**Figure F.4. Santiaguito Lava Dome (Quetzaltenango/Retalhuleu Departments).** The multi-hazard environment associated with the Santiaguito lava dome. (**Top left and right**) the Santiaguito lava dome, taken from Santa María, showing the start of a small eruption. (**Bottom left**) lahars originating from Santiaguito have significant erosive capacity, resulting in the formation of a new river stream gorge, cutting through a town. (**Bottom right**) lahar material enters the Samalá river, and can trigger flooding in this region and the coastal lowlands. The bridge shown is on an important economic transportation route (Highway CA-2) between Guatemala and Mexico. Author's photographs, taken in February 2014.

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# Appendix G. Workshop Visualisations

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<b>Figures G17–31.</b> Stakeholder identification (using 7×11 hazard interaction matrix) of possible hazard interactions in Guatemala .....	515

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**Note to Reader:** Appendix G has been omitted from the e-thesis as it relates to Chapters 5 and 6 which are not included in this version. Please contact the author for further information on this Appendix.

# **Appendix H. Guatemala National Interaction Matrix (Evidence Sources)**

**Note to Reader:** Appendix H has been omitted from the e-thesis as it relates to Chapters 5 and 6 which are not included in this version. Please contact the author for further information on this Appendix.

## Appendix I. Southern Highlands (Guatemala) Interaction Matrix

**Note to Reader:** Appendix I has been omitted from the e-thesis as it relates to Chapters 5 and 6 which are not included in this version. Please contact the author for further information on this Appendix.